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The governance of plant breeding - a social-ecological systems perspective

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To all those who want to seed change . . .

Kurzfassung

Durch den Klimawandel und gesellschaftliche Konflikte erhöht sich zunehmend der Druck auf moderne Agrarsysteme sich zu nachhaltigeren Systemen zu transformieren. Im Zentrum dieser systemischen Transformation zu einer nachhaltigen Landwirtschaft steht das Saatgut zur Produktion von Nahrungs- und Futtermitteln sowie zur Produktion von Pflanzenfasern. Um hohe Erträge zu erreichen benötigen Landwirt*innen Sorten die die entscheidenden Eigenschaften in sich vereinen und sowohl zu den jeweiligen Boden-Klimaräume ihrer Standorte passen als auch die gewünschten Produktqualitäten gewährleisten. Doch der Weg von der Entwicklung dieser Eigenschaften bis zum Anbau auf dem Acker führt durch ein komplexes sozial-ökologisches System.

Jedes Kapitel dieser Dissertation setzt sich mit verschiedenen Organisationsprinzipien sozial-ökologischer Systeme und deren Konsequenzen für die Steuerung, Führung und Governance von Pflanzenzüchtungs- und Saatgutsysteme auseinander. Saatgutsysteme umfassen alle Aktivitäten entlang der Wertschöpfungskette der Saatgutentwicklung und -vermarktung, die notwendig sind, um neue Sorten auf den Acker zu bringen. Die Saatgutentwicklung ist dabei auf eine zuverlässige Weitergabe von genetischem Material durch das Saatgut und Anbausystem angewiesen. Die verschiedenen Aktivitäten werden durch Regeln, Normen und Strategien strukturiert, den sogenannten Institutionen (Ostrom 2005). Um nachhaltigere Ergebnisse zu ermöglichen, müssen diese Institutionen bewusst verändert werden. Die Prozesse, die notwendig sind, um Institutionen zu gestalten, zu erhalten, zu steuern, zu erkennen und durchzusetzen, werden als Governance der Saatgutsysteme bezeichnet. Die Dissertation beschäftigt sich mit der generellen Frage wie die Governance von Saatgutsystemen am besten aussehen sollte um nachhaltigere Saatgut- und Agrarsysteme zu erreichen.

In Kapitel 2 wird untersucht, welchen Herausforderungen sich das Saatgutsystem bei der Steuerung und Organisation der Bereitstellung und Verwendung von genetischer

Vielfalt von Kulturpflanzen stellen muss. Wir haben festgestellt, dass die Bereitstellung symmetrischer und glaubwürdiger Informationen zwischen verschiedenen Akteursgruppen ein reibungslos funktionierendes Saatgutsystem gewährleistet. Im Anschluss, Kapitel 3, analysieren wir vernetzte und angrenzende Handlungssituationen (nested adjacent action situations) sozial-ökologischer Systeme und stellen einen diagnostischen Fragenkatalog zur Verfügung, welcher die vernetzten und mehrschichtigen Variablen des Ressourcensystems für mittlere bis große sozial-ökologische Systeme beinhaltet. In Kapitel 4 entwickeln wir eine Faustformel für die Governance der Pflanzenzüchtungsforschung, welche belegt, dass Genetik, Umwelt, Bewirtschaftung und Rückkopplungen aus dem Sozialen System (GxExMxS) als Kernelemente bei der zielorientierten Governance der Pflanzenzüchtungsforschung zu berücksichtigen sind. Kapitel 5 ist eine empirische Arbeit, die analysiert ob sich Schädlingsepidemien auf die Entscheidungen in der Saatgutvermehrung zur Allokation von Vermehrungsflächen auswirkt. Dies konnte für Vermehrungsflächen in Bayern nicht nachgewiesen werden.

Schlüsselwörter: *genetische Diversität, Neue Institutionen Ökonomie, Pflanzenzüchtung, Saatgutproduktion, Saatgutvermehrung, biotische Schocks, Schädlingsepidemien, Saatgutsysteme, Klimawandelabmilderung, Weizen, soziale Faktoren, missionsorientierte Governance, Forschungspolitik, Missionsziele, nachhaltige Agrarsysteme, sozial-ökologisches Systemframework, genestete Ressourcensysteme, diagnostic, Fallanalyse, Saatgut, Governance, Sortenversuche*

Abstract

Climate change and social conflicts put modern agricultural systems under pressure, necessitating systemic transformations of these systems towards sustainability. At the core of these sustainability challenges to agriculture lie the seed we use to produce plants giving us food, feed and fiber. To achieve high crop yields, farmers need varieties with the right combination of characteristics, called traits, which fit to the pedo-climatic conditions of their farms and to other preferences regarding product qualities. The route from developing a trait combination in a plant that such characteristics, however, is long and novel traits need to pass through a complex social-ecological system to reach the farm gate.

Each chapter of this thesis engages with different organizing principles of social-ecological systems and what they mean for the governance of plant breeding within the seed systems. Seed systems entail all activities along the breeding and seed supply chain needed for creating (new) varieties for use on farms. These activities of plant breeding depend on sustained flows of genetic material within the seed and cropping system. The various activities are structured by rules, norms and strategies, also referred to as institutions (Ostrom 2005). Institutions need to be designed consciously to achieve sustainable outcomes. The aggregated processes of creating, maintaining, directing, recognizing, and enforcing institutions are the governance of the seed system. Overall the thesis inquires how to best govern seed systems towards more sustainable outcomes in seed and cropping systems.

Hence, we first ask what the governance challenges are in providing and appropriating crop genetic diversity as the underlying resource. We found that provisioning symmetric and credible information between different actor groups will grant a smoothly running seed system. Second, we further unpack the activities around the nested adjacent action situations for social-ecological systems and provide a set of diagnostic questions to untangle the nested and multi-tiered variables of the resource system within mid to large-scale SESs. Third, we develop a governance heuristic showing that Genetics, Environment, Management and Social system (GxExMxS) are core elements, which need to be considered when governing plant breeding research under the premise of mission-oriented governance. Fourth, we ask the question whether pest shocks lead to a increase in multiplication area of resistant varieties. Using data from seed variety trials matched with data on seed multiplication area per variety. The no-effect hypothesis could not be refuted.

Keywords: *genetic diversity, new institutional economics, plant breeding, seed production, seed multiplication, biotic shock, pest epidemics, seed system, climate change mitigation, wheat, social factors, mission-oriented governance, research policy, mission goals, sustainable agricultural systems, social-ecological systems framework, nested resource systems, diagnosis, case study analysis, seed, governance, seed variety trials*

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List of Abbreviations

A	**A**ctor
AS	**A**ction **S**ituation
c.p.	**c**eteris **p**aribus
CAS	**C**omplex **A**daptive **S**ystem
DiD	**D**ifference-**in**-**D**ifferences
GS	**G**overnance **S**ystem
Ha	**H**ectars
NAAS	**N**etworked **A**djacent **A**ction **S**ituation
NRS	**N**ested **R**esource **S**ystem
RU	**R**esource **U**nit
RS	**R**esource **S**ystem
SDG	**S**ustainable-**D**evelopment **G**oal
SES	**S**ocial-**E**cological **S**ystem
SESF	**S**ocial-**E**cological **S**ystem **F**ramework
SESMAD	**S**ocial-**E**cological **S**ystems **M**eta-**A**nalysis **D**atabase

Chapter 1

Overview of Thesis

1.1 Background and motivation

Increasing anthropogenic pressure on our earth systems (Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015) has brought about global challenges like climate change (Pachauri et al., 2014) and is accompanied by social conflicts such as the war in Ukraine (Behnassi & El Haiba, 2022). These social and ecological changes put immense pressure on agricultural systems (Pretty, 2018). They influence food security, as local control, access and productivity are hampered. This can skew the allocation of crop staples, necessitating systemic transformations to achieve more sustainable systems (Sachs et al., 2019). Issues of environmental and social sustainability in agricultural systems are intertwined. They result from the interaction of multiple, mutually reinforcing or attenuating social and ecological processes at multiple scales. Social processes include technological, cultural, political and economic processes, whereas ecological include biotic (e.g. host-pathogen dynamics) and abiotic processes (e.g. climate patterns, soil nutrient cycling) (Folke, Biggs, Norström, Reyers, & Rockström, 2016).

At the core of all these sustainability challenges to agriculture lie the seed we use to produce plants giving us food, feed and fiber (Sachs et al., 2019). To achieve high crop yields, farmers need varieties with the right combination of characteristics, called traits, which fit the pedo-climatic conditions of their farms and other human preferences, e.g. baking qualities, they want to achieve. Yet, the route from developing a trait combination in a plant that is more drought tolerant or more pest resistant is long and novel traits need to pass through many hands, before they reach the farm gate (see chapter 2 and 4 for descriptions of different parts of the breeding supply chain).

The plethora of activities allocating seed and changing their characteristics lead from pre-breeding in scientific labs and nurseries to farms. These activities are structured by rules, norms and strategies, also referred to as institutions (Ostrom, 2005). Ostrom (2005, p.3) defined that "institutions are the prescriptions that humans use to organize all forms of repetitive and structured interactions including those within families, neighborhoods, markets, firms, sports leagues, churches, private associations, and governments at all scales." Broadly speaking institutions are rules, norms, and strategies structuring the situations individuals navigate. Within these so-called action situations individuals faced with choices regarding what to do of which each would result in different outcomes (Ostrom, 2005). The prescriptions for human behavior will determine how and where seed and other plant material is allocated. These aggregated processes of creating, maintaining, directing, recognizing, and enforcing these prescriptions are the governance of the seed system. McGinnis (2011a, p.171) defines governance as "process by which the repertoire of rules, norms and strategies that guide behaviors within a given realm of policy interactions are formed, applied, interpreted and reformed (. . .) *governance determines who can do what to whom, and on whose authority*."

In response to the grand challenges mentioned above we need governance to be working effectively and efficiently towards the goals our societies set out for within our ecological contexts. For the different chapters within this thesis these goals of societies revolve around creating sustainable and resilient systems, where we can meet the needs of all (Raworth, 2017) while staying within the boundaries of our earth systems (Rockström et al., 2009). Yet, in order to craft institutions effectively we need to understand what we are doing, when we govern seed systems. To understand the institutions in seed systems one needs to know what they are, why and how they are being crafted and maintained and what consequences they generate in diverse parts of our seed and agricultural systems. This thesis works towards enhancing our understanding of the institutions in seed systems and hence contributes towards the broader question:

How do we best govern seed systems?

The German seed systems can be divided into different processes undertaken by

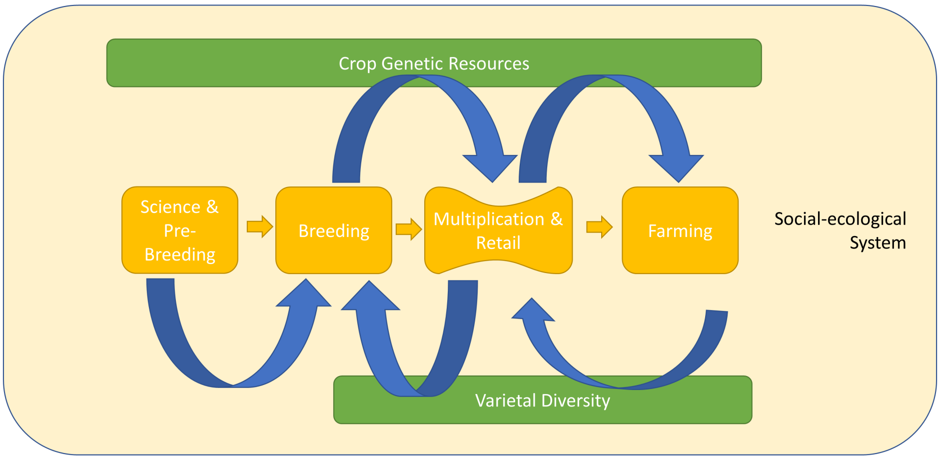

FIGURE 1.1: Overview of seed system processes in focus of thesis.

actor groups passing seed material along their supply chain. The first step along this chain is the creation of traits, variety characteristics, which usually demand lengthy processes of research by plant scientists in a process called pre-breeding, see figure 1.1 (Acquaah, 2007; Becker, 2011). The next step is that breeders will then try to introduce the newly developed traits into current higher yielding crop material, usually referred to as (breeding) lines (Acquaah, 2007; Becker, 2011). Lines are then crafted into varieties. Depending on the crop, some form of contracting between breeders and seed multiplication organizations will take place allocating the portfolios of varieties to be multiplied, seed grown, and then sold to farmers by retailers (Erbe, 2002; W. Thiel, 2014), see yellow boxes and arrows in figure 1.1. While flows of seed and other plant materials pass through the system, represented by the blue arrows in figure 1.1, they change their material forms and overall allelic distributions of the underlying crop genetic resources.

Seed systems entail all activities along the breeding and seed supply chain needed for creating (new) varieties for use on farms. Hence they preset the direction agricultural systems are steered towards in terms of their productivity (Olmstead & Rhode, 2008), resilience (Kliem & Sievers-Glotzbach, 2021), transitioning from one state to another (Sievers-Glotzbach & Tschersich, 2019), potential collapse (Raeburn, 1995; Singh et al., 2008), allocation of agricultural resources, and which kinds of outputs can actually be produced under various pedo-climatic, biotic and socio-economic conditions. Seed systems depend on genetic diversity as their underlying resource for the activities taking place. The flows of genetic material[1] and its corresponding information provide actors with the means for changing and allocating seed materials.

Seed systems are social-ecological systems (SESs) (Berkes & Folke, 1998), as they integrate strong connections and feedback between their social and ecological components that determine the overall emergent dynamics in their outcomes, like changing crop productivity, crop pathogen epidemics or changes in qualities (e.g. baking qualities of flours). Seed and genetic material are not just biological entities sprung from natural selection, but a biotechnology constantly changed by humans (Karafyllis, 2006) and influenced by their co-evolution with nature (Søgaard Jørgensen et al., 2020). Seed materials are social and ecological entities at the same time. Seed are an input, output and (bio)technology for agricultural production - in the case of cereals in a single grain (Gerullis, 2016).

Preiser, Biggs, De Vos, and Folke (2018) identified organizing principles of complex adaptive systems (CASs), which inform our understanding of SESs. The first principle is that SESs are constituted relationally, meaning that the relations and interactions between the sub-components of the SES are more important to our understanding of the whole system than the properties and behavior of the sub-components in themselves. Approaching the seed system with the premise that we are dealing with a SES deviates from preceding research. We distinguish between the resource system (RS; being all those biological and technical means bringing about respective physical units of genetic and seed materials) compared to the resource units (RUs), which are the physical units of genetic and seed material itself. Looking at seed systems as SESs also implies that we examine institutions and their governance by looking at how they lead to better or worse provisioning and appropriation of the RSs and the RUs. Hence we ask our

[1]Genetic material refers to allelic snippets (variants of genes at gene loci), genetic traits (aggregation of specific allelic combinations), breeding lines (aggregation of genetic traits in plants over several generations), experimental variants, and varieties in the form of seed.

Research question of chapter 2: *What governance challenges arise in provisioning and appropriating genetic and varietal diversity along the seed supply chain from breeding nurseries to the farm gate?*

This research question elicits how seed breeding, seed multiplication and variety choice are embedded in different incentive structures, which in relation to each other bring about overall systemic outcomes (e.g. the overall susceptibility of German winter wheat to different pests or yield levels). This aligns the research of chapter 2 with the call for a systems-based approach (Biggs et al., 2021) by looking at how the different sub-components of the seed SES interact and bring about the outcomes of the overall system. If one were to interview all the actors in the SES, one could still reach false conclusions as to what is necessary to transform this system towards a more sustainable state, if one adopted a reductionist approach of looking at the sub-components of the system in isolation (Preiser et al., 2021).

Two other defining features of SESs, however, make reaching reliable conclusions in SES research a tricky task. Radical openness (principle four of Preiser et al. (2018)), which means that the SES is constituted by the activity of the system in relation to the environment (Cilliers, 2002) and context dependency (principle five of Preiser et al. (2018)), which means that the environment suppresses or boosts possible systemic functions (Poli, 2013) blurr the boundaries of SESs. Boundaries in SESs can be set by the physical properties of the system (e.g. pedo-climatic zone for cropping), mental constructions (e.g. who shares which seed material with whom) and the problem of the research question being addressed. Consequently, Researchers may encounter many heterogeneous cases when they want to compare and synthesize insights for and from SESs (Cox, 2014a; Cumming et al., 2020; del Mar Delgado-Serrano & Ramos, 2015; Leslie et al., 2015).

Chapter 3 tries to provide guidance in comparing and synthesizing SES cases, for those SESs where we encounter nested resource systems (NRSs). We want to provide simple instructions on figuring out how the different sub-components of a resource system are nested within each other and how the NRS properties influence SES behaviors and outcomes. Seeds are a good example for such nested systems as genetic snippets bring about characteristics of a plant, plants with different attributes can be bundled to varieties, which bring about cropping outcomes in fields and contribute to the cropping performance (e.g. aggregated yield of farmers in a region). Yet, the physical materials mentioned - also referred to as resource units (RUs) - can in themselves not tell us, what the best form of governance is to steer the seed system towards beneficial outcomes. It is only in conjunction with an action situation that we can know how we might address changes in governance (McGinnis, 2011a). Action situations in large scale SESs are usually connected in different ways. To streamline different heterogenous cases of NRSs we ask the following

Research question of chapter 3: *What diagnostic questions do we need to ask, to decompose the characteristics of large, nested, and tiered resource systems into their constituent variables, while identifying relevant corresponding activities?*

The diagnostic procedure we derive in chapter 3 shall help with determining the boundaries of the SES of inquiry, make the insights from different cases more comparable (Cox, 2011) and find a fitting level of analysis to understand the underlying SES.

The second and third organizing principle describe that a CAS's adaptive capacity and dynamic interactions can lead to non-linear systems behavior. As systems transformations are subject to non-linear processes (Olsson, Galaz, & Boonstra, 2014), it is difficult to understand how we can trigger transformations moving agricultural and seed systems into the right direction if we want to reach the sustainable development goals (Sachs et al., 2019, SDGs). Chapter 4 inquires how intentional changes to research policy for plant breeding can better achieve transformations towards SDGs. Mission-oriented research governance is centered around these inspirational goals. It is the current path taken to reform research in the EU. Yet, for policy makers dealing with plant breeding research it is not clear how effective mission-oriented governance of plant breeding research can be achieved and what one needs to take into account systemically. Approaching mission-oriented research governance from an SES perspective acknowledges the interactions and feedbacks between the multiple nested layers of the underlying RSs and RUs. As policy makers and program managers need to take these complex interactions into account, we ask

Research question of chapter 4: *What heuristic illustrates core elements needed for governing plant breeding research, such that mission-oriented governance can achieve overall sustainability goals?*

We produce a rule-of-thumb (heuristic) for policy makers and science program managers showing that Genetics, Environment, Management and Social system (GxExMxS) are core elements needed when governing plant breeding research.

The sixth organizing principle is concerned with complex causality and emergence (Preiser et al., 2018), meaning that there are usually no unidirectional or linear pathways but recursive causal pathways, which determine the underlying behavior of SESs. Chapter 5 looks into one of these causal links between breeders and farmers, which is vital but usually ignored. Seed multiplication provides those varieties within the seed system which are going to be sold to farmers as new varieties. Considering the climatic changes ahead of us, we want to know whether there is possibility of quick social response when the system is faced with biotic shocks (e.g. pest epidemics). The social response we would expect from a pest epidemic is a change in multiplication area of varieties resistant to the different diseases. The following question arises:

Research question of chapter 5: *How do the portfolios of varieties in seed multiplication react to pest shocks?*

We cannot find support to refute the hypothesis that there is no effect of pest shocks on multiplication area in resistant varieties. We find that being varieties being recommended for different pedo-climatic zones in the seed variety trials show an increase in multiplication area. The estimates show on average a c.p. increase of 156 ha for brown rust, 139 ha for fusarium, and 141 ha for yellow rust. All recommendations estimates are statistically significantly different from zero at the 95 percent confidence interval, see chapter 5.

Each of our research questions is being answered in the following chapters, where we try to contribute to the SES research around the question of how to govern seed systems such that they will lead to more sustainable outcomes in agricultural systems. In the following sections we summarize each thesis chapter, position it in the disciplinary literature and point out its contributions. We finalize this introductory chapter with highlighting limitations of our chapters and some overarching conclusions of this thesis.

1.2 Governance challenges in seed systems and importance of crop genetic resources

Summary

Chapter 2 provides an overview to those parts in the German wheat breeding system, which breed, multiply and farm with wheat seed. It outlines how the incentive structures around provisioning and appropriating genetic and varietal diversity depend on the information of variety performance. We used a qualitative, inductive approach when constructing a consensus over how the wheat breeding system works in Germany by interviews, participant observation, and secondary sources from scientific and grey literature. Our results show that the challenges for governance lie in providing credible and symmetric information on variety performance to all actors. Variety performance means indicators on plant health, e.g. how well a plant withstands a disease, yield, and different quality indicators, like colors or suitability for baking. This type of information will steer breeders to engage in preemptive sharing of breeding material. Multipliers will more easily engage in subcontracting varieties and farmers have better informed variety choices when buying or saving seed.

Positioning in the scientific discourse

Previous to Elinor Ostrom's seminal work on governing the commons and natural resources management (Ostrom, 1990) researchers who dealt with the management of a natural resources (e.g. a fishery or a forest) derived an ideal form of governance of a resource by asking 'what type of good' physical material units under management are (Ostrom, 2005; Williamson, 1985, p.24 ff.). Goods were typified along two dimensions - 'subtractability of use' and 'excludability of users', see figure 2.1 in chapter 2. Subtractability refers to the extent to which using a good or service will reduce the availability of the good or service to others. Excludability relates

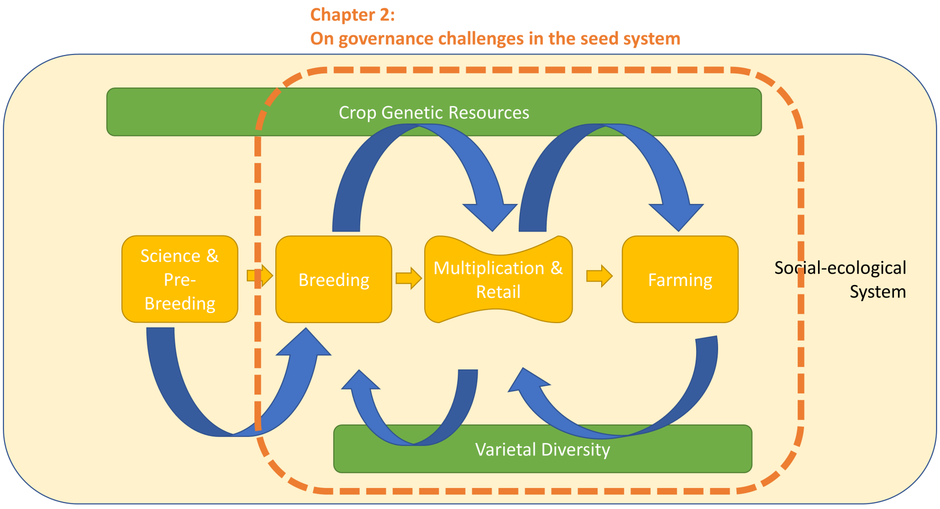

FIGURE 1.2: Positioning of chapter 2 within seed system.

to the difficulty of restricting other users from harnessing benefits of the good or service being provided. Crop genetic material in the plethora of its forms, as allelic snippets (variants of genes at gene loci), genetic traits (aggregation of specific allelic combinations), breeding lines (aggregation of genetic traits in plants over several generations), experimental cultivar variants, and varieties (in the form of seed) has puzzled the scientific community in this regard.

There is quite some discussion on what type of good which crop genetic material is (Halewood, 2013). Scientists relate different forms of crop genetic material to the dimensions of the goods typology. While most scientists acknowledge that individual resource entities from plant breeding systems are multifaceted and do not fit the goods typology, they will still analyze the singular aspects of seed materials to fit into these categories. They focus on the constructed cultural resource component of plant genetic resources (Halewood, 2013), the informational component of seed breeding (Brandl, Paula, & Gill, 2014), the public good attributes of plant breeding research (Brandl & Glenna, 2017a), the intellectual property rights assigned to seed development (Brandl & Glenna, 2017b; Braun, 2021; Godt, 2016), or commons aspects in seed saving Sievers-Glotzbach, Tschersich, Gmeiner, Kliem, and Ficiciyan

(2020). Looking at plant genetic material in this way usually focuses on subunits of a resource stock for appropriation. Yet, the activities related to the respective RUs matter. For example, catch-release fishing compared to fishing for consumption make a difference to the resource; the former will deem it less rivalrous (or subtractable) than the latter (Hinkel, Cox, Schlüter, Binder, & Falk, 2015), as the fish are being put back into the lake in the first type of fishing and consumed in the other case. Hence it is vital to recognize what type of activities are being executed and not how we classify the physical material per se. This means, however, that there is no panacea for managing the whole seed system or even its sub-components under a specific kind of governance.

Contribution

We contribute to the literature by accounting for the complexity of the seed system, when we consider each activity on its own. We derive more nuanced insights from a systemic perspective when looking at multiple activities concurrently rather than singular physical entities on their own. By using an SES perspective we contribute to a) diagnosing when subtractability is relevant for governance and b) unpacking the attributes framing the underlying incentive structures of each resource provisioning genetic and varietal diversity. We find that the governance challenges lie in providing credible and symmetric information on variety performance to different actors. We contribute to the overall challenge of giving policy makers more nuanced rules-of-thumb for regulating and directing activities (Darnhofer, Fairweather, & Moller, 2010) in the seed system rather than panaceas for types of seed material.

1.3 Unpacking dynamics of diverse nested resource systems through a diagnostic approach

Summary

Chapter 3 provides a diagnostic approach, a set of questions, to align the SESF's (McGinnis & Ostrom, 2014; Ostrom, 2009) concepts of RSs and RUs with reality of individual case studies for larger SESs. We go beyond the level of the individual resource management case and provide a set of diagnostic questions allowing

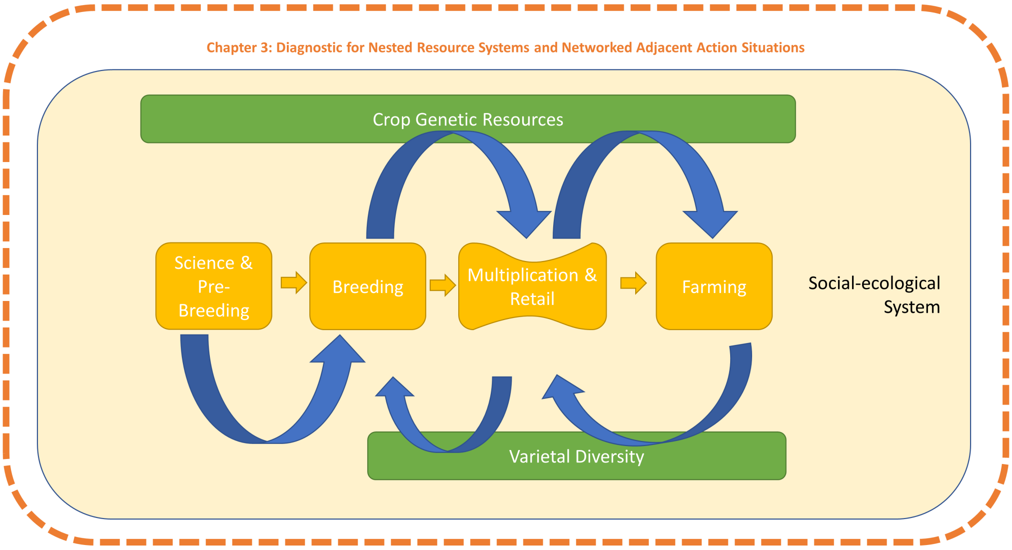

FIGURE 1.3: Positioning of chapter 3 within seed system.

researchers to streamline their cases such that they are comparable across different types of large scale SESs composed of NRSs, see figure 1.3. Applying our diagnostic approach to two cases we show how NRSs influence activities in networks of adjacent action situations (NAAS) as introduced by McGinnis (2011b, NAAS). Action situations denote the hypothetical space where activities within a SES occur, for a detailed definition refer to Poteete, Janssen, and Ostrom (2010, p.40). We compare networked lake systems in Bengaluru, India with German wheat breeding systems. With our diagnostic approach we tease out the scope of the research question, relevant action situations and their spatial reach, relevant activities and how they influence the state of the resource stocks.

Positioning in the scientific discourse

For policy making to effectively resolve complex social-ecological challenges, theories are needed, which dovetail generality, practicality and precision to describe chains of causal mechanisms leading to different SES phenomena (Meyfroidt, 2016; Meyfroidt et al., 2018). Diagnostic approaches have been considered an effective tool in developing such context-dependent generalizations (Cox, 2011).

The plethora of variables, who potentially contribute to different systems behaviors are arranged in frameworks like the social-ecolocial systems framework (SESF) (McGinnis & Ostrom, 2014; Ostrom, 2005). Despite the benefit of frameworks like the SESF, challenges in applying them persist, particularly from the perspective of mid to large scale SESs (Cole, Epstein, & McGinnis, 2019; Epstein et al., 2020; Partelow, 2018; A. Thiel, Adamseged, & Baake, 2015; Villamayor-Tomas et al., 2020) due to a gap in developing coherent tools and techniques to interpret and operationalize the large number of variables contained within the SESF (Cox, 2014a; Cumming et al., 2020; del Mar Delgado-Serrano & Ramos, 2015; Leslie et al., 2015).

Contribution

Chapter 3 contributes towards unpacking and diagnosing the complexities within RSs and RUs in mid to large scale SESs. It provides a generalizable, rigorous approach to SES case study analyses, thereby addressing the mentioned gap in theory building and thus advancing synthesis in sustainability science. We do this by a) introducing the concept of NRS to negotiate complexity of RS-RU interactions, b) developing a diagnostic approach to applying the NRS within mid-large-scale SESs, and c) identifying spatially situated NAASs operating within NRSs. We contribute a diagnostic tool enabling a standardised approach to describing and analysing SESs, both from the perspective of smaller, well-defined SESs as well as mid to large scale NRSs, with the objective of enabling comparability across diverse contexts and cases.

1.4 Mission-oriented governance of research policy and its consequences for the plant breeding system

Summary

Chapter 4 proposes a governance heuristic accounting for the core parts needed to direct plant breeding research: We suggest to use Genetics, Environment, Management and Social system (GxExMxS) as the core elements for defining future breeding goals. These goals are necessary within a grander scheme of research governance where mission-oriented research centers around inspirational, yet attainable goals (Mazzucato, 2018). Based on historic cases, we illustrate why these core elements are needed. Thereof we show what socio-technological risks and bottlenecks exist in the context of current developments in plant phenotyping technologies. We show what factors could hamper the success of mission-oriented research governance in applied breeding programs and the organization of research infrastructures. As a result we recommend long-term investments into human resources and experimental set-ups for agricultural systems necessary to ensure a symbiotic relationship for private and public breeding actors. We also recommend fostering collaboration between social and natural sciences for working towards transdisciplinary breeding targets.

Positioning in the scientific discourse

Chapter 4 focuses on research policy in plant breeding science and applied breeding programs, see figure 1.4. Under Horizon Europe, the EU targets the sustainable development goals (SDGs) through mission-oriented research governance (Mazzucato, 2019). New innovation pathways shall transform current agricultural systems into sustainable ones (Sachs et al., 2019), as we set out on missions like climate-resilient regions (DG Research and Innovation, 2020a), beating cancer (DG Research and Innovation, 2020c), or healthy soils (DG Research and Innovation, 2020b) which requires improved crop varieties and management practices. Speedy success in this respect is vital to lower the use of chemical fertilizers and pesticides, increase crop resilience to climate stress and reduce postharvest losses (Pretty, 2018; Qaim, 2020). For successful transformation towards these goals innovations in plant breeding research are needed (Sachs et al., 2019). So far plant science, however, has ignored wider social systems feedbacks, while governance also failed to deliver a set of holistic breeding goals providing directionality and organization to this field of science.

Mission-oriented governance of agriculture creates a tension between how economists traditionally give policy advice on research and innovations in agriculture – with the state as intervening in failing markets (Alston & Pardey, 1996) - and a kind of governance centering around actively creating pathways of innovation. Hence, policy advice on mission-oriented governance focuses on a) directionality, b) dynamic evaluation, c) organization, and d) risk-and-reward sharing amongst public and

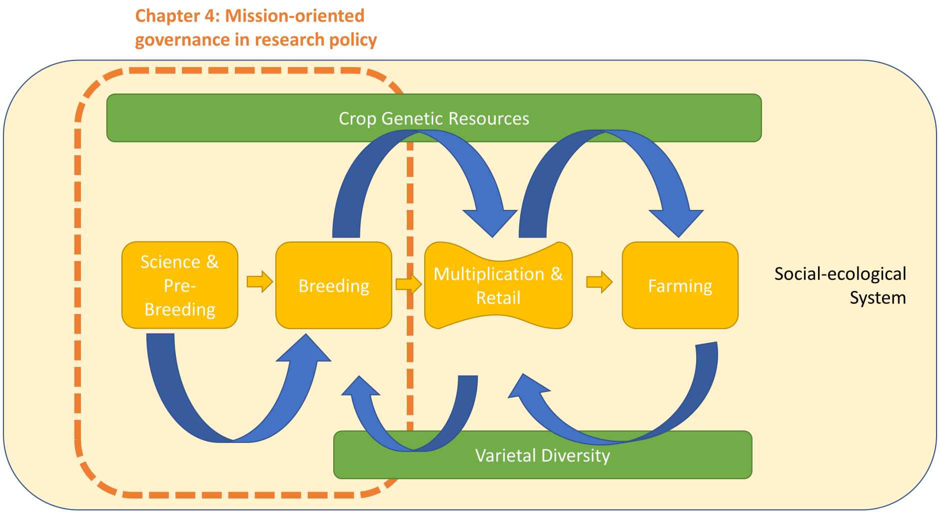

FIGURE 1.4: Positioning of chapter 4 within seed system.

private actors (Mazzucato, 2016). This goes beyond the mere return-on-investment narrative of governmental funding, as put forward by many agricultural economists during the last decades (Alston and Pardey (1996); Fuglie et al. (2011); Hurley, Pardey, Rao, and Andrade (2016); see Alston, Chan-Kang, Marra, Pardey, and Wyatt (2000) for a meta-analysis of this returns on investment literature and Pardey, Alston, and Ruttan (2010) for the basic underlying assumptions and theories).

Contribution

Chapter 4 makes three contributions towards interdisciplinary plant breeding research: 1) It explains milestones in plant breeding with evolutionary principles of Darwinian agriculture in mind (R. F. Denison, Kiers, & West, 2003; R. F. F. Denison, 2012), and adds the ideas of cultural evolution (Henrich, 2016, 2020; Henrich & McElreath, 2003) as a basic background for evaluating breeding goals in terms of governing towards more sustainable agricultural systems. 2) It attempts to communicate to plant scientists, what is meant by taking social systems feedback into account. 3) It gives an overview of recent phenotyping technologies and in what context they need to be understood for policy makers and social and economic scientists.

1.5 Pest epidemics and their impact on multiplication portfolios in winter wheat seed

Summary

In chapter 5 we present evidence of how sensitive seed multiplication portfolios are to pest infestations. We ask whether the seed system is capable of responding quickly through adjusted decision making in seed multiplication areas of resistant varieties. We term this a 'social response' to a biotic shock. This social-ecological analysis hypothesizes that the supply of resistant seed varieties will increase when there are sudden shocks in pest infestations. We use regression analysis (difference-in-differences) to estimate changes in wheat multiplication area as a function of pest incidence, pedo-climatic niches and social variables like institutional information.

Our main findings are: First, we cannot find evidence that supports a reaction to pest epidemics. Pest shocks bring about little or no additional multiplication area in pest resistant varieties. Second, we find that varieties recommended for specific pedo-climatic zones correlate with increasing multiplication area when pest shocks occur.

Positioning in the scientific discourse

Accelerating the adoption and diffusion of new varieties is decisive for agricultural productivity, resilience and adaptive capacity of agricultural systems in response to ecological and social challenges like climate change or social conflicts (Feder, Just, & Zilberman, 1985). The most hard felt effects of climate change will come to us through the increase in extreme weather events (Coumou & Rahmstorf, 2012) influencing crop production negatively (Asseng et al., 2015; Porter & Semenov, 2005; Trnka et al., 2014). Usually we think of these extreme events as temperature peaks (Asseng et al., 2015; Tack, Barkley, & Nalley, 2015) and floods (Gudmundsson et al., 2021; Markonis, Papalexiou, Martinkova, & Hanel, 2019). We tend to neglect that with the change of climatic conditions, biotic factors, like fungal pathogens or insects, adapt likewise to new conditions, and that even new ecological niches open up for these organisms (Blois, Zarnetske, Fitzpatrick, & Finnegan, 2013). This poses

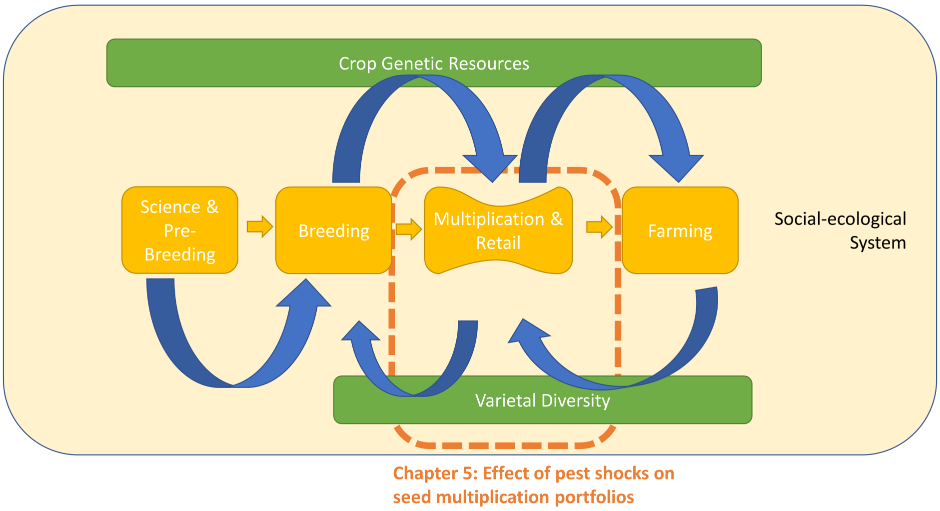

FIGURE 1.5: Positioning of chapter 5 within seed system.

a detrimental threat to crop production in the light of genetic homogenization of crops over the last decades, especially in wheat production systems (Kahiluoto et al., 2019).

Countering pests and abiotic stressors at the same time demand a smooth and effective diffusion of biological innovations in crops (Feder et al., 1985). Yet, diffusing improved varieties to farmers has been a long standing problem (Heisey & Brennan, 1991). Usually farmers, choices have been problematized as incomplete, instead of asking whether they are offered appropriate choices in varieties by seed multipliers and retailers (Barkley & Porter, 1996; Dahl, Wilson, & Wilson, 1999; Heisey & Brennan, 1991). If seed multiplication is lacking ability to react to pest shocks, as our results suggest, then the resilience of agricultural systems is hampered as adaptive strategies of farmers and extension services will not work out and in consequence climate change mitigation policies will be useless having detrimental effects for food security (Acevedo et al., 2018; Challinor et al., 2014).

Contributions

Our results show that the multiplication system in its current state does not react strongly to pest shocks. We herewith contribute to answering how biotic factors may change with climate change, as we go beyond the archetypal inquiry of how rising temperatures will alter yields (Asseng et al., 2015; Tack et al., 2015; Trnka et al., 2014). We ask how the social side of this social-ecological seed system actually reacts to extreme events. We wanted to see whether multiplication agents adapt their portfolios in accordance with the need to counter pests. While this did not turn out as expected, we found that institutional interventions work: Targeted communication of governmental officials publishing recommendations of varieties for farmers in specific pedo-climatic zones and discussing variety trial outcomes with seed multiplication agents has an effect on multiplication portfolios.

Our findings provide evidence for policy makers allocating budgets for variety trials and research projects to counter climate change. We highlight the importance of information provided by extension services and the targeted communication efforts towards the seed multiplication, breeding and farming community to improve the governance of seed supply chains. There is a need to maintain information provisioning on variety resistances, localized governmental recommendations to plant breeders, seed multipliers, retailers and farmers at regional level. Our results indicate that heterogeneity of importance of diseases in pedo-climatic zones prompts a need for improved institutional response and must be continuously supported by the public hand to tackle climate change effectively on a regional level.

Another reason for increased variety testing in cropping regions, which currently do not have intense crop production (marginal areas), is to open up a window of opportunity to find and test mitigation strategies for climate-change-resistant varieties. Pedo-climatic conditions in marginal regions may yield valuable results for breeding for the future. As growing conditions in these regions are usually harsher (droughts, less sufficient soils etc.) they might better depict the growing conditions under climate change than the places where we currently focus trial efforts. Hence within these regions there needs to be an opportunity of testing breeding lines and current varieties beyond the myopic incentive structure of private businesses in breeding. We suggest that it might be better to try out different mitigation strategies in terms of variety specific cropping and targeting breeding efforts in these regions to diversify our efforts in plant breeding for more challenging abiotic and biotic conditions.

1.6 Limitations

The insights gained throughout the different chapters of this thesis are, as any scientific process, is subject to limitations outlined briefly in the following.

Chapter 2, deals with the challenges the German winter wheat breeding system faces in its governance. While the main findings is that credible information accessible to all actors is key in making the system work smoothly, we need to caution the reader on these insights.

It is a hypothesis for a theory on information and signaling specific to the plant breeding sector. While contributing to the overall goal of creating some sort of mid-range theory for governing crop genetic resource systems, as also chapter 3 points out, these insights mark merely the beginning of a research agenda. We are not sure yet whether trust in these situations works in a cumulative fashion or if different forms of trust could substitute for each other, as we did not use any experimental setup to test for this. We cannot say if different forms of information each trigger different forms of trust and corresponding coordination mechanisms. In an environment involving trust between the individuals engaging in the relevant activities, symmetric information distribution of simple performance measures seems unnecessary for the technical process (Braun, 2021). Yet, it suffices to speed up the breeding process itself by preempting the sharing of new variety material, thereby bringing about shorter innovation cycles within the whole system. We cannot be sure if this insight would also extrapolate to other cases. Hence, the diagnostic approach in chapter 3 serves as an first step towards generalizing knowledge across different cases.

A limitation to the diagnostic approach in chapter 3 is that it still needs validation through a community of scientific users. Actual insight will only come about if multiple cases can be compared across multiple settings and this vitally depends on the acceptance and application by the scientists conducting these studies. Yet, already within the scientific community, incentive schemes are currently not aligned such that, e.g. early career scientists have proper incentives to part-take in such grand inquiries (Ledford, 2015; Poteete, Janssen, & Ostrom, 2011) and the infrastructural set-up for these projects is quite laborious (Cox, 2014b). Hence the governance of research itself is important, as we can also see from chapter 4.

The main limitation of chapter 4 is that - due to the focus on pre-breeding technologies - one might think these technologies are a must for achieving SDGs. Yet, it is important to acknowledge that the technologies applied are not going to bring about sustainability in agriculture by their usage per se. They will have to be applied in a diligent manner, working towards social, ecological and economic sustainability, otherwise they will fail in bringing about the mission goals. Especially for the governance of the RIs under Horizon Europe it is important to notice, that they will only help succeed mission goals if staff in these organizations buy into the adaptive evaluation processes (Mazzucato, 2018) and navigate their role as facilitators and promoters of research towards these mission goals.

An open question for chapter 5 remains whether the control observations to our treated units should be weighted further. So far we have not done this, but deem this worthwhile trying in future research to see whether results are going to be notably different in effect size and precision of effects. A clear drawback on using the approach of Callaway and Sant'Anna (2021), is that the use of only clean lead and lag years around a treatment, can lead to much attrition of data. We may loose validity compared to the overall process - as we can see in our yellow rust case, where we were left with not enough observations. Inquiring more into the variation in organizational aspects of governance across different states strikes us as an interesting route for future research. Main limitation for this is the geographic scope of our study. Bavaria is a fairly big and heterogeneous state in Germany in terms of its pedo-climatic conditions. Testing sites are well spread across these. Data from other states would have allowed us to see effects of different governance mechanisms.

A general constraint to this thesis is that each chapter has a different target audience. This necessitates different vocabulary specific to different disciplines for each chapter even though some of the concepts used are effectively the same throughout all chapters. For example we use the term crop genetic diversity differently in each chapter. Chapter 2 introduces varietal diversity, as most non-scientific actors in breeding will not talk about genetic diversity, but more in terms of varieties and hence we have adopted it for the publication in chapter 2 similar to Smale (1996) who also used this term for clarification. Compared to this, chapter 4 will go into more agronomic detail for its audience being scientifically educated program managers and policy makers, who have a basic familiarity with plant science. In chapter 3 we refer to crop genetic diversity mainly as resource or RS and RU. The latter terms are jargon from the political science community also addressed in chapter 2. Overall, we adopted a language that we thought was the best fit for our audience to maintain effective communication on this interdisciplinary topic.

1.7 Conclusions

When taking a systemic vantage point to look at a seed system, the main difference between this thesis and preceding work is that we try to look at the individual processes (see chapter 3), impacts (see chapter 5) and incentive structures (see chapter 2) not in isolation, but in the context-dependencies of a CAS. Dealing with emergent phenomena necessitates to embrace adaptive learning (see chapter 4), maintain diversity (see chapter 2) and reflect connectivity (see discussion on NAAS in chapter 3 and 2) to build resilient systems overall (Biggs, Schlüter, & Schoon, 2015). For the concrete context of this thesis, we draw different conclusions for seed systems and resource management of crop genetic resources in general.

We propose that future studies examine the role trust and biophysical information, like performance of varieties, play in enabling actors to coordinate their transactions involving natural resources in large-scale systems. Our hypothesis is that the credibility of information produced and the symmetry of supplied information are crucial for facilitating socially beneficial outcomes of the coordination mechanisms. We conclude that it will be crucial to any breeding system, but especially in the EU and Germany, that enough governmental money is being put into maintaining and setting up variety trials for bestowing credible and reliable information to all actors along the supply chain. Actors need to be able to trust and access information properly. We will still, need to understand more closely what type of access, allocation and quality information and signalling need to have, so that different actor groups can better engage with these information. Along the same lines goes my call for closer inquiries into how seed multiplication could be optimized for better reacting to biotic shocks, such as pests, which has been not been done as much so far, but will impact productivity as extreme pest shocks become more frequent (Russell, Lee, McCulley, & Van Sanford, 2014). The same is true for pre-breeding and that information produced within the scientific community itself (see chapter 4 discussion of FAIR principles of information sharing).

As such we need a more holistic approach within science to structuring seed systems as SESs. We need context dependent frameworks for how we think about crop genetic diversity in its different material forms. Activities, in their goals and outcomes, are the key to frame how we categorize a resource for deriving more effective governance of seed systems. Relational to the activities being undertaken with these materials, as scientists, we need to reach comparability of results for gaining better insights as to how we might govern these very heterogeneous situations and then give better recommendations in terms of directionality to those people in the seed systems, which craft its institutions. Hence, we propose to develop a more general, sectoral SESF for the governance of plant breeding.

We need to change how we govern plant breeding to reach the SDGs and climate change mitigation goals effectively. We need to see this more as problem of organization of governance interacting with normative goals of governance, as we learned from chapter 4 and 3. Incentive structures need to be aligned with the actual goals of the application of research.

Looking at the challenges extreme weather events and biotic consequences of climate change put out there in future years, we need to prepare the seed systems to maintain our global sources of food and fiber in a manner that regenerates our biosphere (Rockström et al., 2009), while meeting the needs of all (Raworth, 2017).

1.8 Bibliography

Acevedo, M., Zurn, J. D., Molero, G., Singh, P., He, X., Aoun, M., . . . others (2018). The role of wheat in global food security. In *Agricultural development and sustainable intensification* (pp. 81–110). Routledge.

Acquaah, G. (2007). *Principles of plant genetics and breeding*. Malden, MA, USA: Blackwell Publishing.

Alston, J. M., Chan-Kang, C., Marra, M. C., Pardey, P. G., & Wyatt, T. J. (2000). *A meta-analysis of rates of return to agricultural r&d: Ex pede herculem?* (Vol. 113). Intl Food Policy Res Inst.

Alston, J. M., & Pardey, P. G. (1996). *Making science pay: The economics of agricultural r&d policy*. Washington, DC: AEI Press.

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., ... others (2015). Rising temperatures reduce global wheat production. *Nature climate change*, *5*(2), 143–147.

Barkley, A. P., & Porter, L. L. (1996). The determinants of wheat variety selection in kansas, 1974 to 1993. *American Journal of Agricultural Economics*, *78*(1), 202–211.

Becker, H. (2011). *Pflanzenzüchtung*. UTB.

Behnassi, M., & El Haiba, M. (2022). Implications of the russia–ukraine war for global food security. *Nature Human Behaviour*, 1–2.

Berkes, F., & Folke, C. (1998). *Linking social and ecological systems: management practices and social mechanisms for building resilience*. Cambridge University Press.

Biggs, R., Clements, H., de Vos, A., Folke, C., Manyani, A., Maciejewski, K., ... Schlüter, M. (2021). What are social-ecological systems and social-ecological systems research? In *The routledge handbook of research methods for social-ecological systems* (pp. 3–26). Routledge.

Biggs, R., Schlüter, M., & Schoon, M. L. (2015). Principles for building resilience: sustaining ecosystem services in social-ecological systems.

Blois, J. L., Zarnetske, P. L., Fitzpatrick, M. C., & Finnegan, S. (2013). Climate change and the past, present, and future of biotic interactions. *Science*, *341*(6145), 499–504.

Brandl, B., & Glenna, L. (2017a). Intellectual property and agricultural science and innovation in germany and the united states. *Science, technology & human values*, *42*(4), 622–656.

Brandl, B., & Glenna, L. L. (2017b). Intellectual property and agricultural science and innovation in germany and the united states. *Science, technology, & human values*, *42*(4), 622–656.

Brandl, B., Paula, K., & Gill, B. (2014). Spielarten des wissenskapitalismus - die kommodifizierung von saatgut in den usa und in deutschland. *Leviathan*, *42*(4), 539–572. doi: 10.5771/0340-0425-2014-4-539

Braun, V. (2021). Holding on to and letting go of seed: quasi-commodities and the passage of property. *Journal of Cultural Economy*, *14*(3), 306–318. doi: 10.1080/17530350.2020.1824934

Callaway, B., & Sant'Anna, P. H. (2021). Difference-in-differences with multiple time periods. *Journal of Econometrics*, *225*(2), 200-230. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0304407620303948` (Themed Issue: Treatment Effect 1) doi: https://doi.org/10.1016/j.jeconom.2020.12.001

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S., Smith, D., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature climate change*, *4*(4), 287–291.

Cilliers, P. (2002). Why we cannot know complex things completely. *Emergence*, *4*(1-2), 77–84.

Cole, D., Epstein, G., & McGinnis, M. (2019). The utility of combining the iad and ses frameworks. *International Journal of the Commons*, *13*(1).

Coumou, D., & Rahmstorf, S. (2012). A decade of weather extremes. *Nature climate change*, *2*(7), 491–496.

Cox, M. (2011). Advancing the diagnostic analysis of environmental problems. *International Journal of the Commons*, *5*(2).

Cox, M. (2014a). Applying a social-ecological system framework to the study of the taos valley irrigation system. *Human Ecology*, *42*(2), 311–324.

Cox, M. (2014b). Understanding large social-ecological systems: introducing the sesmad project. *International Journal of the Commons*, *8*(2), 265–276.

Cumming, G., Epstein, G., Anderies, J., Apetrei, C., Baggio, J., Bodin, Ö., ... others (2020). Advancing understanding of natural resource governance: a post-ostrom research agenda. *Current Opinion in Environmental Sustainability*, *44*, 26–34.

Dahl, B. L., Wilson, W. W., & Wilson, W. W. (1999). Factors affecting spring wheat variety choices: Comparisons between canada and the united states. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *47*(3), 305–320.

Darnhofer, I., Fairweather, J., & Moller, H. (2010). Assessing a farm's sustainability: insights from resilience thinking. *International journal of agricultural sustainability*, *8*(3), 186–198.

del Mar Delgado-Serrano, M., & Ramos, P. (2015). Making ostrom's framework applicable to characterise social ecological systems at the local level. *International Journal of the Commons*, *9*(2).

Denison, R. F., Kiers, E. T., & West, S. A. (2003). Darwinian agriculture: when can humans find solutions beyond the reach of natural selection? *The Quarterly Review of Biology*, *78*(2), 145–168. doi: 10.1086/374951

Denison, R. F. F. (2012). *Darwinian agriculture: How understanding evolution can improve agriculture*. Princeton: Princeton University Press.

DG Research and Innovation. (2020a, 09). *100 climate-neutral cities by 2030 - by and for the citizens - report of the mission board for climate-neutral and smart cities* (Tech. Rep.). Mission Board for climate neutral and smart cities. doi: https://doi.org/10.2777/46063

DG Research and Innovation. (2020b, 09). *Caring for soil is caring for life: Ensure 75 of soils are healthy by 2030 for food, people, nature and climate - report of the mission board for soil health and food* (Tech. Rep.). Mission Board for Soil health and food. doi: https://doi.org/10.2777/821504

DG Research and Innovation. (2020c, 09). *Proposed mission: Conquering cancer, mission possible* (Tech. Rep.). Mission Board on on Cancer. doi: https://doi.org/10.2777/045403

Epstein, G., Morrison, T. H., Lien, A., Gurney, G. G., Cole, D. H., Delaroche, M., . . . Cox, M. (2020). Advances in understanding the evolution of institutions in complex social-ecological systems. *Current Opinion in Environmental Sustainability*, *44*, 58–66.

Erbe, G. (2002). *Handbuch der saatgutvermehrung*. Agrimedia.

Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic development and cultural change*, *33*(2), 255–298.

Folke, C., Biggs, R., Norström, A. V., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society*, *21*(3). Retrieved 2022-08-28, from `http://www.jstor.org/stable/26269981`

Fuglie, K. O., Heisey, P. W., King, J. L., Pray, C. E., Day-Rubenstein, K., Schimmelpfenning, D., . . . Karmarkar-Deshmukh, R. (2011). Research investments and market structure in the food processing, agricultural input, and biofuel industries worldwide. *Economic Research Service, USDA*.

Gerullis, M. K. (2016). Entstehung privater eigentumsrechte an weiterentwicklungen von weizensaat in den usa und deutschland. In *Biopatente* (pp. 235–260).

Godt, C. (2016). Geistiges eigentumsrecht als instrument zum erhalt biologischer vielfalt? saatgut als sonderfall. In *Biopatente* (pp. 19–54). Nomos Verlagsgesellschaft mbH & Co. KG. doi: 10.5771/9783845275246-18

Gudmundsson, L., Boulange, J., Do, H. X., Gosling, S. N., Grillakis, M. G., Koutroulis, A. G., . . . others (2021). Globally observed trends in mean and extreme river flow attributed to climate change. *Science*, *371*(6534), 1159–1162.

Halewood, M. (2013). What kind of goods are plant genetic resources for food and agriculture? towards the identification and development of a new global commons. *International Journal of the Commons*, *7*(2), 278–312.

Heisey, P. W., & Brennan, J. P. (1991). An analytical model of farmers' demand for replacement seed. *American Journal of Agricultural Economics*, *73*(4), 1044–1052.

Henrich, J. (2016). *The secret of our success: How culture is driving human evolution, domesticating our species, and making us smarter*. Princeton University Press. Retrieved from `https://www.degruyter.com/document/doi/10.1515/9781400873296-019/html`

Henrich, J. (2020). *The weirdest people in the world: How the west became psychologically peculiar and particularly prosperous*. [S.I.]: Farrar, Straus and Giroux.

Henrich, J., & McElreath, R. (2003). The evolution of cultural evolution. *Evolutionary Anthropology: Issues, News, and Reviews*, *12*(3), 123–135.

Hinkel, J., Cox, M. E., Schlüter, M., Binder, C. R., & Falk, T. (2015). A diagnostic procedure for applying the social-ecological systems framework in diverse cases. *Ecology and Society*, *20*(1).

Hurley, T., Pardey, P., Rao, X., & Andrade, R. (2016). Returns to food and agricultural r&d; investments worldwide, 1958-2015.

Kahiluoto, H., Kaseva, J., Balek, J., Olesen, J. E., Ruiz-Ramos, M., Gobin, A., . . . others (2019). Decline in climate resilience of european wheat. *Proceedings of the National Academy of Sciences*, *116*(1), 123–128.

Karafyllis, N. C. (2006). Biofakte–grundlagen, probleme, perspektiven. *Erwägen Wissen Ethik, Jg*, *17*, 547–558.

Kliem, L., & Sievers-Glotzbach, S. (2021). Seeds of resilience: the contribution of commons-based plant breeding and seed production to the social-ecological resilience of the agricultural sector. *International Journal of Agricultural Sustainability*, *0*(0), 1-20. Retrieved from `https://doi.org/10.1080/14735903.2021.1963598` doi: 10.1080/14735903.2021.1963598

Ledford, H. (2015). Team science. *Nature*, *525*, 308–311. Retrieved from `http://nspire.nwciowa.edu/wp-content/uploads/2019/05/interdisciplinarity.pdf`

Leslie, H. M., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K. C., Cota-Nieto, J. J., . . . others (2015). Operationalizing the social-ecological systems framework to assess sustainability. *Proceedings of the National Academy of Sciences*, *112*(19), 5979–5984.

Markonis, Y., Papalexiou, S., Martinkova, M., & Hanel, M. (2019). Assessment of water cycle intensification over land using a multisource global gridded precipitation dataset. *Journal of Geophysical Research: Atmospheres*, *124*(21), 11175–11187.

Mazzucato, M. (2016). From market fixing to market-creating: a new framework for innovation policy. *Industry and Innovation*, *23*(2), 140–156. doi: 10.1080/13662716.2016.1146124

Mazzucato, M. (2018, 02). *Mission-oriented research & innovation in the european* *union: A problem-solving approach to fuel innovation-led growth* (Tech. Rep.). European Commission Directorate-General for Research and Innovation. doi: https://doi.org/10.2777/360325

Mazzucato, M. (2019, 06). *Governing missions: Governing missions in the european union* (Tech. Rep.). European Commission Directorate-General for Research and Innovation. doi: https://doi.org/10.2777/014023

McGinnis, M. D. (2011a). An introduction to iad and the language of the ostrom workshop: A simple guide to a complex framework. *Policy Studies Journal*, *39*(1), 169-183. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1541-0072.2010.00401.x doi: https://doi.org/10.1111/j.1541-0072.2010.00401.x

McGinnis, M. D. (2011b). Networks of adjacent action situations in polycentric governance. *Policy Studies Journal*, *39*(1), 51–78.

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society*, *19*(2). Retrieved from http://www.jstor.org/stable/26269580

Meyfroidt, P. (2016). Approaches and terminology for causal analysis in land systems science. *Journal of Land Use Science*, *11*(5), 501–522.

Meyfroidt, P., Chowdhury, R. R., de Bremond, A., Ellis, E. C., Erb, K.-H., Filatova, T., ... others (2018). Middle-range theories of land system change. *Global environmental change*, *53*, 52–67.

Olmstead, A. L., & Rhode, P. W. (2008). *Creating abundance: Biological innovation and american agricultural development, 1700–1960*. New York, USA: Cambridge University Press. Retrieved from https://www.cambridge.org/core/journals/journal-of-economic-history/article/creating-abundance-biological-innovation-and-american-agricultural-development-17001960-by-olmsteadalan-l-and-rhodepaul-w-new-york-cambridge-university-press-2008-pp-xii-467-8000-cloth-2399-paper/ee59df4d7b4796b44f7391162a636de8

Olsson, P., Galaz, V., & Boonstra, W. J. (2014). Sustainability transformations: a resilience perspective. *Ecology and Society*, *19*(4).

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for* *collective action*. Cambridge university press. doi: 10.2307/1243016

Ostrom, E. (2005). *Understanding institutional diversity*. Princeton, NJ: Princeton University Press.

Ostrom, E. (2009). *Prize lecture - beyond markets and states: Polycentric governance of complex economic systems.* Nobel Web AB.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., . . . others (2014). *Climate change 2014: synthesis report. contribution of working groups i, ii and iii to the fifth assessment report of the intergovernmental panel on climate change*. Ipcc.

Pardey, P. G., Alston, J. M., & Ruttan, V. W. (2010). The economics of innovation and technical change in agriculture. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of the economics of innovation* (pp. 939–984). Amsterdam: North Holland. doi: 10.1016/s0169-7218(10)02006-x

Partelow, S. (2018). A review of the social-ecological systems framework: applications, methods, modifications, and challenges. *Ecology and Society*, *23*(4).

Poli, R. (2013). A note on the difference between complicated and complex social systems. *Cadmus*.

Porter, J. R., & Semenov, M. A. (2005). Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1463), 2021–2035.

Poteete, A. R., Janssen, M. A., & Ostrom, E. (2010). *Working together: collective action, the commons, and multiple methods in practice*. Princeton University Press.

Poteete, A. R., Janssen, M. A., & Ostrom, E. (2011). Working together: Collective action, the commons, and multiple methods in practice. *Journal of Artificial Societies and Social Simulation*, *14*(3), 2. Retrieved from `https://hal.archives-ouvertes.fr/hal-02595370/`

Preiser, R., Biggs, R., De Vos, A., & Folke, C. (2018). Social-ecological systems as complex adaptive systems. *Ecology and Society*, *23*(4).

Preiser, R., Schlüter, M., Biggs, R., García, M. M., Haider, J., Hertz, T., & Klein, L. (2021). Complexity-based social-ecological systems research: philosophical foundations and practical implications. In *The routledge handbook of research methods for social-ecological systems* (pp. 27–46). Routledge.

Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science*, *362*(6417). doi: 10.1126/science.aav0294

Qaim, M. (2020). Role of new plant breeding technologies for food security and sustainable agricultural development. *Applied Economic Perspectives and Policy*, *42*(2), 129–150.

Raeburn, P. (1995). *The last harvest: the genetic gamble that threatens to destroy american agriculture*. University of Nebraska Press.

Raworth, K. (2017). *Doughnut economics: Seven ways to think like a 21st-century economist*. White River Junction, Vermont: Chelsea Green Publishing.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. Stuart III, Lambin, E., ... Foley, J. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2).

Russell, K., Lee, C., McCulley, R. L., & Van Sanford, D. (2014). Impact of climate change on wheat production in kentucky.

Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six transformations to achieve the sustainable development goals. *Nature Sustainability*, *2*(9), 805–814. Retrieved from `https://www.nature.com/articles/s41893-019-0352-9` doi: 10.1038/s41893-019-0352-9

Sievers-Glotzbach, S., & Tschersich, J. (2019). Overcoming the process-structure divide in conceptions of social-ecological transformation: Assessing the transformative character and impact of change processes. *Ecological Economics*, *164*, 106361. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0921800918320603` doi: https://doi.org/10.1016/j.ecolecon.2019.106361

Sievers-Glotzbach, S., Tschersich, J., Gmeiner, N., Kliem, L., & Ficiciyan, A. (2020). Diverse seeds–shared practices: Conceptualizing seed commons. *International Journal of the Commons*, *14*(1).

Singh, R. P., Hodson, D. P., Huerta-Espino, J., Jin, Y., Njau, P., Wanyera, R., ... Ward, R. W. (2008). Will stem rust destroy the world's wheat crop? , *98*, 271-309. Retrieved from https://www.sciencedirect.com/science/article/pii/S0065211308002058 doi: https://doi.org/10.1016/S0065-2113(08)00205-8

Smale, M. (1996). Understanding global trends in the use of wheat diversity and international flows of wheat genetic resources. *CIMMYT - Working Paper*, *96*(2), 75. (with contributions from Pedro Aquino, Jose Crossa, Efren del Toro, Jesse Dubin, Tony Fischer, Paul Fox, Mireille Khairallah, A. Mujeeb-Kazi, Kelly J. Nightingale, Ivan Ortiz-Monasterio, Sanjaya Rajaram, Ravi Singh, Bent Skovmand, Maarten van Ginkel, George Varughese, and Rick Ward)

Søgaard Jørgensen, P., Folke, C., Henriksson, P. J., Malmros, K., Troell, M., & Zorzet, A. (2020). Coevolutionary governance of antibiotic and pesticide resistance. *Trends in Ecology Evolution*, *35*(6), 484-494. Retrieved from https://www.sciencedirect.com/science/article/pii/S0169534720300136 doi: https://doi.org/10.1016/j.tree.2020.01.011

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. *The Anthropocene Review*, *2*(1), 81-98. Retrieved from https://doi.org/10.1177/2053019614564785 doi: 10.1177/2053019614564785

Tack, J., Barkley, A., & Nalley, L. L. (2015). Effect of warming temperatures on us wheat yields. *Proceedings of the National Academy of Sciences*, *112*(22), 6931–6936.

Thiel, A., Adamseged, M. E., & Baake, C. (2015). Evaluating an instrument for institutional crafting: How ostrom's social–ecological systems framework is applied. *Environmental Science & Policy*, *53*, 152–164.

Thiel, W. (2014). *Praxishandbuch saatgutvermehrung* (W. Thiel, Ed.). Erling Verlag.

Trnka, M., Rötter, R. P., Ruiz-Ramos, M., Kersebaum, K. C., Olesen, J. E., Žalud, Z., & Semenov, M. A. (2014). Adverse weather conditions for european wheat production will become more frequent with climate change. *Nature Climate Change*, *4*(7), 637–643.

Villamayor-Tomas, S., Oberlack, C., Epstein, G., Partelow, S., Roggero, M., Kellner, E., . . . Cox, M. (2020). Using case study data to understand ses interactions: a model-centered meta-analysis of ses framework applications. *Current opinion in environmental sustainability*, *44*, 48–57.

Williamson, O. E. (1985). *The economic institutions of capitalism: Frims, markets, relational contracting*. New York: The Free Press.

Chapter 2

Toward understanding the governance of varietal and genetic diversity[†]

Abstract: Varietal and genetic diversity sustain modern agriculture and is provided by breeding systems. Failures in these systems may cause insufficient responses to plant diseases, which threatens food security. To avoid these failures, an understanding of the governance challenges in providing varietal and genetic diversity is required. Previous studies acknowledge the complexity of seed breeding, framing the discussion in terms of rivalry and excludability. We consider breeding systems as social-ecological systems that focus on activities that generate varietal and genetic diversity and their adaptive ability. We use an inductive approach based on qualitative methods combined with the social-ecological system framework (SESF) to depict how highly context-dependent German winter wheat breeding, multiplication, and farming activities are. Our results show that the challenges for governance lie in providing credible and symmetric information on variety performance to all actors. This is the means to steer actors into collective action by subcontracting, buying, or saving seed. Based on our application of the SESF to the German wheat breeding system, we propose to develop a more general, sectoral SESF for the sustainable governance of plant breeding by offering an adaptable template for analyses of seed systems in other contexts.

***Keywords**: genetic diversity; new institutional economics; plant breeding; seed production; social-ecological systems framework*

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2.1 Introduction

One of the greatest challenges to modern agriculture is increasing productivity while using fewer resources and reducing negative environmental impacts (Rockström et al., 2017). Plant breeding seeks to improve the crop varieties used for agriculture (Becker, 2011) and has contributed to increasing yields, especially over the last 100 years (Evenson & Gollin, 2003; Huang, Pray, & Rozelle, 2002; Qaim, 2020). Although intensification reduces land expansion, the increase in land productivity is accompanied by environmental damage through the use of chemical fertilizers, crop protection agents, and other yield–enhancing inputs (Pretty, 2018). Nonetheless, plant breeding is expected to further generate land- and resource-saving growth of yields, increase pest-resistance, and consequently ease the trade-off between food security and environmental impacts.

Seeds are not only an input but rather a technology shaping agricultural systems. For example, farmers will be more successful at sustaining organic cropping if their seeds are resistant to those pathogens handled by chemical crop protection agents in conventional farming (Denison, 2012). Breeding systems supply farmers with a choice of seed varieties, which allows them to pick those that best fit their specific biophysical conditions (climate, soil, pest, and weed pressures), their cropping system, and other preferences. New varieties, however, need to be created, multiplied, and then sold and used on farms. A breeding system therefore contains all those activities needed for creating new varieties to be used on farms. We see the breeding system as a social-ecological system (SES); i.e., a nested, multilevel system that provides essential services to society (Berkes & Folke, 1998). The essential services refers to supplying genetic material and its corresponding information flows. Genetic material refers to allelic snippets (variants of genes at gene loci), genetic traits (aggregation of specific allelic combinations), breeding lines (aggregation of genetic traits in plants over several generations), experimental cultivar variants, and varieties in the form of seed. For the purpose of our discussion, we limit ourselves to appropriating and provisioning activities of genetic material by breeders (creating new varieties), multipliers (multiplying seed), retailers (selling seed), and farmers (using the varieties in cropping).

Plant breeding is defined as "the creation, selection and fixation of superior plant phenotypes in the development of improved cultivars" (Moose & Mumm, 2008). A plant phenotype is the observable outcome of the genetic combination of different alleles of a plant under environmental conditions. Breeders can create new varieties only if they select an improved combination of traits. However, they will be able to select this combination of traits only if there are pre-existing allelic combinations in the genes that are capable of producing the desired traits. Therefore, breeders can create a wide set of different varieties, using combinations of different traits, only if they have genetic variation in their breeding material. This is called genetic diversity. Varietal diversity refers to the variation in the set of available varieties.

Genetic and varietal diversity is crucial to maintaining or increasing yields and providing other desirable traits. Historically, epidemics of plant diseases have destroyed entire harvests and slashed yields to a minimum. The black rust epidemics in 1904 and 1916 reduced the wheat harvest in the U.S. Great Plains to one-tenth of its previous yield (Salmon, Mathews, & Leukel, 1953). Governmental intervention and the existence of a few cultivars with disease-resistance genes prevented further dramatic yield losses (Salmon et al., 1953). Today, once again, world food security is threatened by plant diseases, such as Ug99, a new strain of black rust. This can potentially lead to a global plant epidemic with most severe harvest loss if not counteracted by improving diversity in resistance traits (Singh et al., 2011).

To prevent such disasters and maintain the overall functioning of breeding systems, we need to understand the opportunities and constraints faced by breeders, farmers, and other actors in the breeding systems. These opportunities, like the information a breeder receives in exchange for planting a colleague's material in one's nursery, or how multipliers subjectively think about the economic potential of a variety, are affected by the institutional arrangements structuring these situations. Like Ostrom (2005), we understand institutions as "prescriptions that humans use to organize all forms of repetitive and structured interaction (. . .) at all scales". These institutions, which are classified as rules, norms, or strategies (Ostrom, 2005), channel the exchange of genetic material between breeders, the varieties contracted by multipliers, and varieties used by farmers. Regulating these human activities may lead to desirable or undesirable outcomes in social and ecological performance measures; for example, whether there are enough different varieties to choose from for cultivation. Likewise, the institutional arrangements determine whether a breeder possesses the right breeding material and incentives to produce new varieties. Therefore, the challenge for actors who craft these institutions arises in designing rules and considering existing norms such that varietal and genetic diversity can be maintained over time. Given these concerns, we attempt to answer the following question: What governance challenges arise for providing varietal and genetic diversity in breeding systems?

In the next section (Breeding systems as social-ecological systems), we motivate our general approach for using an SES perspective and point to literature that analyzes governance in breeding systems. As we look at breeding systems as SESs, we outline our ontological framework to identify governance challenges in the section The social-ecological systems framework as an ontology for breeding systems. Then, based on the social-ecological system framework (SESF) (Ostrom, 2009), we explain that biophysical context determines activities in breeding SESs, and present three economic transaction theories, which we employ within the SESF. In the Methods section, we explain our operationalization of the elements of the breeding systems. Our results show for the case of winter wheat breeding in Germany how producing information on biophysical processes influences activities and governance challenges thereof. Here, we present the governance challenges for providing genetic and varietal diversity in breeding, multiplying, and farm-saving seed. In our discussion, we reflect on the need for resilient seed systems. We present our hypothesis on trust and biophysical information and how this ties together with future crafting of mid-range theories and potential uses for a seed sector SESF. In our conclusion, we summarize our findings and propose further testing of our hypothesis.

2.1.1 Breeding systems as social-ecological systems

2.1.1.1 *Motivation for general approach*

We motivate the general approach addressing our research question in the remainder of this introduction. The literature on governing breeding activities frames

		Excludability of users	
		Easy	Difficult
Subtractability of use	High	Private good	Common pool resources
	Low	Toll or club good	Public good
			Collective goods

FIGURE 2.1: Typology of goods and services adapted from Ostrom (2005), including definition from Hinkel et al. (2015).

breeding material, traits, lines, seed, or innovation in seed in terms of two attributes—"subtractability" and "excludability of users" (Fig. 2.1). Subtractability refers to the extent to which using a good or service will reduce the availability of the good or service to others. Excludability relates to the difficulty of restricting other users from harnessing benefits of a good or service being provided. Collective goods subsume all goods and services with nontrivial cost of exclusion. These two attributes imply that resource units are merely physical subunits of a resource stock. Most researchers acknowledge that individual resource entities from plant breeding systems are multifaceted and do not fit this goods typology. They draw their readers' attention to different aspects of seed materials, such as the constructed cultural resource component of plant genetic resources (Halewood, 2013), the informational component of seed breeding (Brandl, Paula, & Gill, 2014), the public good attributes of plant breeding research (Brandl & Glenna, 2017), or intellectual property rights assigned to seed developed (Godt, 2016). Sievers-Glotzbach, Tschersich, Gmeiner, Kliem, and Ficiciyan (2020) provide an overview of literature on the different forms of seed commons in recent years.

Despite these concerns of lacking categorical fit, most studies use a good or service as the vantage point for their analyses. Hinkel et al. Hinkel, Cox, Schlüter, Binder, and Falk (2015) emphasize that no resource is rivalrous or excludable per se, but rather is dependent on the activities related to the respective resource units. For example, it is important to differentiate whether people are engaged in recreational fishing using catch-release, or if fishing is a source of food, which remove their catch from the resource system.

In breeding and farming, it is difficult to exclude stakeholders from seed saving and infinitely farm-saving seed. If the cost of exclusion from the benefits of a good or service are nontrivial, then we define these as collective goods, as in Hinkel et al. (2015). Hence, we classify seed material as collective goods, which necessitates the specification of the degree of subtractability of the good along specific activities. Each activity in an action situation should therefore be considered on its own in how it subtracts units from a resource stock. Action situation denotes the metaphorical space where activities of actors occur. For details, we refer to Poteete, Janssen, and Ostrom (2010).

Taking an activity-focused perspective, however, opens up the possibility to (a) diagnose in what action situations subtractability is relevant, and (b) unpack the attributes adding to the underlying social dilemmas of the action situations. We show how to possibly define the resource system and resource unit context to determine how their attributes influence subtractability in action situations that provide genetic and varietal diversity.

Furthermore, the activity-focused perspective allows us to explore government options in a more differentiated manner. Formerly, an ideal form of government was associated with different kinds of goods as a panacea for failing resource management (Ostrom, 2010b). Usually, a free market was deemed ideal for private goods and a hierarchical government for public goods. Yet, these ideotypes of governance prove impractical when looking at context-dependent situations like governing agricultural research for seed innovations (Brandl & Glenna, 2017).

Policy-makers need a clearer idea of which activities to regulate under what conditions. Crafting effective policies needs midrange theories, which account for context but still are generalizable to multiple variants of the same subject of governance. For example, different kinds of breeding, such as conventional, organic, or participatory breeding (Chable, Conseil, Serpolay, & Le Lagadec, 2008), may exist under the same regulatory schemes. These schemes need to accommodate for breeding of fruit (Wolter & Sievers-Glotzbach, 2019), vegetables (Chable et al., 2008), and grain (Gerullis, 2016), although the individual types of crops pose very different challenges when being improved by breeders. To develop theories fit for effective governance, we need to provide a baseline to be capable of saying how the current systemic configuration functions. Looking at resources from the usual dichotomous perspective may lead to panacea prescriptions of governance rather than to context-dependent heuristics of governance (Darnhofer, Fairweather, & Moller, 2010).

We tackle these mentioned deficits in conceptualizing the breeding system as a SES and analyze its governance challenges. We apply the SESF developed by Ostrom (2009) and McGinnis and Ostrom (2014), taking an activity-focused analytical perspective. The SESF is the only SES framework that puts equal weight on the social and ecological system (Binder, Hinkel, Bots, & Pahl-Wostl, 2013). It was developed with a focus on sustainable outcome performance of governance-related research questions (Binder et al., 2013; Poteete et al., 2010). We want to establish a starting point for developing future midrange theories that serve the sustainable governance of breeding systems. To effectively do so, we present where the current governance challenges in seed breeding occur and how they are tackled by different coordination mechanisms in industrialized plant breeding systems.

We apply the SESF to German winter wheat breeding because it poses an instructive case: winter wheat is one of the most produced cereals worldwide and in Germany. Wheat is a self-pollinating crop, which makes it an archetype of line breeding—the most popular technology in breeding cereals throughout the last century (Becker, 2011). Wheat has a high productive value for German farmers and breeders. The German wheat breeding sector comprises 21 active breeders. Thus, the case of German winter wheat lies in-between crops that are bred in a setting of high market concentration, such as maize, and small, localized breeding activities, such as legumes. We expect the case of German winter wheat to be highly instructive as a large-scale agricultural resource system with a variety of different attributes.

2.1.1.2 *The social-ecological systems framework as an ontology for breeding systems*

This subsection presents the ontological framing of our analysis, the SESF, and underlying premises—resilience of SESs, social dilemmas, and governance challenges. Ontology means the essence of reality (Poteete et al., 2010), and an ontological framework is a guide to arrange essential features of complex systems, like SESs. The SESF is used to include the underlying structure of SESs around an underlying action situation where activities are governed to solve (or not) a social dilemma. Yet, one needs theories to connect the systems' entities meaningfully.

Our premise is to treat breeding systems as SESs. Resilience—defined as the "capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks" (Walker, Holling, Carpenter, & Kinzig, 2004) —is the underlying desired goal. Therefore, we stress the importance of (a) maintaining the link between social and ecological systems, and (b) maintaining the defining system functions. Our research question in this context is how does the breeding system provide genetic material flows such that food and fiber for human consumption can be sufficiently supplied while maintaining ecosystem service provision from connected ecological systems? As such, the provided flows of genetic material, mainly in the form of seed, need to fit farming purposes to ensure varieties are adapted to specific ecological contexts and farming objectives.

That is, for individual cropping and breeding systems, maintenance and function is context-dependent because each cropping system has different configurations and attributes of social and biophysical entities. However, for different types of breeding systems, the capability of providing functions and the desirability of outcomes needs to be assessed (Carpenter, Walker, Anderies, & Abel, 2001). The SESF serves as a tool capable of arranging different system parts into a framework with the underlying focus on the performance of governance (Binder et al., 2013; Poteete et al., 2010).

Social dilemmas arise when individuals are tempted to take an action but the collective will be better off if all (or most individuals) take other action(s) (Poteete et al., 2010). As outlined, nontrivial cost arises from keeping someone from undertaking undesirable activities, termed as the cost of exclusion (Hinkel et al., 2015). Collective goods are a category of dilemmas where these costs arise from undesirable appropriation activities. If some actors overuse a resource, those activities may then reduce other actors' potential use. In its extreme form, this may lead to the unrecoverable overuse of a resource and a collapse of the resource stock. The governance challenge is to implement institutional arrangements such that (a) activities of appropriating a collective good will not overuse it, and (b) the collective good in question will be created, maintained, and improved over time. The first is a canonical appropriation action situation, while the latter signifies the canonical provision action situation (Hinkel et al., 2015). Different factors influence the core relationship of individuals solving a social dilemma. Solving a social dilemma usually entails some form of collective action or cooperation in activities of individuals. Cooperation among individuals is highly context-dependent (Poteete et al., 2010). In the SESF, we separate the context into a micro-situation, identifying attributes that directly affect individual behavior and broader social-ecological variables.

The premise for using the SESF is that we can unpack influencing factors of activities in a hierarchical manner. The SESF by design allows for using different theories within the same framework, making it possible to compare the economic coordination mechanisms currently regulating the different material and information flows within the breeding system. There are many entities, system features, interactions, and feedback loops that can be aggregated and disaggregated to concepts that influence the outcomes of activities in a SES. We assume that these variables are subsystems—one nested within the other (Simon, 1996). Therefore, the SESF divides the underlying SES into different tiers.

The first tier of the SESF comprises the resource units as part of the resource system. The resource units function as inputs to the action situation, and the governance system defines rules for actors participating in the action situation, with interactions leading to outcomes (Ostrom, 2009). The second tier is most commonly represented as an extensive list of potential subconcepts of the various first tier concepts deemed relevant for the focal action situation. These concepts can further be subcategorized into more tiers if necessary. They will contribute by explaining how the micro-situation influences the behavior of individuals. We concentrate on those governance challenges regarding the links between the social and biological domain connected to the appropriation and provision activities of the collective goods in question. Therefore, we concentrate on breeding, seed multiplying, and seed-saving/seed buying activities.

2.1.1.3 *Biophysical context*

The SESF has been developed for analyzing the governance of small-scale resource systems. Likewise, the design principles from Ostrom (1990) inform the sustainability of small-scale resource systems. Projects like the Social-Ecological Systems Meta-Analysis Database (SESMAD) (Cox, 2014)) explore sustainable governance of large-scale resource systems. Breeding systems of whole countries—as in our case—are large-scale resource systems, since they go beyond one spatially well-defined area and include several soil–climatic niches (Acquaah, 2007; Cox, 2014). For the sustainable governance of large-scale natural resource systems, findings and theories are not yet available to serve as design principles (Ostrom, 1990). Partelow (2018) suggested aggregating insights on different resource system types into sectoral SESFs for finding the context-dependent unique yet shared variables of different natural resource types, such as fisheries or forests.

In the SESF, biophysical entities are segregated into resource system and resource units, which aggregate to a resource stock. The classic example is a fish being one unit of a fish stock, and the underwater ecology and all the technical infrastructure (e.g., fishing boats) to provide the fish is the resource system. Varietal and genetic diversity are idiosyncratic resources in the sense that they are both dependent on human activities and need to be sown, managed, and actively improved by humans. Changes in crop seed attributes will be produced only if humans actively change the nature of a plant. Degradation of varietal and genetic diversity stems from not undertaking the respective activities. Not sowing a variety will lead to the disappearance of its genetic or phenotypic traits and its loss from the common gene pool or varietal stock. Hence, seeds are biofacts (Karafyllis, 2006), meaning they are biological material, a natural resource, and a (human-designed) technology at the same time.

Moreover, the "quantity" of our resource stock (pool of varieties or gene pool) is the difference in traits and not the mere number of varieties or genes present. "More" genetic material or varieties is not superior to "less" material, but whether the material at hand can satisfy the needs of human end-uses is decisive. From an economic perspective, varieties are bundles of attributes where each farmer or breeder has a unique satiation point for a specific combination of attributes compared to bundles that deviate from this ideal combination (Varian, 2006). Therefore, the governance challenge for varietal and genetic diversity is to steer the community of actors to continuously use seeds such that a desirable set of traits is available despite potential individual incentives to behave otherwise.

2.1.1.4 *Theories of transactions*

We are not interested in the SESF as a mere descriptive collection of variables, but want to inquire about how biophysical features connect to the social system. We want to know how processes that create biophysical information influence the coordination mechanisms of human-nature transaction in the relevant action situations. We base our choice of theories about these connections on the descriptions of our interviewees and on how secondary literature frames the respective activities as (1) cooperative undertaking of material exchange between seed businesses (Brandl & Glenna, 2017; Gerullis, 2016)(observation 1, 2, 12, 19, 22, 23), (2) contracting and subcontracting in seed multiplication (Thiel, 2014)(observation 3 and 4), and (3) "the seed market" (Brandl et al., 2014; Braun, 2021)(observations 1–9). We use economic theories of transaction to show the disparity in what is relevant for coordination mechanisms to function from the perspective of the economic ideal and what actors identify as relevant. This also justifies our use of the SESF, as it was designed to accommodate multiple theories in one framework and makes them comparable with respect to the scrutinized entities. Hence, we analyze the relevance of the theories in the context of the coded action situations.

We compare the theories of transaction with our observations based on Ostrom (2010a) "broader theory of human behavior". Ostrom (2010a) outlines how trust and reciprocity, apart from behavior like norm adoption or learning, will lead to a higher or lower likelihood of self-organization of the actors involved in a social dilemma. As we look at activities in coordination mechanisms that allocate resources to observe how individuals deal with (potential) social dilemmas in human-nature transactions, we show how reciprocity and trust are steered within coordination mechanisms in markets, individual contracting, and collective action through social norms (Ostrom, 2010a; Poteete et al., 2010).

Standard market theory assumes that prices are the only market signals driving the behavior of actors participating in transactions, and that competitive markets deliver economically efficient results (Levačić, 1991). Producers and consumers are brought together in a mutually advantageous exchange of goods or services, and diverging interests are resolved through a price on which both parties agree (Callon, 1999). Owing to the structure of market transactions, actors in markets are able to put their trust in the system itself rather than into other parties involved in the transactions. Because the transaction in a market is near instantaneous from the moment an individual enters the transaction to its fulfillment, there is no reciprocity or reputation building taking place in this setting. Both parties can leave the market transaction without lasting ties, as strangers to each other (Callon, 1999).

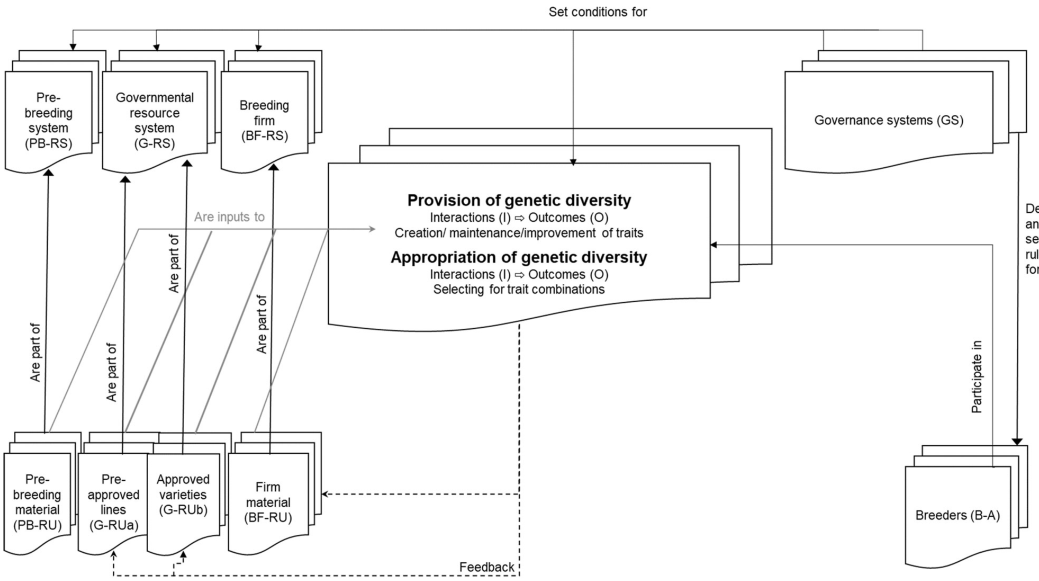
Collective action gives stakeholders a chance to manage the natural resource system sustainably. It provides the option of using the resource over an infinite time horizon if they choose to bear the cost of self-organizing. Reputation, trust, and reciprocity play major roles here, where different structural variables such as the number of participants, face-to-face communication, heterogeneity of participants, or past experiences influence these three concepts and their linkages, thereby leading to different levels of cooperation. For a more extensive list of these variables, see Poteete et al. (2010). Natural resource systems usually bring about their resource units with a time lag and in very different forms. While in a market, all activities regarding the appropriation of goods and services can be transferred into money equivalents (Callon, 1998), not everything a natural resource system produces can be calculated in one type of (metaphorical) currency. Trust and the entanglement in dependencies from other actors bridge structural and time differences of the transactions taking place. Moreover, the time lag gives actors the chance to reciprocate and frame these activities as seemingly selfless (Callon, 1998), expressing trust and building more personal bonds between individuals, such as friends.

Subcontracting occupies a middle ground between market and subcontracting settings. Its time horizon is finite but not instantaneous. There is usually a time gap between the fulfillment of one party's obligation and the return of the service/good by the other party. Both individuals cannot part as strangers before both sides receive their due, but neither can they rely on a lasting bond to balance any open account. They may specify their mutual obligations in a contract, configuring every little detail of the relationship through bargaining, negotiations, and mutual adaptions (Lorenz, 1991). Again, the underlying challenge is to collapse time frames and goods or services exchange into one contract, even though they are delivered with a lag and in (potentially) different forms. Such specifications, be they written or merely verbal, are however limited by the underlying transaction cost involved in bargaining, negotiation, and adaption processes. Not all actions can be sufficiently controlled or monitored, even if they are set in writing within a contract (Lorenz, 1991). For the duration of a contract, the involved actors are thus neither strangers nor friends to each other but are locked into reciprocation and trust over a negotiated time horizon.

2.2 Methods

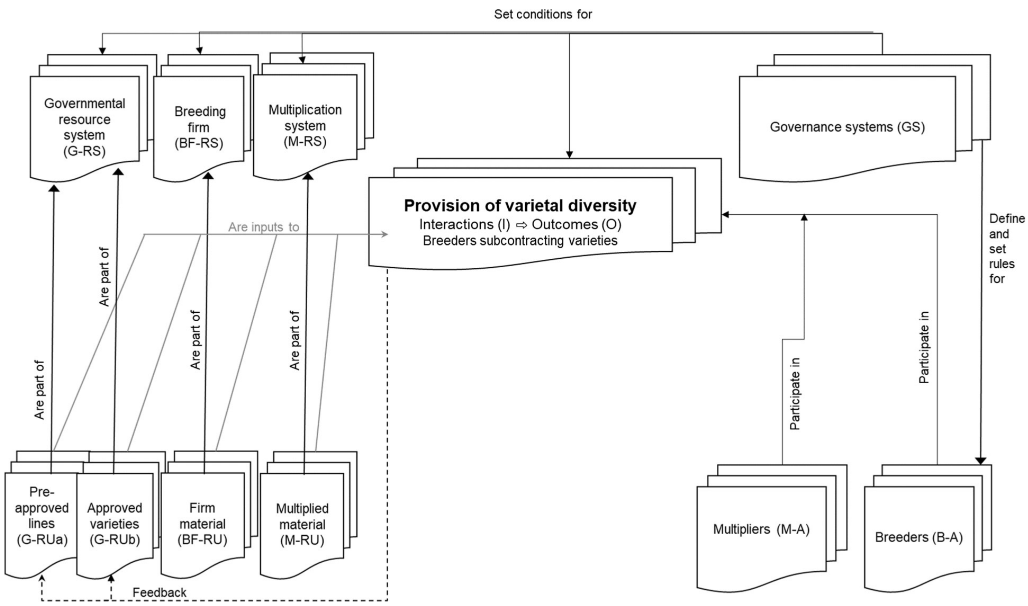
This section lays out how data for the German winter wheat breeding sector case were gathered and how we operationalized the SESF for unpacking the micro-situations around breeding, multiplying, and seed-saving activities. We took an inductive approach in our research design (Bernard & Bernard, 2013) to accommodate for a wide variety of data types: (a) qualitative interviews, (b) participant observation, and (c) secondary sources from scientific literature or practical guide books on breeding, farming, and seed multiplication.

Data collection followed a grounded theory style process (Bernard & Bernard, 2013), as plant breeding is very heterogenous in terms of explicit and implicit knowledge (Brandl et al., 2014; Timmermann, 2009). Strauss and Corbin (1994) state that "the methodology's central feature is that its' [sic] practitioners can respond to and change with the times (. . .), as conditions that affect behavior change, they can be handled analytically". We conducted qualitative, initially open and later semi-structured interviews with open questions. To avoid misrepresentation of individual attitudes and



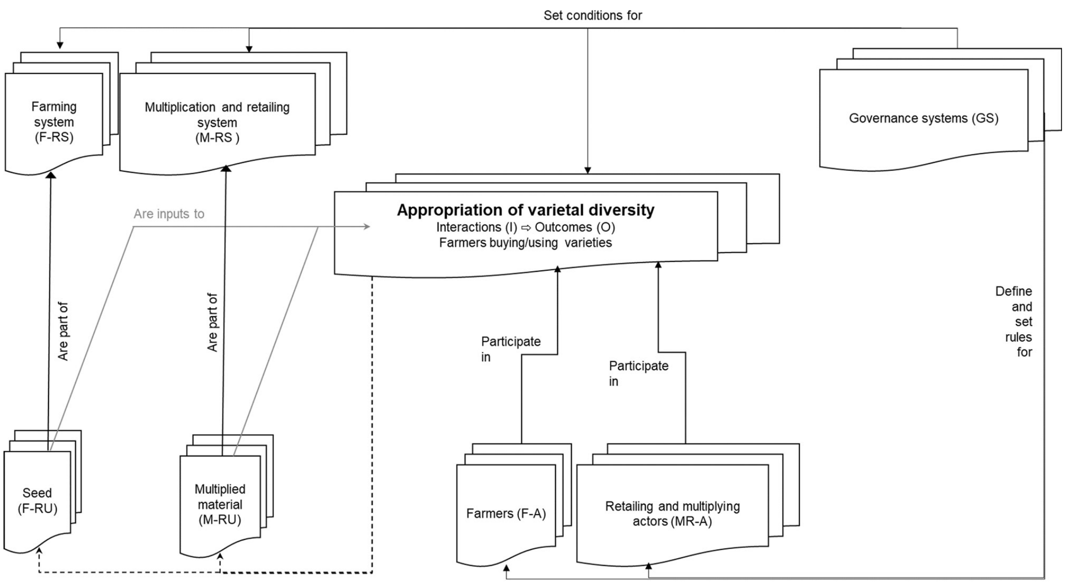
First-tier variables are taken from McGinnis and Ostrom (2014), with alternative variables for governance system. Because there are multiple resource systems with resource units and actor groups, these variables are preceded by an abbreviation for the respective group. Social, economic, and political settings and related ecosystems are not accounted for because they were not found to be relevant for the investigated level of analysis. Relevant sources for the included variables were mainly interviews 1, 2, 3, 7, 8, 10, 12-15, 17-20, 22, 24-30, and 32; see Table A2.1.

FIGURE 2.2: First-tier social-ecological system framework components for provisioning and appropriating genetic diversity.



First-tier variables are taken from McGinnis and Ostrom (2014), with alternative variables for governance system. Because there are multiple resource systems with resource units and actor groups, these variables are preceded by an abbreviation for the respective group. Social, economic, and political settings and related ecosystems are not accounted for because they were not found to be relevant for the investigated level of analysis. Relevant sources for the included variables were mainly interviews 1, 2, 3, 4, 6, 8, 9, 14, 21, 23, and 33; see Table A2.1.

FIGURE 2.3: First-tier social-ecological system framework components for provisioning varietal diversity.



First-tier variables are taken from McGinnis and Ostrom (2014), with alternative variables for governance system. Because there are multiple resource systems with resource units and actor groups, these variables are preceded by an abbreviation for the respective group. Social, economic, and political settings and related ecosystems are not accounted for because they were not found to be relevant for the investigated level of analysis. Relevant sources for the included variables were mainly interviews 4, 5, 9, 11, 8, 16, 21, 23, 31, and 33; see Table A2.1.

FIGURE 2.4: First-tier social-ecological system framework components appropriating varietal diversity.

viewpoints, interviewees' claims were anonymized, fed into modified questionnaires, and then presented to subsequent interviewees for comment. Through this iterative approach, we consolidated individual perspectives into a knowledge consensus of the plant breeding community. To account for survivor bias and sequentiality, these consolidated accounts were presented to the first round of interviewees for validation in a final feedback loop. Interviews were conducted throughout 2016–2017, with revisits on selected topics in 2019, on four occasions (see Appendix B, Table A2.1 for a detailed listing of topics). During the 2019 round, we sought mainly to update information in the face of changes in the industry (pathogen disease events, merges and acquisitions, business trends) and to complete information missing from earlier accounts. Our 18 interviews were complemented by participant observations on 21 occasions (see also Appendix B, Table A2.1). We used participant observation to supplement our interview data with practical, first-hand experience of processes in breeding programs (Bernard & Bernard, 2013). All quotations were translated from German into English.

Interviews and participant observations are numbered in brackets following each paragraph. Information on retailing and multiplication was drawn from secondary and legal sources as suggested by Cox (2015) to complement case study work on SESs. Our initial access to winter wheat breeding came from contacting two private wheat breeding firms: a southern Bavarian cereal breeder and the other from Lower Saxony in northern Germany. This allowed us to sample further interview partners in both regions through snowballing (Bernard & Bernard, 2013). Because southern Germany has smaller spatial segments in its ecological niches compared to northern Germany, we wanted to account for potential differences.

There is less market concentration in German winter wheat breeding compared to other crops such as maize or rapeseed (Brandl & Glenna, 2017). German plant breeding is done by 58 different private businesses that produce commercial seed, of which 21 have winter wheat programs. Public research centers support German agricultural extension to farmers and conduct research projects with breeders. The Federal Research Centre for Cultivated Plants and the Bavarian State Research Center for Agriculture are prominent actors at the federal and state level, respectively. Both institutions support public plant breeding through public–private partnerships (Brandl et al., 2014). The employees of governmental organizations are usually referred to as "public breeders", although producing new varieties is not their main goal. Instead, they provide public infrastructure for variety trials and pre-breeding programs.

Interview transcripts were initially coded openly (Bernard & Bernard, 2013). In the subsequent step, we used the diagnostic procedure by Hinkel et al. (2015) to determine underlying social dilemmas and the different entities of the SES to ensure comparability with other SESF cases. These codes were conceptually matched with the SESF variables, for which the results can be seen in Figs. 2.2 2.32.4 2–4 for the first tier and in Appendix A, Figs. A1.1–1.3 for the second tier. Hinkel et al. (2015) provide a set of 10 questions to identify and interpret the different attributes of the units of the resource (RU) and their providing resource systems (RS) together with the action situation and governance system (GS) from the SESF. RU and RS were codified as suggested by Hinkel et al. (2015) to characterize governance challenges in relation to two types of action situations: one is a provisioning action situation in which certain actors face the collective challenge to maintain, create, or improve the collective good; the other is an appropriation action situation in which actors face the collective challenge to avoid overuse of a collective good. We use the identified actor groups, RU stocks, and RSs in the following for representing the first tiers of the SESF in breeding, multiplication of seed, and appropriating seed by seed-saving or seed buying (Figs. 2, 3, and 4, respectively).

There are shortcomings to our approach. Our sampling through snowballing from those breeders in our vicinity may have introduced a bias to a certain degree, as we were not able to interview breeders from one of the firms dominating the international seed market, such as Bayer Crop Science or Syngenta. Moreover, the heterogeneity of the data posed a challenge in terms of integrating them into the SESF, and would not have worked without Hinkel et al. (2015). Yet, we are still missing a proper diagnosis to operationalize the GS variables of the SESF in correspondence to the RS.

2.3 Results

This section presents the results of using the SESF for German winter wheat breeding. We present the governance challenges arising from breeding, multiplying, and using seed for farming. The three action situations show how social dilemmas in breeding systems depend on how information on biophysical context is created and distributed. In Fig. 5, we provide an overview of the main activities in the breeding system, comparable to the examples provided in Hinkel et al. Hinkel et al. (2015). Fig. 5 shows which and how different activities contribute to the two outlined provisioning situations. Each activity–to–RU relationship yields different levels of subtractability.

In this section, terms in parentheses refer to variables or entities in Figs. 2, 3, 4, or 5. Second-tier SESF variables—also in parentheses—are preceded by two letters that indicate the corresponding entity they refer to in the corresponding first tier. They can be found in Appendix A, Fig. A1.1 for appropriating and providing genetic diversity, Fig. A1.2 for providing varietal diversity, and Fig. A1.3 for appropriating varietal diversity.

Collective Goods	Actors	Benefits	Activity	Stock of RU	Subtractability	Ressource System	Provisioning Action Situation
Diverse set of genotypes = genetic diversity	Breeders (B-A)	Future value of a genetically diverse system	Pre-breeding	Rest of primary genepool	Low	Techniqual facilities and nurseries used for pre-breeding (BF - RS)	Breeders maintain well-performing varieties, which they supply, adapted to the current conditions by ensuring a sufficiently diverse set of on-nursery-genetic diversity to select from
				adapted breeding material to temperate German climate	Medium		
		Income from licenses of Z-Saatgut and income from resowing licences	Creating /maintaining /improving inhouse variation	Lines submitted to trials for value of cultivation and use	High	Testing sites for value of cultivation and use trials; machinery and other infrastructure involved in the cropping process; governance expenditure used for the testing; calculating power for data processing (BF - RS)	
				All available varieties on Descriptive Variety List	Low		
				Diversity of genotypes and knowledge about internal lines within individual breeding firm	High	Nurseries; machinery; laboratories anything technical or subcontracted by the individual breeding firm (G - RS)	
			Selecting from inhouse variation		High		
			Subcontracting varieties to multipliers/ agricultural retailers	Total expenditure of agricultural retailers / multipliers	High		Multipliers / retailers supply a set of varieties fitting different ecological niches and preferences of farmers
Diverse set of varieties = varietal diversity	Multipliers (M-A)	Income from sublicensing of certified seed and income from selling multiplied seed to breeders/retailers	Selling certified seed to agricultural retailers	Total expenditure of agricultural retailers	High	Farming equipment for sowing, growing, harvesting seed (M – RS)	
			Multiplying seed for breeders	Total expenditure of breeders for licensed activities	Medium		
				Multiplied seed			
	Agricultural Retailers (R-A)	Income from selling other inputs	Selling certified seed to farmers		High	Storage equipment for storing and selling seed (M – RS)	
		Income from selling seed	Selling fertilizers and pesticides matching the respective seed	Farmers total expenditure	Low		
				All available seed			
	Farmers (F-A)	Income from selling one's yield	Conventional/organic winter wheat cropping	Other inputs to farming	Medium	Farming equipment for sowing, growing, harvesting seed (F – RS)	
		Security from stable yields over the years					

FIGURE 2.5: Overview of provisioning action situation for seed production of German winter wheat based on the diagnostic procedure from Hinkel et al. (2015).

Varietal diversity is crucial to the farming system because the available variation enables farmers (F-A) to choose the variety appropriate for their needs. The main benefits to farmers from cropping a variety are the security and income derived from stable and high yields over the years. In Germany, farmers will buy varieties listed on the Descriptive Variety List from agricultural retailers (R-A) if they do not save seed on their own. Breeders subcontract rights to multiply varieties to multipliers and retailers through different licensing relationships, involving marketing organizations and other governing actors (GS). Breeders (B-A) and multipliers earn income through license fees from selling varieties to farmers. For retailers, seeds are merely one input among others sold to farmers. Breeders have a future value from a diverse gene pool available for their breeding activities. Breeders supply the initial material from which multipliers propagate the marketed seed (M-RU). In Germany, breeders receive licensing fees for sales of certified seed and for farm-saved seed (F-RU), which farmers voluntarily pay to a (private) governing organization, called Saatguttreuhand, which reimburses breeders for these seeds [1, 3, 4, 6, 11].

2.3.1 Providing genetic diversity

To develop new varieties, breeders need genetic variation in different candidate cultivars. Next, they select those candidate variants from the plots of the candidate cultivars, which are planted for inspection, with desired observable traits under different environmental and management conditions (Becker, 2011) (see Fig. 2 [first-tier variables] and Appendix 1, Fig. A1.1 [second-tier variables]). Having data on agronomic traits for different genotypes is central to decision-making in plant breeding—"the data [are] key" [27]. The different input materials are marketed varieties (G-RUb), pre-approved lines (G-RUa), pre-breeding material (PB-RU), and a breeding firm's own material (BF-RU). Asked whether there is a global gene pool, one breeder responded, "no no no. . . the gene pool is what [breeders] build up themselves, each unique to themselves—the employees and the breeders. There are breeders who always register the same variety type, because they believe that's how a variety needs to look like—their ideotype. There is a gene pool of the individual breeder, which is there. And it depends upon philosophy of the breeder how far he wants to break that up—and for what target market he is breeding for" [2]. Breeders' gene pools therefore depend heavily on their decision-making.

Breeders tackle two main types of decisions: crossing, and selecting for a targeted genetic and phenotypic variation within their material (Timmermann, 2009). Depending on the size of a firm's breeding program, this potentially involves planning a hundred to several hundreds of crosses per year. Selecting variants deemed as good candidates for varieties (positive selection) or not worthwhile keeping (negative selection) means inspecting several thousand variant plots per year (Timmermann, 2009). Based on the information available on agronomic performance data and its quality, breeders decide which genotypes to use for crossing and during selection (GD-I1) [1, 2, 10, 17, 18, 19, 26, 27, 28, 29, 30].

Time, nursery space, and information on material are scarce in the breeding process. Information on traits is produced by sowing, inspecting, and harvesting the different materials in different testing sites and nurseries sustained by the breeding firms (BF-RS) and different governmental organizations (G-RS; PB-RS). Time is critical in breeding because it takes on average 12 years to establish a desired trait combination in a variety. The size of nurseries determines how much space there is each year for inspecting their different lines. Nurseries together with greenhouses, cooling chambers, and all other required technology elements make up the resource system's size (BF-RS3) and determine the number of candidate varieties (lines) submitted for approval. While big firms will have multiple locations around the world to test their breeding material (BF-RS9; BF-RU7b), and greenhouses, big nurseries, and the newest technological setup (BF-RS4; B-A9), small- and medium-sized breeders lack capital for such equipment, thereby leading to heterogeneity among actors in their socioeconomic attributes (B-A2) [1, 2, 10, 26, 27, 28, 29, 30, 12, 13, 14, 15].

Breeders employ different strategies to increase their selection pressure. One is to have multiple nursery sites to test breeding material throughout the year. Multiple testing sites can gather rich data on variation in cultivar performance under different biotic and abiotic conditions (Becker, 2011). Another strategy is to exchange information (GD-I2a), material (GD-I2b), and nursery space (GD-I2c) at different sites with colleagues or to cooperate in research projects (GD-I5) [1, 2, 29, 30].

In anticipation of the spread of public information, breeders will share their information and material on a bilateral basis before they are obliged to do so by law. Breeders usually have bilateral contracts with their colleagues that give each other access to their pre-approved material (G-RUa), which gives them the opportunity to cross-in material of colleagues 1 or 2 years ahead of time. This leads to a spillover of traits between different firms and spreads attractive traits throughout all firms' gene pools. Most breeding firms cooperate in research projects (PB-RS) and with public breeding programs (PB-RS) to conduct research for introducing more exotic material (GD-I7/8). These projects give breeders the opportunity to circumvent lengthy and costly screening and back-crossing activities with non-adapted material, the so-called pre-breeding material (PB-RU). It can take up to 30 years until certain traits of genetically distant material are transmitted into adapted material, carry the desired traits, and exhibit the same yields as adapted varieties [1, 29, 30, 25].

2.3.2 Governance challenges of providing genetic diversity

The governance challenge in providing genetic diversity (GD-O2) originates in supplying and using an ample set of different genotypes to/by breeders (GD-O1; GD-I1). The potential social dilemma for genetic diversity is that no variation is left to cross with, which reduces the scope for improvements in agronomic traits. One of the interviewed breeders uttered this concern: “You know, people say—and that is actually a bit frustrating—that today there is only 5% variation left in the wheat genome [in Germany], the rest is fixed, because these are positive traits, which are the same for all varieties. . . and that is a considerable narrowing.. . . Germany’s [wheat] gene pool has a quite close degree of [pedigree] relationship” [2]. The underlying problem here is that breeders may mainly be crossing-in those traits that are easy to cross-in but not those traits that need more breeding effort to enter a gene pool, although they might be necessary for long-term desirable cropping systems (All-RU3; GD-O2). In cereals, “quantitative resistances against diseases [exemplify] difficult-to-breed-for traits” [24]. Quantitative resistance traits depend on multiple gene loci, and therefore will not be breached as easily by pathogens. Establishing quantitative resistance traits in combination with high yields is difficult for breeders and can be the effort of “a whole career” [1]—“40 years” [2]. It is easier to take qualitative traits with known single gene loci and cross them into one’s material, aided by genetic markers. Yet, these are “easily breached” [24] by pathogens.

Breeders exhibit the attributes highlighted as tentative for collective action (Ostrom, 2010a). They improve, maintain, and use their material within self-organized research projects. They also set informal norms for their activities within the community. The targeted activities create new candidate varieties using the RUs under scarce space, time, person-power, and nursery locations. Inspecting material “at a colleague’s nursery” [29], or even when they will inspect it for each other, means that one has more information to base one’s decisions on as a breeder. Mutual trust and reciprocation in individuals (Burt, Christman, & Kilburn Jr, 1980) play vital roles here because one party needs to trust in the other to use and allocate resources toward their colleague’s material “which others will exchange with you” [30] in the long run. They cooperate with each other in activities over a 45-year time horizon. They share material and corresponding information or participate and share investments in public–private research projects on costly traits. All of these activities are undertaken based on trust between the individuals and the reputation they build over time (B-A6). As such, the governance of breeding material for German winter wheat complies with collective action theory (Ostrom, 2010a) [1, 2, 31].

The German governmental system (GS) symmetrically supplies information on qualities and agronomic performances of all lines submitted for public approval (G-RUa6; G-RUb6) to all participating breeders (B-A1; GD-I2a), as a benchmark of "seeing the performance of the competition" [7], and aids in research of "hard-to-get-to" [25] traits, which may demand more breeding effort than usual crop attributes. Yet, trust is supplemented by information. Symmetric information is a key feature of the transaction relationship between breeders. The information on the cultivars' (RUs) performance of qualities and agronomic attributes are key signals to a breeder's decision process on which material to use for breeding (GD-I1)—"if I see something good in the material [of others'], I will cross it in right away" [29]. Public information provision is key because it supplies breeders with the same comparable information and facilitates early exchange of material among breeders [1, 8, 24].

2.3.3 Providing varietal diversity

Providing varietal diversity depends on breeders successfully subcontracting variety multiplication (see Fig. 3 and Appendix A, Fig. A1.2) and marketing seed to farmers (see Fig. 4 and Appendix A, Fig. A1.3). Farmers (F-A) may sow three types of seed: farm-saved seed, certified varieties used before, and certified seed from a new variety (Heisey & Brennan, 1991). The proportion of newly bought (M-RU) compared to farm-saved seed (F-RU) is called variety turnover and determines the seed demanded. Seed turnover has been between 50% and 60% for German cereals in recent years, "with increasing tendencies" [23]. Turning toward buying certified seed depends on the value-added (F-RU4) and other advantages farmers receive from using certified seed (F-A7; F-A3), such as better germination qualities or forgoing "the hustle of dressing and pilling" the respective seed themselves (AV-I3; AV-I5) [5, 16, 21, 23].

Varieties are experience goods (Nelson, 1970). If the yield from a new variety is not living up to its expectation (F-RS7), there is no possibility to recover the damage. Farmers ideally pick those varieties that fit the biotic and abiotic circumstances of their farm (F-RS) and other preferences in yield and crop qualities (AV-O1; AV-O2). Farmers, however, may not pick optimal varieties with respect to their specific conditions. They choose varieties without resistances—sometimes because "a neighbor recommended [it]" [5,6]—and end up with applying more pesticides than necessary (Dachbrodt-Saaydeh et al., 2018), or they may have a short memory in picking their varieties because they "only consider the last year" [23]. If farmers, however, do not buy varieties with resistances, then those varieties will not have a market share big enough to be profitable for multipliers (M-RU4). Hence, multipliers abolish their multiplication (PV-I1), and the respective resistance traits will "cease from the existence" [24] of the set of varieties (PV-O1) [1, 2, 3, 6, 24, 31].

To forgo rent-seeking by retailing actors (M-A), public variety trials (G-RS) produce "unbiased" [9] information on how varieties perform in different trial locations as an orientation for farmers' variety choices (PV-I2). There is, however, a "varying supply of [public trial] information for [different] states in Germany" [9] (AV-I2). Some varieties "work well" [1, 2] across different soil–climatic regions and are a potentially significant source of yield and revenue (M-RU2; PV-I5). Some varieties are fit for more "specific regions" [6]—ecological niches. Varieties that perform well in a growing region (G-RS9; G-RUa) will be recommended for that soil–climate region and will be listed as such (see annual reports from the state variety trials, such as Nickl and Schmidt (n.d.)). State trial conductors will choose the varieties they deem fit for the individual regions, given the variety's characteristics in the national trials (G-RUb). They will for example "look at the [varieties'] performances in the diseases important for the region" [23] and then put those varieties into the state variety trials. Supply and demand of those varieties will therefore vary across different regions [5, 16, 23, 35, 9].

The appropriation situation is incorporated into the provisioning situation as the economic reasoning of the multipliers in providing varieties includes expectations on what farmers will buy later on. As holders of the plant variety protection rights (GS1; GS3; GS7), breeding firms are granted the right to multiply, prepare, and market seed material for a variety (§10 SortSchG (1985)—Plant Breeders' Rights Act). Breeders transfer these rights to multiplication and retailing businesses in exchange of licensing fees (Erbe, 2002). Variety performance in national and state trials gives multipliers a first signal of how much a variety might be worth (AV-I2; PV-I2; M-RU4). This can have detrimental effects, as "one year [of bad performance] can destroy 20 years of breeding" [23], and multipliers will not buy the respective variety. Multipliers strive to have enough seed ready for sale in time. With wheat, it will take 3–4 years (M-RU2) of propagation until a reasonable amount of seed can be supplied (M-RS5; Becker 2011:33). Multipliers try to decide on which varieties to subcontract as early as possible (M-RU7a) [1, 2, 3, 6, 9, 23].

2.3.4 Governance challenges of providing varietal diversity

The governance challenge for providing varietal diversity is to coordinate an adequate supply of varieties multiplied and sold to farmers that fit their ecological needs and other preferences (PV-O1). For varietal diversity, the potential social dilemma is two-fold. First, farmers may not choose the varieties that fit their actual needs for many different reasons, which can lead to an underuse of certain traits (AV-O1). Second, multipliers may be prone to supply only "big varieties" [5] and abolish varieties that service small ecological niches or certain traits, such as resistances, due to lower revenue potential (PV-I1) [4, 35].

Both subcontracting variety multiplication and seed markets are forms of decentral coordination. Breeders subcontract the multiplication of their varieties to multiplying and retailing actors. Information on agronomic performance and baking qualities from public variety trials serve as signals on the attractiveness of a contracted variety to the involved parties (BF-RU4; M-A7). Farmers likewise take the information as signals for their decision on which variety to buy (F-A7; F-RU4; M-RU4) [4, 5, 35].

Trust plays multiple roles in seed marketing and multiplication. Seed marketing depends heavily on the trust farmers have in trial results. Retailer and farmer are per se strangers to each other and engage only in an instantaneous transaction relationship (Callon, 1999). They may not trust each other directly, but both parties trust in the market system, establishing their private property rights over seeds purchased as a commodity (GS7) and qualities guaranteed by seed regulations and monitoring of multipliers and retailers (GS1; GS3) [21, 23, 32, 4, 5, 35]. Subcontracting of a variety establishes an expedient mutual dependency between breeder and multiplier. For the length of a contract, ranging from a few to 25 years, they are neither friends nor strangers (Lorenz, 1991), and both parties do not reciprocate their actions beyond the contract. Levels of trust will, however, be influenced by the information supplied by public trials [6, 8, 33, 34].

Publicly supplied trial information produces different kinds of informational settings in both action situations. It brings about informational symmetry between farmers and retailers. This status cannot be reached for breeders and multipliers because breeders will always know more about the variety subcontracted because they have more information on a variety's descendance. Yet, the increase in information through official trials will provide the multiplier with enough information to enter a subcontract. Retailers have greater incentives to sell varieties that are susceptible to pathogens because they sell complementing crop protection products. Nonetheless, breeders need to trust retailers to fairly market their varieties next to varieties from competing breeders. Trust is expedient in this situation because one actor is incapable of monitoring the activities of the other properly. Hence, they enter a mutually dependent transaction relationship.

2.4 Discussion

We presented a case of three different action situations (breeding, multiplication, farming) in a breeding SES and showed how three different coordination mechanisms direct human-nature transactions of winter wheat seed. We used the SESF as a tool to operationalize the different entities in the breeding SES, to ensure a systematic procedure that enables comparison with future cases of similar systems (Cox, 2014; Partelow, 2018), and to employ different theories within the same ontological framework. We showed how the production and distribution of biophysical information coincides with different forms of trust affecting transactions with different time horizons. For seed systems, the commonly employed economic theories may not bring about the relevant aspects for heuristics of governance in breeding, multiplication, and farming.

The production of biophysical information drives all coordination mechanisms involved. Where theory on markets of homogenous goods would suggest that the price is the only relevant signal, seeds prove to be a heterogenous good with limited fit to this model and to the narrative of their governance usually coming with it. Information on agronomic performance as communicated through public trial outcomes explicitly addresses this heterogeneity in seed and gives farmers, who are heterogeneous actors in heterogenous environments themselves, the possibility of finding a matching variety. Information on agronomic performances is key in stipulating actors in buying seed or seed-saving activities. Theory on collective action (Ostrom, 2010a) describes processes in breeding well because it links biophysical information variables to activities. What breeding actors identify as key components of their activities converges with what theory suggests. Individual trust, reciprocity, and reputations play a vital role in breeding activities spanning long time horizons. Theory on subcontracting seems adequate in the role it attributes to expedient trust because it includes (agronomic) information signals for actors to engage in multiplying. However, further scrutiny into how subcontracting is influenced by spatial difference and the coinciding ecological niches is necessary here.

2.4.1 A hypothesis on trust and biophysical information

We propose that future studies examine the role trust and biophysical information play in enabling actors to coordinate their transactions involving natural resources in large-scale systems. Our hypothesis is that the credibility of information produced and the symmetry of supplied information are crucial for facilitating socially beneficial outcomes of the coordination mechanism. By informational asymmetry we refer to some participants in a transaction having more information on the resource system and units than others. The biophysical information of varieties—in wheat we consider 23 attributes commonly measured in trials (Nickl & Schmidt, n.d.)—is of higher dimensionality than the price in Akerlof (1970) classical example of the used car market. It signals the type of ecological niche the variety may fit. Therefore, our notion of symmetry or asymmetry of information refers to whole bundles of context-dependent information on varieties. Relevant for our hypothesis is whether it influences the trust relationship between the interacting individuals. Credibility of information is relevant and produced by joint public production and quality management of field trials (results over multiple locations and multiple variants). The state and federal variety trials produce unbiased information for all actors in the system. The relevant aspect for our hypothesis is whether one has trust in the process that produces the information.

Based on the information available to us, we cannot be sure whether trust in these situations works in a cumulative fashion and if different forms of trust could substitute for each other. Also, we cannot say if different forms of information each trigger different forms of trust and corresponding coordination mechanisms. If actors produce information "credibly" and supply it symmetrically, then transactions over material (in our case, seed) can be facilitated in a coordination mechanism where actors may part as strangers (Callon, 1999)—in our case, a seed market. We suspect this may be due to individuals trusting in the market system rather than the individuals they trade with directly. When looking at contracting in multiplication, information supplied from an actor who has no stakes in the transaction brings about expedient trust. This type or amount of trust is sufficient to stipulate contracting between parties that initially have very asymmetric information. We suspect credible production of information can compensate for the negative effects asymmetric information would have otherwise. In an environment involving trust between the individuals engaging in the relevant activities, symmetric information distribution of simple performance measures seems unnecessary for the technical process (Braun, 2021) but suffices to speed up the breeding process itself by preempting distribution of new variety material, thereby bringing about shorter innovation cycles within the whole system.

2.4.2 Need for resilient breeding systems

As a scientific community, we need to be capable of comparing our cases on the governance of different agricultural SESs to form a reasonable knowledge base for constructing better heuristics for their governance. Darnhofer et al. (2010) advocate that the resilience concept should be used as a heuristic for governance of agricultural systems. Others have called for predictive models as policy-informing tools for governing SESs under the premise of "resilience from what to what" (Carpenter et al., 2001). There is already ample literature on how to frame agroecosystems for farming and how to measure their resilience (Cabell & Oelofse, 2012; Rasch, Heckelei, Storm, Oomen, & Naumann, 2017). So far, breeding systems have not gained the same kind of attention. The presented governance challenges, however, show that breeding systems, although in some subunits are very similar to a farming system, are substantially different.

2.4.3 Mid-range theories on social-ecological systems

Nonetheless, we want to caution our readers: providing heuristics for robust governance of seed systems in the future is not achieved by merely putting variables into the SESF. We need theory to interpret the relationship of those variables. For example, if the information provided to actors needs to be of a certain type to activate or channel a coordination mechanism, such as a seed market, into a more sustainable direction, then providing additional information through public trials would have advantageous effects according to our hypothesis. If we take the production of more pest-resistant varieties, then it is vital that public trials show counterfactual variants of varieties with no pesticide application to show the reliability of the varieties' resistance traits. However, if the current system were changed to abolish or reduce the trials, this would hamper the credibility of information and thereby negatively influence the introduction of new resistant cultivars.

For developing mid-range theories (Cumming et al., 2020; Meyfroidt et al., 2018) for breeding SESs, further cases of different types of grains, legumes, fruit trees, and other crops would have to be analyzed and subsequently synthesized into a sectoral SESF for breeding systems. We propose further synthesis to produce such a sectoral SESF for the plant breeding sector; for the sake of brevity, we would call it "seed SESF". A seed SESF may highlight variables that are unique but essential for plant breeding systems in general (Partelow, 2018) and develop diagnostic theories (Poteete et al., 2010) to govern plant breeding successfully. Scientists may develop better heuristics for governance—as demanded by Darnhofer et al. (2010)—for breeding systems, which are easy for policy-makers and other stakeholders to use and understand. Adapting current rules, norms, and strategies to future challenges in breeding, with a robust knowledge of mechanisms and attributes of the complex adaptive system at hand, will be crucial for the future resilience of all agricultural systems.

2.5 Conclusions

We illustrated how the SESF can be used to analyze the different action situations of the seed-producing system. Complemented by economic theories, we identified the governance challenges arising from social dilemmas in providing varietal and genetic diversity. Our qualitative findings in conjunction with our theoretical underpinnings allow us to hypothesize on the relationship between information provisioning and trust of actors in engaging in coordinating mechanisms, which distribute the seed and breeding material.

For the German case of winter wheat, all action situations coordinate transactions of seed material and property rights. The transaction relationships depend on information on the agronomic performance of varieties, which in turn are contingent upon ecological conditions of the resource systems producing them. Producing and distributing credible information on the agronomic performance of varieties to all actors directs the activities in the breeding system. There are varying kinds of asymmetric information between the different actors (breeding) or actor groups (multiplication and farming) in the action situations. According to the employed theories in these settings, these asymmetries would lead to adverse effects in outcomes. We found, however, that the same types of governance processes facilitated different kinds of trust between the stakeholders, thereby compensating for lack of information to sustain smooth functioning of the overall system.

In subcontracting multiplication and retailing of seed, the governance challenges are to advance symmetric distribution of information between actor groups. In subcontracting, trust between the breeding firm and multiplying actors is an expedient relationship. Individuals count on the other party behaving without guile because this would lead to termination of business relationships or ex post moral hazard on both sides. In farming, no trust is necessary to facilitate buying seed. Farmers are inclined to trust the public information system on agronomic performances of varieties and not the retailers' recommendation. In breeding, the governance challenge of providing genetic diversity to a common pool is to symmetrically distribute public information within the group of actors—breeders—to ease collective action. Individual breeders trust each other with their breeding material, such that the relationship among them is based on the judgment of the individual and on their reputation in the community, yet, this is a lengthy process. State information provisioning speeds up the innovation processes in breeding overall.

Credible information provided by the governance system may substitute for the intensity of trust and entanglement needed to cooperate. As we see from this case, provisioning of public trial information is vital for maintaining genetic and varietal diversity in crops. While this hypothesis needs further testing on its details in other contexts of breeding, we view this insight as relevant to future regulations and public investment. For example, when we talk about allotting funding for field trials in individual states, we see that our findings would advocate for investing in these state trials, such that their quality and credibility is maintained, and information stays publicly accessible in the future.

Author Contributions

Author contributions statement according to contributor roles Taxonomy - Maria Gerullis: conceptualization; methodology; qualitative coding; writing - original draft, review; edits; visualization. Thomas Heckelei: writing - review and editing; supervision; funding acquisition. Sebastian Rasch: writing - review and editing; supervision.

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Data availability

Because the field notes and other case material cannot in their entirety be anonymized or pseudonymized, they will not be available for sharing. We encourage interested readers to contact the corresponding author, M.K.G., to discuss the article content and qualitative coding procedures. All three authors are employed by a publicly funded German University and must comply with General Data Protection Regulation (EU) 2016/679 and German data protection standards. The concrete processes and regulations of the University of Bonn apply here and can be requested from the data protection office of the University of Bonn (https://www.datenschutz.uni-bonn.de/de).

2.6 Bibliography

Acquaah, G. (2007). *Principles of plant genetics and breeding*. Blackwell Publishing.

Akerlof, G. A. (1970). The market for "lemons": Quality uncertainty and the market mechanism. *The Quarterly Journal of Economics*, *84*(3), 488–500. Retrieved from `http://www.jstor.org/stable/1879431`

Becker, H. (2011). *Pflanzenzüchtung*. UTB.

Berkes, F., & Folke, C. (1998). *Linking social and ecological systems: management practices and social mechanisms for building resilience*. Cambridge University Press.

Bernard, H. R., & Bernard, H. R. (2013). *Social research methods: Qualitative and quantitative approaches*. Sage.

Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society*, *18*(4). doi: 10.5751/es-05551-180426

Brandl, B., & Glenna, L. L. (2017). Intellectual property and agricultural science and innovation in germany and the united states. *Science, technology, & human values*, *42*(4), 622–656.

Brandl, B., Paula, K., & Gill, B. (2014). Spielarten des wissenskapitalismus: Die kommodifizierung von saatgut in den usa und in deutschland. *Leviathan*, *42*(4), 539–572. Retrieved from http://www.jstor.org/stable/24206470

Braun, V. (2021). Holding on to and letting go of seed: quasi-commodities and the passage of property. *Journal of Cultural Economy*, *14*(3), 306–318.

Burt, R. S., Christman, K. P., & Kilburn Jr, H. C. (1980). Testing a structural theory of corporate cooptation: interorganizational directorate ties as a strategy for avoiding market constraints on profits. *American Sociological Review*, 821–841.

Cabell, J. F., & Oelofse, M. (2012). An indicator framework for assessing agroecosystem resilience. *Ecology and Society*, *17*(1).

Callon, M. (1998). Introduction: the embeddedness of economic markets in economics. *The sociological review*, *46*(1_suppl), 1–57. doi: 10.1111/j.1467-954X.1998.tb03468.x

Callon, M. (1999). Actor-network theory—the market test. *The sociological review*, *47*(1_suppl), 181–195.

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From metaphor to measurement: resilience of what to what? *Ecosystems*, *4*(8), 765–781.

Chable, V., Conseil, M., Serpolay, E., & Le Lagadec, F. (2008). Organic varieties for cauliflowers and cabbages in brittany: from genetic resources to participatory plant breeding. *Euphytica*, *164*(2), 521–529.

Cox, M. (2014). Understanding large social-ecological systems: introducing the sesmad project. *International Journal of the Commons*, *8*(2), 265–276. doi: 10.18352/ijc.406

Cox, M. (2015). A basic guide for empirical environmental social science. *Ecology and Society*, *20*(1).

Cumming, G., Epstein, G., Anderies, J., Apetrei, C., Baggio, J., Bodin, Ö., . . . others (2020). Advancing understanding of natural resource governance: a post-ostrom research agenda. *Current Opinion in Environmental Sustainability*, *44*, 26–34.

Dachbrodt-Saaydeh, S., Sellmann, J., Strassemeyer, J., Schwarz, J., Klocke, B., Krengel, S., & Kehlenbeck, H. (2018). *Netz vergleichsbetriebe pflanzenschutz, zwei-jahresbericht 2015 und 2016, analyse der ergebnisse der jahre 2007 bis 2016: Network of reference farms for plant protection, bi-annual report 2015 and 2016, analysis of results of 2007 to 2016*. Julius Kühn-Institut.

Darnhofer, I., Fairweather, J., & Moller, H. (2010). Assessing a farm's sustainability: insights from resilience thinking. *International journal of agricultural sustainability*, *8*(3), 186–198.

Denison, R. F. (2012). *Darwinian agriculture: how understanding evolution can improve agriculture*. Princeton University Press.

Erbe, G. (2002). *Handbuch der saatgutvermehrung*. Agrimedia.

Evenson, R. E., & Gollin, D. (2003). Assessing the impact of the green revolution, 1960 to 2000. *science*, *300*(5620), 758–762.

Gerullis, M. K. (2016). Entstehung privater eigentumsrechte an weiterentwicklungen von weizensaat in den usa und deutschland. In *Biopatente* (pp. 235–260).

Godt, C. (2016). Geistiges eigentumsrecht als instrument zum erhalt biologischer vielfalt? saatgut als sonderfall. In *Biopatente* (pp. 19–54). Nomos Verlagsgesellschaft mbH & Co. KG. doi: 10.5771/9783845275246-18

Halewood, M. (2013). What kind of goods are plant genetic resources for food and agriculture? towards the identification and development of a new global commons. *International Journal of the Commons*, *7*(2), 278–312. doi: 10.18352/ijc.412

Heisey, P. W., & Brennan, J. P. (1991). An analytical model of farmers' demand for replacement seed. *American Journal of Agricultural Economics*, *73*(4), 1044–1052.

Hinkel, J., Cox, M. E., Schlüter, M., Binder, C. R., & Falk, T. (2015). A diagnostic procedure for applying the social-ecological systems framework in diverse cases. *Ecology and Society*(1). Retrieved from `http://nbn-resolving.de/urn/resolver.pl?urn=nbn:de:bvb:19-epub-34583-2`

Huang, J., Pray, C., & Rozelle, S. (2002). Enhancing the crops to feed the poor.

Nature, *418*(6898), 678–684.

Karafyllis, N. C. (2006). Biofakte–grundlagen, probleme, perspektiven. *Erwägen Wissen Ethik, Jg*, *17*, 547–558.

Levačić, R. (1991). Markets and government: an overview. *Markets, Hierarchies and Networks. The Coordination of Social Life, London: SAGE*, 35–47.

Lorenz, E. H. (1991). Neither friends nor strangers: Informal networks of subcontracting in french industry. *Markets, hierarchies and networks: the coordination of social life*, 183–191.

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society*, *19*(2). doi: 10.5751/es-06387-190230

Meyfroidt, P., Chowdhury, R. R., de Bremond, A., Ellis, E. C., Erb, K.-H., Filatova, T., . . . others (2018). Middle-range theories of land system change. *Global environmental change*, *53*, 52–67.

Moose, S. P., & Mumm, R. H. (2008, may). Molecular plant breeding as the foundation for 21st century crop improvement. *Plant Physiology*, *147*(3), 969–977. doi: 10.1104/pp.108.118232

Nelson, P. (1970). Information and consumer behavior. *Journal of Political Economy*, *78*(2), 311-329. Retrieved from `https://doi.org/10.1086/259630` doi: 10.1086/259630

Nickl, L. H. A. W. T. E., U., & Schmidt, M. (n.d.). Versuchsergebnisse aus bayern 2017 faktorieller sortenversuch winterweizen. *Landessortenversuch Winterweizen*.

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge university press. doi: 10.2307/1243016

Ostrom, E. (2005). *Understanding institutional diversity*. Princeton University Press.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(5939), 419–422. doi: 10.1126/science.1172133

Ostrom, E. (2010a, nov). Analyzing collective action. *Agricultural Economics*, *41*, 155–166. doi: 10.1111/j.1574-0862.2010.00497.x

Ostrom, E. (2010b). Beyond markets and states: polycentric governance of complex economic systems. *American economic review*, *100*(3), 641–72. doi: 10.1257/aer.100.3.641

Partelow, S. (2018). A review of the social-ecological systems framework: applications, methods, modifications, and challenges. *Ecology and Society*, *23*(4).

Poteete, A. R., Janssen, M. A., & Ostrom, E. (2010). *Working together: collective action, the commons, and multiple methods in practice*. Princeton University Press.

Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science*, *362*(6417). doi: 10.1126/science.aav0294

Qaim, M. (2020). Role of new plant breeding technologies for food security and sustainable agricultural development. *Applied Economic Perspectives and Policy*, *42*(2), 129–150.

Rasch, S., Heckelei, T., Storm, H., Oomen, R., & Naumann, C. (2017). Multiscale resilience of a communal rangeland system in south africa. *Ecological Economics*, *131*, 129–138.

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., . . . others (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, *46*(1), 4–17.

Salmon, S., Mathews, O., & Leukel, R. (1953). A half century of wheat improvement in the united states. *Advances in Agronomy*, *5*, 1–151.

Sievers-Glotzbach, S., Tschersich, J., Gmeiner, N., Kliem, L., & Ficiciyan, A. (2020). Diverse seeds–shared practices: Conceptualizing seed commons. *International Journal of the Commons*, *14*(1).

Simon, H. A. (1996). *The sciences of the artificial*. MIT press. doi: 10.7551/mitpress/12107.001.0001

Singh, R. P., Hodson, D. P., Huerta-Espino, J., Jin, Y., Bhavani, S., Njau, P., . . . Govindan, V. (2011). The emergence of ug99 races of the stem rust fungus is a threat to world wheat production. *Annual review of phytopathology*, *49*, 465–481.

Strauss, A., & Corbin, J. (1994). Grounded theory methodology: An overview.

Thiel, W. (2014). *Praxishandbuch saatgutvermehrung* (W. Thiel, Ed.). Erling Verlag.

Timmermann, M. (2009). *Der züchterblick: Erfahrung, wissen und entscheidung in der getreidezüchtung*. Shaker.

Varian, H. R. (2006). *Intermediate microeconomics: A modern approach: Seventh international student edition* (7th ed.). WW Norton & Company.

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and society*, *9*(2).

Wolter, H., & Sievers-Glotzbach, S. (2019, apr). Bridging traditional and new commons: The case of fruit breeding. *International Journal of the Commons*, *13*(1), 303. doi: 10.18352/ijc.869

Chapter 3

Unpacking dynamics of diverse nested resource systems through a diagnostic approach†

Abstract: The social-ecological systems (SES) framework (Ostrom, 2009) typologically decomposes SES characteristics into nested, tiered constituent variables. Yet, aligning the framework's concepts of resource system (RS) and resource unit (RU) with realities of individual case studies pose challenges if the underlying SES is not a single RS, but a larger nested RS (NRS). Using a diagnostic approach, we describe NRSs – observable in larger SESs - dependent upon activities and networks of adjacent action situations (NAAS) containing them. An NRS includes the larger RS and multiple interlinked semi-autonomous subsidiary RSs, each of which support simultaneous, differently managed appropriation of individual RUs. We further identify NAASs operating within NRSs in two diverse empirical cases – networks of lake systems in Bengaluru, India and German wheat breeding systems- representing a lever towards understanding transformation of SESs into sustainable futures. This paper contributes towards unpacking and diagnosing complexities within mid to large scale RSs and their governance. It provides a generalizable, rigorous approach to SES case study analyses, thereby advancing methods for synthesis in sustainability science.

Keywords: *Social-ecological systems framework (SESF); nested resource systems; networked adjacent action situations; diagnosis; case study analysis*

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3.1 Introduction

Effective policy making, around complex social-environmental challenges, requires development of mid-range theories straddling generality, realism, and precision across diverse explanatory variables (Meyfroidt et al., 2018). Middle range theories are "contextual generalizations that describe chains of causal mechanisms explaining a well bounded range of phenomena, as well as conditions that enable, trigger, or prevent these causal chains" (Meyfroidt, 2016). A diagnostic approach has been long considered effective in developing such contextual generalizations (Cox, 2011). The Institutional Analysis and Development framework (IADF) (Ostrom, 1990) and its ecologically grounded successor (Cole, Epstein, & McGinnis, 2019), the Social Ecological Systems Framework (SESF) (McGinnis & Ostrom, 2014; **?**) are powerful tools in this context, at the core of which lie the concept of action situations (ASs). Articulated in later versions of the SESF (Cole et al., 2019; Ostrom & Cox, 2010) the AS is a complex of actor-resource interactions - influenced by four key components (or first tier components of the SESF): resource systems (RSs), resource units (RUs), governance systems (GSs) and actors (As). ASs in this complex represent the space where policy decisions are devised based upon the actor's relative positions within the complex as well as the various rules they are constrained or enabled by (McGinnis, 2011). A focal action situation represents patterns of interactions amongst actors and ecosystem resources within the system of interest. These interactions include social and ecological components, each of which can further be decomposed into smaller elements, as well as be situated within the context of broader aggregations (McGinnis, 2011). Despite their utility, challenges in applying the IADF and SESF persist, particularly from the perspective of mid-large-scale SESs (Cole et al., 2019; Epstein et al., 2020; Partelow, 2018; Thiel, Adamseged, & Baake, 2015; Villamayor-Tomas et al., 2020), due to a gap in developing consistent techniques to interpret and operationalize the large number of variables contained within them (Cox, 2014a; Cumming et al., 2020; del Mar Delgado-Serrano & Ramos, 2015; Leslie et al., 2015).

SES challenges further consist of the need to acknowledge and address multiple, interdependent ASs where the outcome of one AS can influence trajectories or outcomes of other ASs. This phenomenon has been explained through the networked adjacent action situation (NAAS) concept developed by McGinnis (2011). Expanding upon the concept of ASs, at the core of the NAAS lie interactions between the four first tier components of the SESF described earlier. However, studies have pointed out (Cox, 2008; Epstein, Vogt, Mincey, Cox, & Fischer, 2013; Hinkel, Cox, Schlüter, Binder, & Falk, 2015; Vogt, Epstein, Mincey, Fischer, & McCord, 2015) that two of these components: the RS and RU remain insufficiently decomposed, challenging the utility of applying the NAAS concept to mid-large-scale SESs.

In this paper, we engage with these two gaps - lack of consistency in applying the SESF and the linked concern of insufficient decomposition of RS and RU. We do this by a) introducing the concept of Nested Resource Systems (NRS) to negotiate complexity of RS-RU interactions, b) developing a diagnostic approach to applying the NRS within mid-large-scale SESs, and c) identifying spatially situated NAASs operating within NRSs. We focus explicitly and strategically on the RS and RU components of the SESF. We then provide a diagnostic tool that enables a standardised approach to describing and analysing SESs, both from the perspective of smaller, well-defined SESs as well as mid-large-scale NRSs, with the objective of enabling comparability across diverse contexts and cases. We demonstrate the applicability of our diagnostic process through comparison across two diverse and distinct systems – networks of lakes in south Indian Bengaluru (Unnikrishnan, Manjunatha, & Nagendra, 2016; Unnikrishnan, Nagendra, & Castán Broto, 2021) and German winter wheat breeding systems (Gerullis, Heckelei, & Rasch, 2021). In subsequent sections of this paper, we describe the NRS followed by a section detailing our diagnostic process. We then demonstrate its applicability to two distinct cases.

3.1.1 The context

Application of the SESF to cases requires a three-tiered process – a) selecting the focal level of analysis; b) selecting variables to be measured and implementation of indicators for those variables (data collection and analysis), and c) communicating results of the analysis across research communities through a common base of shared terms (McGinnis & Ostrom, 2014). In mid-large-scale SESs, one often finds that it is difficult to both draw systemic boundaries as well as specify which components of the SES become the RS and RU and in what context. We argue that this challenge arises because mid-large-scale SESs are inherently nested wherein multiple SESs may exist within each other and are bounded by a larger SES, while not necessarily being linked or networked with each other. This observation was first articulated by Cox (2010, 2014a) in his application of the SESF to the Taos acequia irrigation system.

As an example, if we consider the Yellowstone National Park as our system of interest (and therefore the RS), this does not automatically imply that other components of the park exist solely as RUs within that RS. Yellowstone National Park contains multiple potential SESs nested (but not necessarily networked with reference to how system boundaries are defined, or the question being investigated) within it – lakes, rivers, grasslands, calderas, that may or may not be hierarchical in their organization with reference to the park. Therefore, there is a need to explicitly decompose the RS and RU into possible further subcomponents (Cox, 2010, 2014a). Multiple RUs and RSs may be involved in equally numerous ASs; further diverse institutional arrangements may affect multiple ASs simultaneously (Villamayor-Tomas, Grundmann, Epstein, Evans, & Kimmich, 2015). NAASs operating in such SESs are thus usually scattered not just along societal and institutional dimensions, but also along spatial and ecological ones.

Several approaches to addressing these challenges have been proposed – addition of a seventh core subsystem category to the SESF – that of ecological rules, allowing analysts to incorporate ecologically derived knowledge into their cases (Epstein et al., 2013). Oberlack et al. (2018) advance the idea of telecoupled RS which refer to RS connections across multiple SESs spread across large distances. Cole et al. (2019) define processes by which social, ecological, and institutional factors interact across ASs producing social-ecological outcomes, through combining the SESF with the IADF (Cole et al., 2019). Schlüter et al.Schlüter, Haider, et al. (2019) have extended the NAAS approach to include explicit consideration of relations that exist between human and non-human entities; in other words, between social and the ecological components of the SES. In doing so, they propose the Social Ecological Action Situation (SEAS) framework, which recognizes three distinct forms of ASs, namely the Social AS, Ecological AS, and the Social-Ecological

AS (Schlüter, Haider, et al., 2019; Schlüter, Orach, et al., 2019). Möck, Vogeler, Bandelow, and Schröder (2022) propose that spatial scales, temporal change within systems, and resource linkages may be integrated through an approach of layering ASs as an analytical technique in applying the IADF (as opposed to the conventional technique of comparing temporally and spatially fixed aspects of the ASs).

We argue that while each of these approaches add lot of value, they do not, however, engage with the root challenge of reconciling decomposition of the RS and RUs. The concept of telecoupled RSs (Oberlack et al., 2018) while coming close to this decomposition does not engage with the idea that multiple systems can exist embedded within each other but might not always be connected in their processes and functions - consider for example, our earlier discussion of the Yellowstone National Park. This means that NAASs operating within these first-tier components remain spatially aggregated, implying that the links between RSs and their spatial dimensions still need to be explicitly recognized. Further, an analyst applying the SESF with the objective of comparing across diverse cases against a broader goal of generating middle range theories, would need a standardized approach towards unpacking and describing the complexity of their cases both from the perspective of decomposed RS and RUs as well as the complex array of NAASs that emerge from these contexts.

To address these gaps, we first articulate in greater detail the idea of NRSs. We then build upon and expand the diagnostic procedure developed by Hinkel et al. (2015) to include considerations of NRSs. This distinction allows us to account for multiple, simultaneously occurring NAASs that collectively give rise to SES outcomes.

3.2 Articulating the idea of Nested Resource Systems (NRS)

The idea of NRS becomes important when one considers dynamics of mid-large-scale SESs in particular. In these contexts, one cannot assume that there are distinctive or easily defined RSs and RUs. Rather, there can be multiple RSs, and further, each of these RSs can act as RUs depending upon the context within which they are being investigated. For example, let us consider a system represented in its entirety by multiple spatially connected lakes. Traditionally, we would imagine the entire lake system to be the RS and individual lakes within that system to be RUs. However, each individual lake is also capable of providing RUs such as fish, water, or pasturage on its own, thus allowing it to simultaneously function as an RS. Resource flows in this system can occur through multiple pathways – within an individual lake (for example pasturage or harvesting fish from a lake), between two individual lakes in a network (for example water overflowing from one lake into the next via channels connecting the two), or across the entire network of lakes (for example, a system of water flows or the mobility of fish across the entire network). RUs too may be drawn at any of these levels – one can withdraw water from a single lake or across the system, while fishing or grazing livestock can occur only at the level of individual lakes. If we were in the traditional manner to imagine the entire network of lakes to be our RS and individual lakes to be RUs, this distinction is not captured effectively. To address this discrepancy, we propose the idea of the Nested Resource Systems (NRS) – conceptualized through Figure 3.1. Highly relevant to mid-large-scale systems whose boundaries are not so easily defined, we propose that NRSs may be considered as a complex of several individual semi-autonomous subsidiary RSs that may or may not be connected through physical connections. Each subsidiary RS can both provide RUs from the perspective of the NRS but is equally capable of acting as a standalone RS (thus semi-autonomous). There are system connections between different subsidiary RSs. These may come about by biophysical structure such as elevation gradients, or (such as in other systems) social structures like supply chains when seeds are bred, multiplied and sold as farming input in plant breeding systems. Activities, embedded in ASs can occur separately or simultaneously at four different spatial locations: a) within the subsidiary RSs, b) across individual RSs, c) between the subsidiary RSs and the overall NRS, and d) within the overall NRS. These ASs thus can occur across different levels of the NRS, and the outcome of any AS is likely to influence other ASs at any level of the NRS, causing spatially significant adjacencies. Actors operate across the NRS, leading to NAASs, where outcomes of individual ASs occurring at any one level can influence and be influenced by other ASs occurring at other levels. It is important to note that the NRS is situated within its biophysical environment and has multiple (not necessarily linked) components which when taken together define the SES.

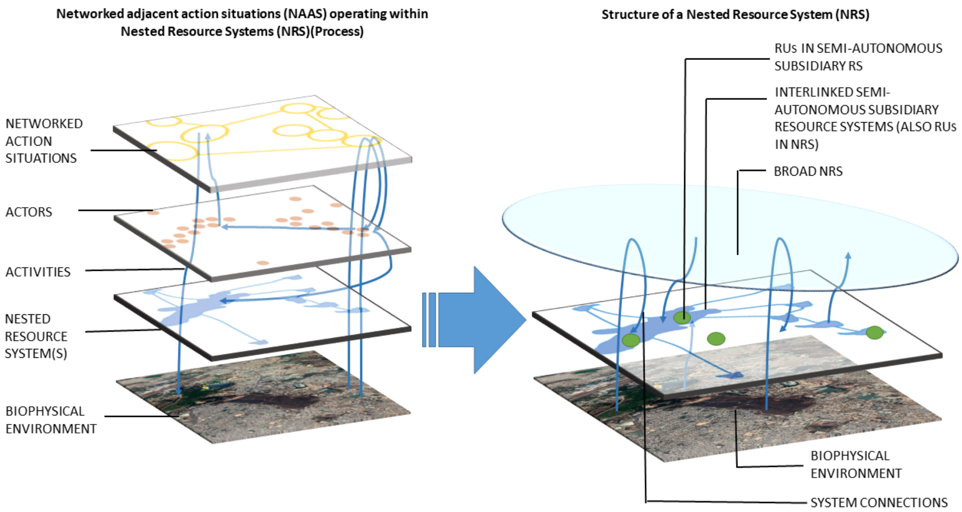

FIGURE 3.1: Structure of an NRS with NAASs operating within it

3.3 Methods

In subsequent sections of this paper, we elaborate on how NRSs may be operationalized when studying the dynamics of diverse SESs. To do this, we first developed a diagnostic protocol to logically unpack different components of an NRS and further articulate NAASs within them that lead to SES outcomes. This diagnostic process was developed through a series of iterative discussions and deliberations amongst the research team drawing on our varied expertise and contextual knowledge of diagnostic protocols and mid-large-scale SESs. Like its use in healthcare, a diagnostic approach can tease out complexity within an SES as well as address the panacea problem (Frey & Cox, 2015; Young et al., 2018). It allows the researcher to examine individual characteristics of a problem to identify governance arrangements that may best be suited towards addressing those characteristics (Young, 2010; Young & Gasser, 2002). Diagnosis identifies underlying causes of a problem and works on the principle that addressing the problem would require intervention at causal levels (Cox, 2011). It typically involves asking and answering a series of questions about the system such that subsequent questions build upon and add to information presented by previous ones (Berkes, 2007; Frey & Cox, 2015; Ostrom, 2007).

Like the SESF, diagnosis allows typological decomposition of a complex system into its individual components allowing the researcher to unpack non-linear webs of relationships built by individual variables in SESs. It allows the construction of multi-level theories guided by similarities and differences between systems at multiple levels of specificity (Frey & Cox, 2015). Such theories can then be used to provide some degree of generalizability and predictability to generate useful prescriptions on interacting with complex SESs (Cox, 2011) and in the longer term, enable the creation of middle range theories.

Hinkel et al. (2015) establish a diagnostic procedure by providing a sequence of questions to facilitate stepwise interpretation and application of the SESF across diverse cases. The approach as outlined by them serves as a valuable starting point for this paper due to the following reasons. First, the approach explicitly focuses on RS and RU, due to their role in facilitating focal ASs and therefore the starting point towards applying the SESF to a given case (McGinnis & Ostrom, 2014). Hinkel et al. (2015) advance the idea that the appropriation AS is inclusive of actors performing activities that depend upon a common stock and further subtract from it. Thus, the diagnostic tool they propose explicitly focuses on activities affecting the RU, allowing for the diagnosis of complex conditions within the SES such as multiple, overlapping, and heterogeneous actors and governance regimes. This is important because it has been shown that defining a stock as a collective good is not very effective largely because a stock by itself is not subtractable – it only becomes subtractable in relation to the activity associated with it (Hinkel et al., 2015). Subtractability as a characteristic is therefore only relative to the activity being performed in relation to the SES, while the property of excludability is related to actors performing the activity. Our diagnostic process builds on this premise and begins with identifying broad social ecological challenges that the analyst wishes to address, the research question as relating to the identified challenge/s and further the specific SES or NRS that they engage with. We then provide a schematic that guides the analyst towards identifying normative assumptions behind the outcomes they envision, and a series of questions designed to unpack the complexity of RS and RU variables within the identified SES or NRS. The schematic follows on to guide the analyst towards identifying NAAS, the spatial dimension within which they occur, and outcomes that are generated as a result. These outcomes are then linked to the research question posed by the researcher, external influencing variables, normative considerations, and further on back to the broad SES challenge/s that they have engaged with. We acknowledge that ASs can take a wide range of incentive structures within natural resource governance and can include forms of cooperation, conflict, or indifference (Bruns & Kimmich, 2021) characterise these through a game theoretical approach as win-win, discord, and threat, with exchange, coordination, and independence as their primal archetypes) and it remains up to the researcher to determine the nature of incentive structure associated with the SES challenge they are investigating.

At various stages of the diagnostic process, we provide checkpoints that allow the analyst to ascertain whether their case study may be interpreted using the frames we provide. We do this so that focus remains on outcomes relating to SEASs that occur within SESs/NRSs

We then tested the efficacy of our diagnostic process on unpacking SES/NRS and their associated NAAS dynamics across two distinctive and well-studied empirical cases. Our two cases represent distinct kinds of NRSs: on one hand are networks of lakes, representative of traditionally studied common pool resources (other examples include fisheries and irrigation systems). On the other hand, we engage with German winter wheat breeding systems representing non-traditional, technologically mediated SESs (other examples include bioenergy and climate systems). Breeding systems differ from farming systems, as the underlying RU is the flow of genetic differences contained within physical material, like seed or plant parts (Gerullis et al., 2021), thus simultaneously making them divisible packages on a lower level (individual varieties or genes) and continuous streams of material on higher levels (maintained resistance to pathogens over time).

Plant breeding systems therefore show both characteristics of what McGinnis and Ostrom (2014) define as social-ecological technical systems (SETS). Firstly, people dependent upon these systems view services derived from it as continuous streams (as unlike traditional SESs where services can be obtained in discrete packets – for example yields of fish from a lake). In wheat breeding, the benefits are measured through continued selection and propagation of the most suitable varieties for a geographic region. The second distinguishing characteristic of SETS is that there is often clear separation between actors possessing technical expertise to understand construction and maintenance of the system, and those whose sole concern rests with continued access to the resource (McGinnis & Ostrom, 2014). In German winter wheat systems, clear separation exists between laboratory and field research stations (providing technical expertise) and commercial wheat farmers (who only depend upon continued access to favourable varieties).

We draw upon our long-term empirical research, see for example (Castán Broto, Sudhira, & Unnikrishnan, 2021; Gerullis et al., 2021; Unnikrishnan & Nagendra, 2020; Unnikrishnan, Nagendra, & Castan Broto, 2020) conducted in these contexts using mixed methods such as historical archival research, textual analysis, historical GIS, oral history interviews, semi-structured qualitative interviews, participant observation, and secondary research methods in elucidating arguments used to apply the diagnostic process to each case.

3.4 Results

3.4.1 A diagnostic approach to unpacking NRS/NAAS dynamics

Figures 3.2, 3.3, and 3.4 outline the diagnostic procedure we follow towards analysing and interpreting our cases. We exclude purely social outcomes from this diagnostic process because our focus is on NRSs and changes within the RS usually occur because of social-ecological or purely ecological processes. Of course, if one were to consider governance systems and actors who form other first tier components of the SESF, social outcomes become equally important drivers of social-ecological outcomes. However, for purposes of clarity in this diagnostic, which unpacks nestedness of RSs, we are excluding other first tier components of the SESF. Thus, when listing out ASs, even though we use the typology provided by Schlüter, Haider, et al. (2019), we focus on SEASs as occurring within our NRS and its subsidiary RS. Our diagnostic tool (see Figures 3.2, 3.3, and 3.4) is built keeping in mind the fact that multiple activities can contribute to one AS. For a step-by-step direction on how the diagnostic process may be applied to individual cases, please see Appendix C.

3.4.2 Case applications of diagnostic approach

In the following sections of this paper, we apply our diagnostic process towards unpacking complexity in structure and processes occurring within the two distinct NRSs that we have identified earlier. It is important to highlight two considerations here. Firstly, delineation of system boundaries as well as the broad SES challenge/s within it relate to the specific normative research question being addressed. This distinction recognizes that a system can be conceptualized in multiple ways and studied through multiple framings, however it is up to the researcher to choose which framing is most useful for the purposes of answering the research question they originally set out to explore. Secondly, the rest of this paper focuses on demonstrating the applicability of the diagnostic process we have developed, exemplified by the two case studies we have chosen, that builds on our long-term research in those areas.

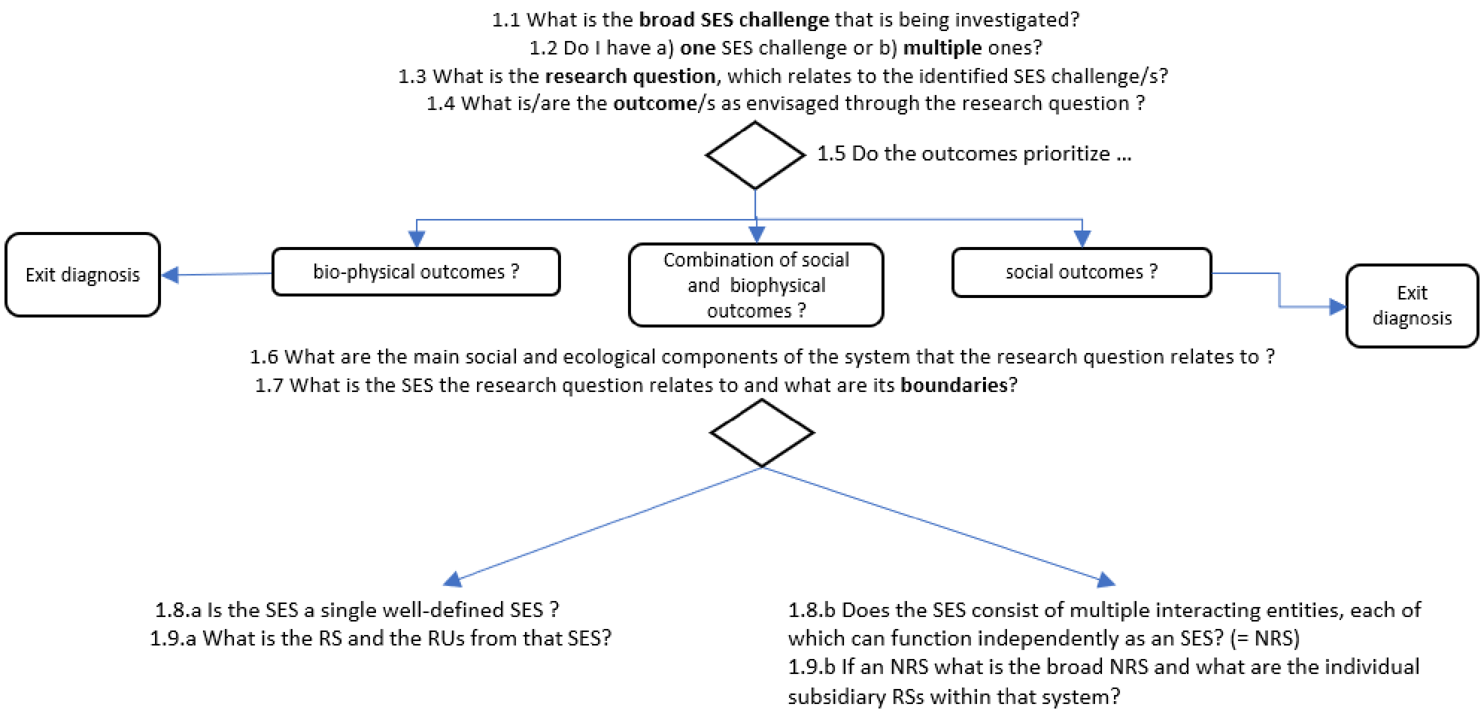

FIGURE 3.2: Diagnostic procedure: section 1

3.4.2.1 *Networks of blue urban commons in Bangalore, India*

Understanding drivers of coproduction around urban commons (such as lakes, parks, gardens etc) such that they produce ecologically grounded and socially just outcomes has been a long-acknowledged SES challenge. In this section of the paper, we use the case of networks of blue commons in south Indian Bengaluru to unpack this challenge. This case is a good example of a traditionally studied SES, which easily lends itself to the idea of an NRS. Landlocked, situated in a rain shadow, and devoid of a major water source such as a river, the city has been unusually prosperous since ancient times and has served as a strategic location for colonial establishments (Unnikrishnan & Nagendra, 2020).

This success of the city is partly attributed to a series of engineered water bodies dating back to about the 4th century CE which provided water to the city. These rain-fed reservoirs (tanks, lakes, or keres) were built by tapping into the city's elevation gradient and utilizing its naturally undulating terrain. Individual reservoirs were connected by channels, creating an engineered system of flows. Originally constructed to support agrarian communities, these reservoirs over time became integral to the cityscape, providing critical urban ecosystem functions and benefits (Unnikrishnan & Nagendra, 2020). This system of engineered water bodies transformed into novel ecosystems (Unnikrishnan et al., 2020), characterized by complex interactions between society and nature, in turn functioning as complex social ecological landscapes.

Urban lake networks provide several shared long-term social-ecological benefits - these include microclimate regulation, supporting resource dependent livelihoods, acting as biodiversity hotspots, and recharging shallow groundwater reserves. At the same time, given increasing pressures of urbanization, and the landlocked character of Bengaluru, these reservoir systems have increasingly been viewed as a fluid conduit for the city's sewage - a way to flush out wastewater from the city and into neighbouring regions. Lakes and their channels have also been seen as easily appropriable spaces to convert into other public infrastructure (malls, bus stands, and stadiums). Surviving reservoirs have either lost connectivity in parts of the chain or are treated as standalone water bodies where systemic connections are overlooked. We therefore have multiple social dilemmas arising in this context. An overarching one relates to the maintenance of connectivity between individual reservoirs of the SES versus conversion of these spaces into other forms of built land use. A similar social dilemma is presented at the level of individual lakes within the network: the maintenance of individual water bodies versus their conversion into built structures or their reimagination as primarily economically driven entities (Unnikrishnan et al., 2016). Individual lakes provide similar and relatively long-term ecosystem services as the larger network - microclimatic regulation, biodiversity, support for resource-based livelihoods, and serve as a local water reservoir. At the same time, in the short term, they are attractive prospects either for redevelopment as real estate or to enhance the value of existing real estate by providing aesthetic and recreational services (Unnikrishnan et al., 2016). This latter viewpoint brings with it several social-ecological challenges: converting lakes into built up spaces increases the risk of urban flash flooding, creates social vulnerabilities among resource dependent populations, and reduces diversity of ecosystem services they provide. However, the larger trend in the region seems to be driven towards an aesthetic and recreation dominated urban vision (Unnikrishnan et al., 2016) -a vision that seems to have sustained itself across at least two centuries.

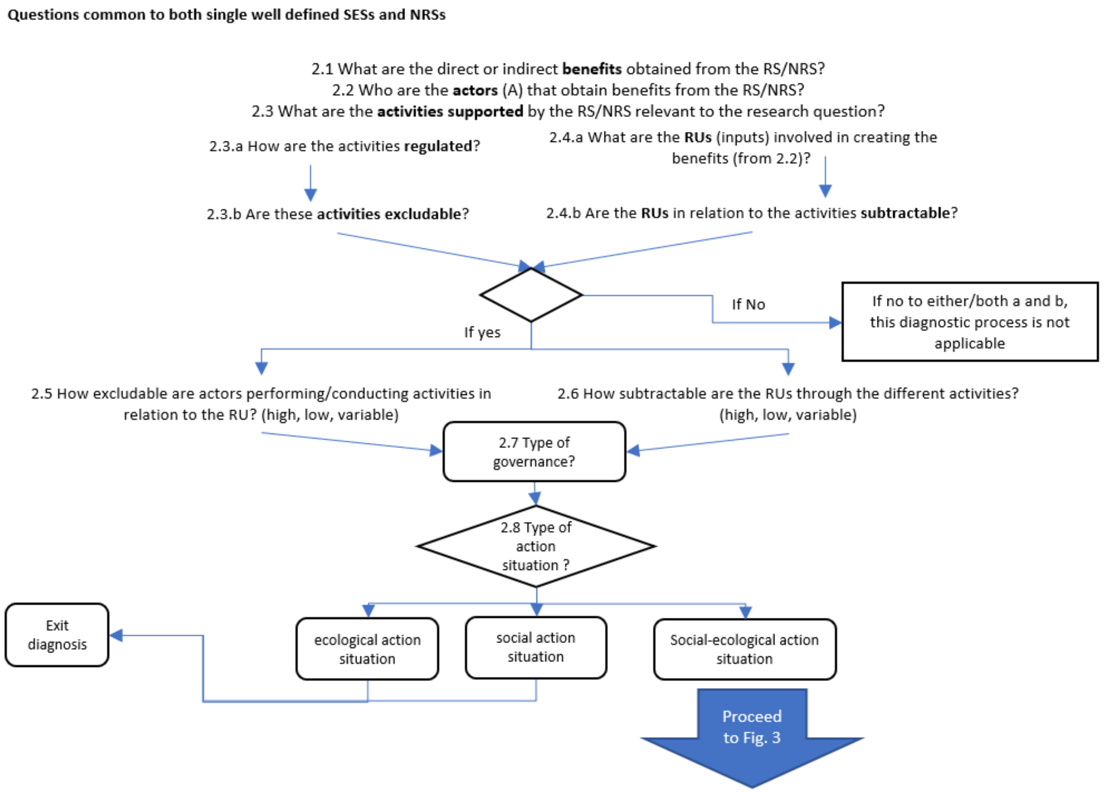

FIGURE 3.3: Diagnostic procedure: section 2

Considering this contextual background, the objective of applying our diagnostic process is to understand what motivates co-production in this network of lakes in Bengaluru? In other words, what drives inherently heterogeneous communities to invest in the resource collectively? Normatively, we seek to understand what factors may influence heterogeneous communities to engage in lake restoration such that one may achieve favourable ecological outcomes (such as improved water quality or biodiversity) alongside socially just ones (such as representation of diverse interests in the resource). As the network of lakes consists of several individual lakes connected through channels, each of which in turn provide various social-ecological benefits, this system is representative of an NRS. The broad NRS is represented by the network of lakes, while individual water bodies within the network form semi-autonomous subsidiary RSs. Each semi-autonomous subsidiary RS can act as an RU within the NRS but is equally capable of providing RUs (such as fish, water etc) by themselves. Actors within this NRS are represented by internally and externally heterogeneous groups of people drawing tangible and intangible benefits - ecosystem services (Reid et al., 2005) - from the resource. Provisioning ecosystem services (material and quantifiable benefits obtained from the system) take the form of entities such as water for commercial and subsistence uses, fish, urban forage, etc. The diversity of intangible benefits such as support for spiritual beliefs, community building, recreation, and aesthetics, are cultural ecosystem services provided here. Of benefit to the general population and subsequent generations living around the lakes are various regulating services such as pollination, and microclimatic regulation, along with supporting ecosystem services such as nutrient recycling and biodiversity maintenance.

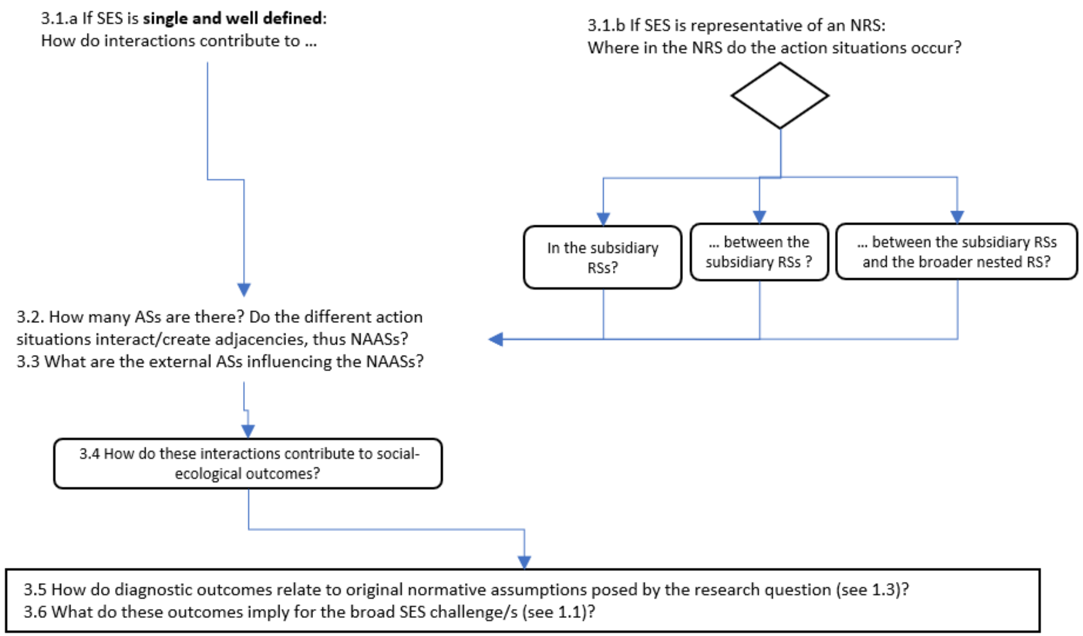

FIGURE 3.4: Diagnostic procedure: section 3

Farmers, fishers, recreationalists, urban foragers, nodal agencies and various other actor groups undertake different activities in and around the NRS. Several actor groups draw benefits from the NRS, through varied activities that are regulated in multiple ways (see Appendix D for detailed listing of actor groups and institutional arrangements). The number of actors undertaking these activities as well as ways in which these activities are regulated have implications for the subtractability of stocks of RUs (stock of fish or number of entire lakes), in relation to the activity (fishing or draining entire lakes for building), as well as how easily excludable other actors are from conducting the same activity. These may influence the availability of various ecosystem services.

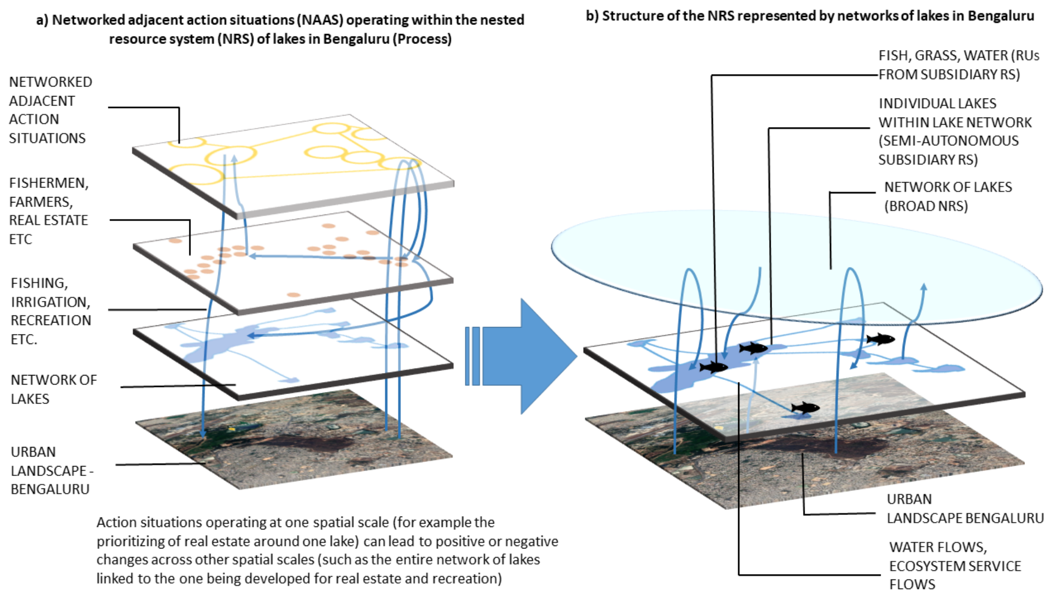

FIGURE 3.5: Exemplary illustration of the network of urban lakes as an NRS with NAASs operating within

Figure 3.5 exemplarily illustrates various activities that give rise to ASs, which occur at multiple levels of the network. Some ASs occur only at the level of the individual lake, whereas others, while taking place at individual lakes, can be influenced by activities occurring elsewhere across the network. For example, the AS characterised by occupying spaces around lake banks and associated fishing activity takes place at the level of individual lakes within the NRS. At the same time, fishing is dependent upon proper functioning of systemic connections across the network. The availability of fish within individual lakes, as well as the quality of water supporting those fish, are both characteristics of the SES that are dependent upon RU flows across the network. Thus, this AS, while occurring at the level of an individual lake remains deeply embedded within system dynamics of the larger network that it belongs to. This is different from the AS involving appropriation of pasturage from banks of lakes to support livestock grazers, which necessarily occurs only at the level of individual lakes - its functioning remains relatively independent of activities occurring within the broader network.

These ASs do not exist independently of each other however, and there are several adjacencies which are created. For example, ASs involving privileged gated communities who appropriate land around individual lakes for real estate, almost always are linked to ASs involving local nodal agencies who are responsible for maintenance and governance of the entire network of lakes. Similarly, ASs involving the appropriation of land and water in and around an individual lake (which are themselves influenced by the larger network that they are part of) are linked to those involving appropriation of pasturage from around individual lakes, largely due to the association between agricultural practices and livestock rearing in the region. What this means is that adjacencies are not created simply between two ASs, but that they can occur along different spatial levels within the NRS. Each of these interactions further link themselves to social-ecological outcomes - in this case with its explicit focus on motivations for co-production, we define these outcomes by the ecosystem services that are enabled or disabled within the system.

In applying our diagnostic process to this case (Appendix D), we find that only four user groups (nodal agencies, gated communities, private institutions, and urban recreationalists) possess all the following attributes: a) access, appropriation, management and/or exclusion rights; b) despite being affected by the larger lake network, tend to operate at the level of individual lakes; c) Access to stakeholder collaboration and information flow; and d) the ability to directly influence form and function of the ecosystem, while accessing only cultural ecosystem services. This means that power to influence the SES is monopolized by these groups of actors, providing them with greater incentive to engage in co-production efforts towards the resource. Ecologically, this means that efforts are not systemic but targeted only to individual lakes, meaning that the entire NRS is not sustainably rejuvenated.

There are other actor groups who only have access and appropriation rights, are more diverse, depend mostly on provisioning ecosystem services, and who in some cases draw meaning from the systemic nature of the resource. However, these groups cannot influence the condition of the resource or be involved in decision making processes around it. Hence there is very low incentive for these actors to come together and engage in co-production efforts. This implies that in this case, the success of coproduction around blue commons seems intimately linked to how inclusive the process is to diverse stakeholders of the NRS.

3.4.2.2 *German winter wheat breeding systems*

We utilize our diagnostic process to answer what governance challenges arise in appropriating and provisioning ASs for crop genetic diversity in German winter wheat breeding systems? Relevant for answering this research question therefore is a combination of social and biophysical outcomes. We need to know whether a) breeders are creating varieties maintaining their long-term genetic pool; b) subcontracting and selling varieties such that farmer's needs and preferences are being met; c) farmers are choosing varieties according to their own ecological niches and preferences, such that negative ecological and societal impacts are minimized.

Plant breeding systems ("breeding systems" subsequently) are good examples of SETSs involved in creating, maintaining and improving seeds of different crop varieties for farmers to produce food and fibre for human use. Aside from usual resources used in farming like land, water, fertilizer, and chemicals, breeding systems depend upon genetic variation contained in different plant materials used for breeding. These are very diverse and range across physical material from single allelic snippets, seed, other plant parts, single plants to variant plots and fields. For actors involved in breeding activities (breeders, plant scientists) these physical flows coincide with information for observing genetic differences in these materials - called traits. As one can tell from this inherent nestedness these are another NRS. Plant breeding systems as nested, multilevel systems supply and provide affordance for different flows of genetic material in any form and its corresponding information.

We refer to the overall stock of these traits as "genetic diversity" in the following. For actors in seed multiplication, retailing and farming, relevant information results from differences in bundles of traits, called varieties. We refer to the overall stock of these trait bundles as "varietal diversity" in the following.

A multitude of actors are scientists working in crop science or pre-breeding, breeders/breeding firms, seed multipliers, different governmental and non-governmental organizations, and farmers, who plant the varieties and provide their harvest to the system for processing food and fibre. Breeding systems are nested in their underlying genetic set-up along pedo-climatic zones, for which pre-breeding and breeding actors develop varieties. There are economic benefits, mainly income, created for all actors along the seed supply chain: Income is generated from variety licensing and subcontracting, selling seed and sales of other inputs accompanying seed (crop protecting agents, fertilizer, machinery). Farmers sell their yield and as such security from stable yields over the years is also a direct economic benefit. Other benefits generated by the system are the future value of a genetically diverse system, and may entail ecosystem services touched by agriculture, like nutrient cycling, groundwater quality, pollination and biodiversity maintenance. The benefits are created from multiple levels within the NRS. While scientists are changing the RUs on a molecular level, applied breeders are interested in changing whole plants, farmers sow seed in on the level of their farm plots, retailers push for sales across regions, and governance organizations care about the multiplication areas in regions and states.

A social dilemma in the appropriation of genetic diversity occurs when breeders reduce the genetic variation in their used material to the point where their gene pool does not contain certain needed traits to maintain cultivar yields anymore, e.g., resistance against a fungus. This may occur when breeders focus their breeding practice on mainly "low hanging fruit" such as qualitative resistance traits. As qualitative traits are determined by only a few allele sequences in the DNA, there is less delay in progress when establishing a new trait into a new variety candidate. Modern molecular marker technologies will allow breeders to find these at a low cost, once they are identified. Thereby they can be easily combined into new varieties. Focusing on qualitative traits, nonetheless, comes at the expense of more complicated traits, as there is a trade-off between different breeding goals. If breeders decide to put more resources towards breeding resistance traits they cannot pursue other goals with equal power, as breeders are restricted in their nursery space, person-power and nursery locations within different environments. A reduction in complex resistance traits would reduce genetic diversity negatively across all breeders. Maintaining genetic diversity of all kinds of traits, however, is vital for sustaining breeding activities and agricultural systems in the long-term.

A social dilemma in the appropriation of varietal diversity emerges on a higher level. When too many farmers plant only one variety over large areas, new strains of pests can evolve thereof. One example of this is the occurrence of European yellow rust epidemics in winter wheat of recent decades (Bayles, Flath, Hovmøller, & de Vallavieille-Pope, 2000), where strains of plant pathogens evolved from overuse of susceptible varieties. To counteract pests, farmers spray pesticides to prevent the risk of yield losses. Yet, farmers end up spraying more pesticides than necessary (Dachbrodt-Saaydeh et al., 2018), leading to unwanted externalities in their natural environment. There is a social dilemma that emerges overarching the two social dilemmas shown above. If farmers revert to over-spraying for risk-reduction every year, they need not rely on choosing varieties with well-working resistance but will choose susceptible high yielding varieties (Dachbrodt-Saaydeh et al., 2018).

This decreases the market share in varieties with well-working quantitative resistance traits and leads to an added disincentive for breeders to invest in costly generation of these traits. The objective of applying the diagnostic process is to understand how to maintain varietal and genetic diversity considering the described perverse effects. For German winter wheat cropping, part of these effects are intercepted by governmental regulation and public information diffusion. This is enabled through extension services and public-private breeding efforts. For example, through pre-breeding programs, or encouraging social norms amongst breeders, in ways that reward breeders with the prestige of creating varieties containing complex traits. We are interested in how governing material and information flows on the different levels of the NRS bring about different outcome patterns in genetic and varietal diversity.

Breeders, seed multipliers, retailers and farmers undertake various activities (see Appendix D), which change the shape and size of underlying resource stock of genetic diversity, where each activity is bound by different institutional arrangements, yielding a multitude of NAASs. For example, breeders' activities will influence the stock of RUs of in-nursery genetic diversity and devise the available varieties for other actors. Institutional response in collective norms on material exchange, state regulations on variety approval and open access to approved varieties influence how the social dilemmas are met. Excludability of actors from various activities is easy, difficult or in some cases varies by individual, as some enabling preconditions determine whether one can undertake the activity. Likewise, subtractability of the resource stock through activities may vary by individual actor or depend on heterogeneous spatial circumstances - for example, subcontracting of varieties for different regions depends on the ecological niches covered.

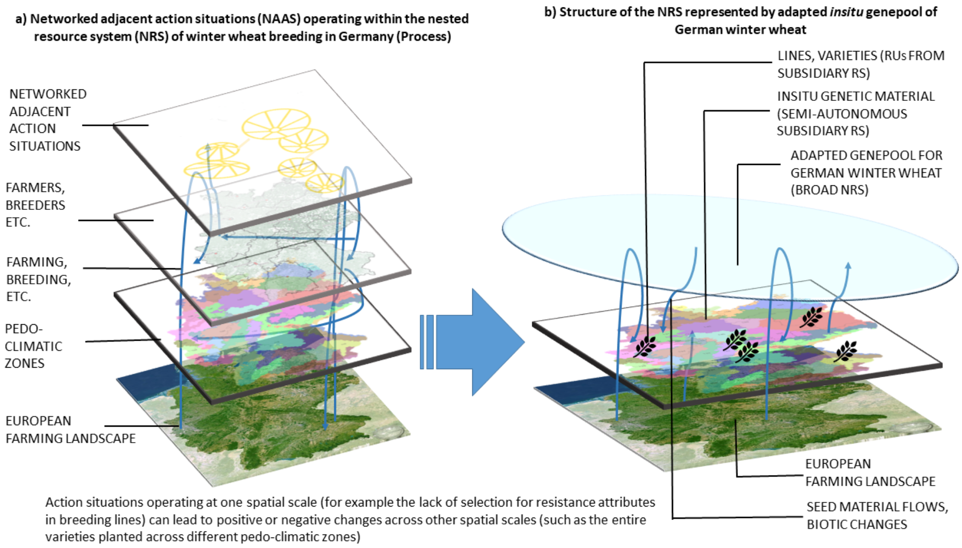

FIGURE 3.6: Exemplary illustration of the German winter wheat breeding system as an NRS with NAASs operating within

The earned and expected income gain incentivizes different actors to undertake the activities. Information flows on different agronomic performances of individual biological material (genetic snippets, lines, varieties) direct concrete genetic material to their purpose and spatial positions within the system, leading to different ecological performance measures. Figure 3.6 exemplarily shows that ASs are networked in two ways: First through the NRS, where changes on one level of the RS, e.g. on molecular level of genetic traits, will bring about consequences on other levels, a resistance trait being present in a variety, which are relevant to other ASs, such as pest outbreaks in fields of farmers. Second, through transactions taking place between different actors in the respective ASs, where breeders will exchange breeding material containing resistance traits and produce varieties which are resistant to certain pests. Multipliers subcontract these varieties if they perform well and sell them through retailers to farmers. Where farmers will only spray less if they have varieties available to them which are resistant to different diseases. These relationships are dynamic. The ecological world constantly evolves, where pests evolve resistance to formerly tolerant varieties, and plant research is racing to keep up with natural selection. Likewise, social mechanisms of market transactions, subcontracting and collective action change as wider economic and political settings change over time and exert comparable social selection pressures.

Three individual social dilemmas in networked ASs need to be overcome for not encountering negative environmental impacts on the overall system level: Breeders need to invest collectively in quantitative resistance traits to have these in their varieties. Multipliers need to be willing to subcontract these resistant varieties and forego income from accompanying plant protection agents, so that farmers may sow varieties with stable resistances against pests and spray less crop protection agents. In all three of these ASs, the incentives each actor group is faced with, points in different directions.

3.5 Discussion and Conclusions

In this paper, we engaged with two broad challenges of the SESF. First, we build upon the gap first articulated by Cox (2014a) on insufficient decomposition of RS and RU. We attempt to formalize this within the structure of an SES by introducing the NRS - the idea that an RS can function simultaneously as both RS and RU depending upon framing of the problem at hand and the boundaries of the system that emerge as a result of that particular problem frame. We show how NRSs contribute to NAASs as nestedness of the NRS leads to a biophysical connection between different ASs (Schlüter, Haider, et al., 2019). Depending upon one's inquiry our diagnosis makes physical connections between different ASs visible, providing opportunity to showing these connections spatially, and thus making NAASs spatially explicit (Möck et al., 2022).

Secondly, we propose a diagnostic tool to aid analysts in applying the SESF and articulating associated NAASs to their cases in a standardised manner, allowing for greater comparability across diverse cases (Kimmich, Baldwin, Kellner, Oberlack, & Villamayor-Tomas, 2022). We thus take a step forward in the direction of addressing the acknowledged gap of establishing a protocol for NAAS research (Kimmich et al., 2022; Müller et al., 2013). We have tested the diagnostic process within the context of two distinct systems - an SES characterized by urban lake networks in Bengaluru and an SETS represented by German winter wheat breeding systems. We believe that this diagnostic process may be used successfully in unravelling complexities of other kinds of SESs such as knowledge commons or what are called "new commons". In this section of the paper, we reflect upon the utility of these approaches in expanding our understanding of the SESF and its application to understanding environmental governance challenges.

We believe that decoupling RS and RU bring with it distinct methodological advantages when applying the SESF to cases. Firstly, it allows us to engage with complex dynamics of mid- large-scale systems where there is significant diversity of simultaneously occurring activities operating at multiple spatial levels. Secondly, it allows us to engage with fluidity of boundaries existing between RS and RU components, while understanding that identities of the RS and RU are largely dependent upon specific activities as opposed to being defined as fixed systemic characteristics (Hinkel et al., 2015). Thirdly, given that RS and RU form the starting point for defining focal ASs, this decoupling allows us to incorporate consideration of simultaneity of interconnected ASs occurring across multiple spatial levels and leading to cumulative outcomes on the SES, which makes it representative of NAASs. It therefore provides a first step towards unpacking substitution effects and redundancies that emerge from the complex interplay between actors, their activities, and regulation of those activities.

The application of our diagnostic tool, following the deconstruction of RS and RU allows the analyst to unpack the SES in a standardised manner. This allows for comparisons across diverse cases through meta-analysis – the systematic and consistent coding of cases using the SESF, following which the analyst can observe for patterns of similarities and differences across cases (Ostrom & Cox, 2010). These comparisons also provide useful data points for large N-case studies of NAASs and therefore serve as a base to aid the generation of middle range theories.

The two cases we analyse using this diagnostic tool help us outline some of these similarities and differences. Both cases are diverse in that they are representative of two distinct systems – an SES and SETS, that are difficult to compare across the geographies in which they occur. At the same time, in decomposing RS and RU components of these systems and applying the diagnostic process, several commonalities come to fore. Firstly, there exist physical connections between RUs in the different ASs of each system - for example the channels which connect individual lakes within the NRS (enabling flows of water) are comparable to the flows of genetic material enabled in the form of seeds. Second, both systems have multiple social dilemmas occurring at different scales - some of these form overarching dilemmas, while others restrict themselves to the subsidiary RSs in these systems. A complication that emerges from the presence of these multiple dilemmas is that overarching social dilemmas cannot be addressed without engaging with those that occur at lower scales of influence. This is further complicated by inherent heterogeneities emerging between actors, activities, and ASs at multiple levels of the NRS. Third, diagnosis brings out commonalities in the kinds of substitution effects emerging with respect to activities occurring within the NRS through a consideration of simultaneously occurring ASs. For example, the substitution of provisioning food activities in the lake NRS with increased aesthetic and recreational ones would mean that certain user groups are almost immediately excluded from decision making involving the NRS. Fourth, both systems show redundancies in that multiple actor groups can perform the same activity, or that multiple identities are assumed by the same actor group, therefore with potential to influence the rules-in-use governing these systems. The presence of redundancies mean that you can either be an all-in-one entity internalising harmful effects, or you have multiple redundant groups (for example, the farmer/livestock owner) with different abilities to negotiate harmful effects. In the latter case, negative effects are likely to be experienced by those excluded from decision making either through negotiation or imposition by other groups, as has been demonstrated in both cases we analyse.

From a managerial perspective, these commonalities provide insight into critical points of intervention needed in NAASs occurring within NRSs. From the perspective of lake networks, the analysis highlights the need to include information flows across all actor groups, especially those who engage with both systemic and individual levels of the NRS. For example, nodal agencies and real estate groups engage in decision making around converting lakes, which influences the entire system, yet they do not include fishermen and farmers, who are affected by these decisions. A potential goal therefore is to reach stewardship for the lakes' condition across all actor groups, as each individual group can through overuse, hamper social-ecological outcomes of the NRS. From the perspective of plant breeding systems, an important governance challenge involves public agents providing information of variety trials within and across actor groups depending on the level of the RS at which actors operate. For example, maintaining genetic diversity amongst breeders depends on common use and exchange of breeding material, in lengthy processes over several years, which obfuscate causal links between management decisions and breeding outcomes. Distributing information amongst breeders from trials pre-empts this process and minimizes opportunities of defecting amongst breeders, incentivizing individual improvements of the genetic pool. Yet, economic considerations of ASs later in the seed supply chain (NAASs), influence which material breeders use. Hence, a potential goal for plant breeding systems governance is that variety trials give information such that decision making by breeders and farmers enables a choice of more sustainable strategies for choosing varieties and breeding material.

These insights on systems could have been generated by other means and using other frameworks. Using the proposed diagnosis, however, will nudge the researcher to explicitly illustrate a) how the nestedness of an RS does influence decision making of the actors (incentive structure), b) how biophysical configurations and information flows arising thereof diverge or overlap for different actor groups. Explicitly showing connections or disconnects between configurations of RS and incentive structures, can aid in development of context specific, feasible solutions.

There are some caveats to using this diagnostic process. Applying it to a case requires that the analyst already possesses embedded knowledge of the system. Our diagnostic process also does not intend to prescribe normative views of interactions and outcomes; rather it encourages the analyst to make their own normative assumptions explicit in the process of applying the SESF to a particular case through critical reflection. Our conceptualization of the NRS and its subsequent application into the diagnostic process restricts itself to RS and RU components of the SESF. Engagement with how NRS and NAASs interact across diverse GSs would be a very useful next step along with engaging explicitly with second-tier variables of the SESF. Similarly, advancing diagnostic tools to enable dynamic comparisons across temporally situated NRSs and NAASs will enable better comparisons, aiding development of middle range theories drawing on institutional emergence. Future research should explore applying this diagnostic tool to multiple cases for comparison and meta-analysis, drawing upon the SESF and NAASs. There is potential for databases like the Social Ecological Systems Meta-Analysis Databases (Cox, 2014b) to be expanded by building upon this diagnostic tool (Appendix D is a prototype database), to provide large-n cases for further analysis, enable visualization of system patterns and processes, and build theory.

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3.7 Bibliography

Bayles, R., Flath, K., Hovmøller, M., & de Vallavieille-Pope, C. (2000). Breakdown of the yr17 resistance to yellow rust of wheat in northern europe. *Agronomie*, *20*(7), 805–811.

Berkes, F. (2007). Community-based conservation in a globalized world. *Proceedings of the National academy of sciences*, *104*(39), 15188–15193.

Bruns, B., & Kimmich, C. (2021). Archetypal games generate diverse models of power, conflict, and cooperation. *Ecology and Society*, *26*(4), 2.

Castán Broto, V., Sudhira, H., & Unnikrishnan, H. (2021). Walk the pipeline: Urban infrastructure landscapes in bengaluru's long twentieth century. *International Journal of Urban and Regional Research*, *45*(4), 696–715.

Cole, D., Epstein, G., & McGinnis, M. (2019). The utility of combining the iad and ses frameworks. *International Journal of the Commons*, *13*(1).

Cox, M. (2008). Balancing accuracy and meaning in common-pool resource theory. *Ecology and Society*, *13*(2).

Cox, M. (2010). *Exploring the dynamics of social-ecological systems: the case of the taos valley acequias*. Indiana University.

Cox, M. (2011). Advancing the diagnostic analysis of environmental problems. *International Journal of the Commons*, *5*(2).

Cox, M. (2014a). Applying a social-ecological system framework to the study of the taos valley irrigation system. *Human Ecology*, *42*(2), 311–324.

Cox, M. (2014b). Understanding large social-ecological systems: introducing the sesmad project. *International Journal of the Commons*, *8*(2).

Cumming, G., Epstein, G., Anderies, J., Apetrei, C., Baggio, J., Bodin, Ö., . . . others (2020). Advancing understanding of natural resource governance: a post-ostrom research agenda. *Current Opinion in Environmental Sustainability*, *44*, 26–34.

Dachbrodt-Saaydeh, S., Sellmann, J., Strassemeyer, J., Schwarz, J., Klocke, B., Krengel, S., & Kehlenbeck, H. (2018). *Netz vergleichsbetriebe pflanzenschutz, zwei-jahresbericht 2015 und 2016, analyse der ergebnisse der jahre 2007 bis 2016: Network of reference farms for plant protection, bi-annual report 2015 and 2016, analysis of results of 2007 to 2016*. Julius Kühn-Institut.

del Mar Delgado-Serrano, M., & Ramos, P. (2015). Making ostrom's framework applicable to characterise social ecological systems at the local level. *International Journal of the Commons*, *9*(2).

Epstein, G., Morrison, T. H., Lien, A., Gurney, G. G., Cole, D. H., Delaroche, M., . . . Cox, M. (2020). Advances in understanding the evolution of institutions in complex social-ecological systems. *Current Opinion in Environmental Sustainability*, *44*, 58–66.

Epstein, G., Vogt, J., Mincey, S., Cox, M., & Fischer, B. (2013). Missing ecology: integrating ecological perspectives with the social-ecological system framework. *International journal of the Commons*, *7*(2).

Frey, U., & Cox, M. (2015). Building a diagnostic ontology of social-ecological systems. *International Journal of the Commons*, *9*(2).

Gerullis, M., Heckelei, T., & Rasch, S. (2021). Toward understanding the governance of varietal and genetic diversity. *Ecology and Society*, *26*(2).

Hinkel, J., Cox, M. E., Schlüter, M., Binder, C. R., & Falk, T. (2015). A diagnostic procedure for applying the social-ecological systems framework in diverse cases. *Ecology and Society*, *20*(1).

Kimmich, C., Baldwin, E., Kellner, E., Oberlack, C., & Villamayor-Tomas, S. (2022). Networks of action situations: a systematic review of empirical research. *Sustainability science*, 1–16.

Leslie, H. M., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K. C., Cota-Nieto, J. J., . . . others (2015). Operationalizing the social-ecological systems framework to assess sustainability. *Proceedings of the National Academy of Sciences*, *112*(19), 5979–5984.

McGinnis, M. D. (2011). An introduction to iad and the language of the ostrom workshop: a simple guide to a complex framework. *Policy Studies Journal*, *39*(1), 169–183.

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and society*, *19*(2).

Meyfroidt, P. (2016). Approaches and terminology for causal analysis in land systems science. *Journal of Land Use Science*, *11*(5), 501–522.

Meyfroidt, P., Chowdhury, R. R., de Bremond, A., Ellis, E. C., Erb, K.-H., Filatova, T., . . . others (2018). Middle-range theories of land system change. *Global environmental change*, *53*, 52–67.

Möck, M., Vogeler, C. S., Bandelow, N. C., & Schröder, B. (2022). Layering action situations to integrate spatial scales, resource linkages, and change over time: the case of groundwater management in agricultural hubs in germany. *Policy Studies Journal*, *50*(1), 111–142.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., . . . Schwarz, N. (2013). Describing human decisions in agent-based models–odd+ d, an extension of the odd protocol. *Environmental Modelling & Software*, *48*, 37–48.

Oberlack, C., Boillat, S., Brönnimann, S., Gerber, J.-D., Heinimann, A., Speranza, C. I., . . . Wiesmann, U. (2018). Polycentric governance in telecoupled resource systems. *Ecology and Society*, *23*(1).

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge university press.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *Proceedings of the national Academy of sciences*, *104*(39), 15181–15187.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(5939), 419-422. Retrieved from `https://www.science.org/doi/abs/10.1126/science.1172133` doi: 10.1126/science.1172133

Ostrom, E., & Cox, M. (2010). Moving beyond panaceas: a multi-tiered diagnostic approach for social-ecological analysis. *Environmental conservation*, *37*(4), 451–463.

Partelow, S. (2018). A review of the social-ecological systems framework. *Ecology and Society*, *23*(4).

Reid, W. V., Mooney, H., Cropper, A., Capistrano, D., Carpenter, S., Chopra, K., . . . others (2005). Ecosystems and human well-being : synthesis / millennium ecosystem assessment. , 1–153.

Schlüter, M., Haider, L. J., Lade, S. J., Lindkvist, E., Martin, R., Orach, K., . . . Folke, C. (2019). Capturing emergent phenomena in social-ecological systems. *Ecology and Society*, *24*(3).

Schlüter, M., Orach, K., Lindkvist, E., Martin, R., Wijermans, N., Bodin, Ö., & Boonstra, W. J. (2019). Toward a methodology for explaining and theorizing about social-ecological phenomena. *Current Opinion in Environmental Sustainability*, *39*, 44–53.

Thiel, A., Adamseged, M. E., & Baake, C. (2015). Evaluating an instrument for institutional crafting: How ostrom's social–ecological systems framework is applied. *Environmental Science & Policy*, *53*, 152–164.

Unnikrishnan, H., Manjunatha, B., & Nagendra, H. (2016). Contested urban commons: Mapping the transition of a lake to a sports stadium in bangalore. *International Journal of the Commons*, *10*(1).

Unnikrishnan, H., & Nagendra, H. (2020). Quenching a city's thirst: The shifting waters of bangalore.

Unnikrishnan, H., Nagendra, H., & Castan Broto, V. (2020). Water governance and the colonial urban project: the dharmambudhi lake in bengaluru, india. *Urban Geography*, *42*(3), 263–288.

Unnikrishnan, H., Nagendra, H., & Castán Broto, V. (2021). Water governance and the colonial urban project: the dharmambudhi lake in bengaluru, india. *Urban Geography*, *42*(3), 263–288.

Villamayor-Tomas, S., Grundmann, P., Epstein, G., Evans, T., & Kimmich, C. (2015). The water-energy-food security nexus through the lenses of the value chain and the institutional analysis and development frameworks. *Water Alternatives*, *8*(1), 735–755.

Villamayor-Tomas, S., Oberlack, C., Epstein, G., Partelow, S., Roggero, M., Kellner, E., . . . Cox, M. (2020). Using case study data to understand ses interactions: a model-centered meta-analysis of ses framework applications. *Current opinion in environmental sustainability*, *44*, 48–57.

Vogt, J. M., Epstein, G. B., Mincey, S. K., Fischer, B. C., & McCord, P. (2015). Putting the" e" in ses: unpacking the ecology in the ostrom sociale-cological system framework. *Ecology and Society*, *20*(1).

Young, O. R. (2010). Institutional dynamics: Resilience, vulnerability and adaptation in environmental and resource regimes. *Global Environmental Change*, *20*(3), 378–385.

Young, O. R., & Gasser, L. (2002). *The institutional dimensions of environmental change: fit, interplay, and scale*. MIT press.

Young, O. R., Webster, D., Cox, M. E., Raakjær, J., Blaxekjær, L. Ø., Einarsson, N., . . . others (2018). Moving beyond panaceas in fisheries governance. *Proceedings of the National Academy of Sciences*, *115*(37), 9065–9073.

Chapter 4

From genes to policy: Mission-oriented governance of plant-breeding research and technologies[†]

Abstract: Mission-oriented governance of research centers around inspirational, yet attainable goals and targets the sustainable development goals (SDGs) through innovation pathways. The transformation from current into sustainable agricultural systems requires improved crop varieties and management practices. Speedy success in this respect is vital to lower the use of chemical fertilizers and pesticides, increase crop resilience to climate stress and reduce postharvest losses. A key question is how this success may come about? So far plant breeding research has ignored wider social systems feedbacks, but governance also failed to deliver a set of holistic breeding goals providing directionality and organization. To address these challenges, we propose a heuristic illustrating the core elements needed for governing plant breeding research: Genetics, Environment, Management and Social system (GxExMxS) are the core elements for defining future breeding goals. We illustrate this based on historic cases and in context of current developments in plant phenotyping technologies and derive implications for governing research infrastructures and breeding programs. We deem long-term investments into human resources and experimental set-ups for agricultural systems necessary to ensure a symbiotic relationship for private and public breeding actors and recommend fostering collaboration between social and natural sciences for working towards transdisciplinary breeding targets.

***Keywords**: mission-oriented governance; plant breeding; research policy; mission goals; sustainable agricultural systems*

[†]This chapter is presented here as working paper with further co-authors: Pieruschka, R., Fahrner, S., Hartl, L., Schurr, U. Heckelei, T.

4.1 Introduction

With Horizon Europe there is a €95.5 billion program fostering mission-oriented research and innovation in Europe (Mazzucato & McPherson, 2019), entailing a new approach to research and its governance aiming to achieving the SDGs (Mazzucato, 2018). Mission orientation calls for a changed role of state and public organizations. Public organizations are supposed to act entrepreneurial, meaning they need to actively set innovation pathways and create markets, instead of only intervening in failed markets (Mazzucato, 2013). This implies a change in governance of research centered around specific, inspirational, yet, attainable goals, called missions (Mazzucato, 2018). Similar to the Apollo mission, putting a man on the moon, mission-oriented governance in Europe sets out with missions on, for example, climate-resilient regions (DG Research and Innovation, 2020a), beating cancer (DG Research and Innovation, 2020c), or healthy soils (DG Research and Innovation, 2020b). Mission goals need to be supported and brought about aided by appropriately governed research and innovation activities. We call these new efforts of governance 'mission-oriented governance'. The different mission goals are developed such that they prioritize those systemic transformations with the best leverage towards reaching the SDGs (Sachs et al., 2019).

Achieving SDGs, demands that systemic transformation occurs in (1) education, gender, and inequality; (2) health, well-being, and demography; (3) energy decarbonization and sustainable industry; (4) sustainable food, land, water, and oceans; (5) sustainable cities and communities; and (6) digital revolution for sustainable development (Sachs et al., 2019). The agricultural sector is touched by all of these transformations: Be it through land-use efficiency, developing more productive plants, reducing food waste, impacts of unequal supply of education in rural areas, or applications of biotechnology in medicine amongst many others. Mission-orientated governance aims to facilitate these transformations from current agricultural production into sustainable agricultural systems (Sachs et al., 2019).

Core to sustainable agriculture is plants with improved properties and management practices allowing circularity and decoupling negative impacts (Pretty, 2018; Sachs et al., 2019). Currently plant production and breeding focus on increased yields, which needs to be extended to include other sustainability aspects, such as lower use of chemical fertilizers and pesticides, crop resilience to climate stress, and reduced postharvest losses (Qaim, 2020). Hence, plant breeding needs to provide the scaffold for efficient use of resources like water, nutrients, and minimization of pollutants in plant production. Targeted improvements of plants through plant breeding, however, are bound by evolving social and technological systems in research accelerating plant breeding.

Our objective is to propose a governance heuristic illustrating core elements needed for governing plant breeding research, such that its mission-oriented governance can achieve overall sustainability goals. Genetics (G), environment (E), management (M), and social system feedbacks (S) influence plant breeding outcomes. Symbolized by GxExMxS (as governance heuristic) we motivate, that holistic and systemic considerations need enter the creation of mission-oriented policy targets for plant improvements.

Yet, mission-oriented governance of agriculture creates a tension between how economists traditionally give policy advice on research and innovations in agriculture – with the state as intervening in failing markets (Alston & Pardey, 1996) - and a kind of governance centering around actively creating pathways of innovation. Hence, policy advice on mission-oriented governance focuses on a) directionality, b) dynamic evaluation, c) organization, and d) risk-and-reward sharing amongst public and private actors (Mazzucato, 2016). Directionality addresses how one may pick concrete targets and evaluation measures of effectiveness, which are broad enough to not stymie bottom-up exploration, discovery, and learning of involved actors within breeding contexts. Organizational challenges are related to building RIs advancing plant breeding providing sufficient absorptive capacity and long-run patience for high-risk undertakings, yet remain agile and innovative from within. This entails tackling how one can foster risk-and-reward sharing amongst public and private actors when RIs promise overall benefits. We adopt this approach in the following for research policy advice on mission-oriented governance of new approaches and technologies for phenotyping.

Phenotyping is the current bottleneck in developing advanced quantitative approaches to breeding needed for successfully creating improved crops . Developing ways for non-invasive high-throughput phenotyping and quantitative analytics is necessary for developing these new processes and tools for creating sustainable plant attributes. The European research infrastructure on plant phenotyping (Forschungszentrum Jülich, Institute for Plant Sciences, 2021), currently being implemented, provides services like access to plant phenotyping facilities, competencies and data. Since 2002 the European Strategy Forum on Research Infrastructures (ESFRI) put forward the establishment of Research Infrastructures (RIs) integrated across Europe. RIs are public organizations that are supposed to provide access and other services to physical and virtual infrastructures for researchers across the EU (e.g. experimental facilities, biological samples, scientific data) and integrate national towards pan-European and global efforts (European Strategy Forum on Research Infrastructures, 2021). The RIs can develop their pan-European strategies towards providing research services and adapting RIs' governance such that SDGs can be met in long-term. Accordingly, mission-oriented governance of plant breeding research – private and public - is supposed to support and bring forward breakthroughs in plant breeding research, and the EMPHASIS RI will be a vital part in implementing this strategy.

To meet our objective, we first introduce the 'nuts and bolts of plant breeding (section 2.1), then introduce what we mean by sustainability for agricultural systems (section 2.2) and how plant breeding in the past promoted and failed in achieving these goals. We highlight historic cases illustrating how genetics (G), environment (E), management (M), and social system (S) influenced plant breeding outcomes in the past (section 2). Symbolized by GxExMxS we motivate, that holistic and systemic considerations need enter the creation of mission-oriented policy targets for plant improvements (section 3). Then we introduce new modes and technologies of phenotyping, which will change and accelerate plant breeding processes (section 4.1). We discuss related economic implications for variety development in governing individual breeding programs (section 5.1) and point at potential challenges and bottlenecks in reaching sustainability goals (section 5.2). We then illustrate what mission-orientation under the premise of sustainability means for the governance of RIs developing phenotyping technologies and potential threats to their effectiveness (section 5.3 and 5.4) before concluding.

4.2 From genes to institutions – history and governance of plant breeding towards sustainability

In the following, we first describe basic terms for plant breeding Then we illustrate the role plant breeding plays for the sustainability of societies and how we use the term sustainability for this paper. We then illustrate with historic cases what role phenotyping played in plant breeding and how modern advances in phenotyping technologies evolved from past challenges in sustaining societies.

4.2.1 Key terms in plant breeding

Phenotyping is observing the appearance of a plant and evaluating its products (Fiorani & Schurr, 2013). It is vital for plant breeding being concerned with selecting amongst different candidates those variants of plants showing superior attributes, also called traits (Becker, 2011). Breeding processes usually aim at a dedicated breeding target, a combination of superior attributes. Breeding targets are for example improving yield, resistance to pathogens, or having a certain quality, such as baking qualities. All observable measures, as they appear in a plant, are termed phenotype. The phenotype, however, is connected to the genotype.

A genotype is the genetic material of an organism and hence carries the hereditary information recorded in the organism's genome. Changes in the genotype lead to changes in the plant's phenotype dynamically interacting with its environment (Pieruschka & Schurr, 2019). Breeders usually denote this relationship between genotype (G) and phenotype (P) by using the formula P=GxExM with E for environment and M for the management of the plant. In practice plant scientists measure phenotypic traits under different conditions of environment and management (ExM) and connect these insights to the genetic makeup of the plant (G) (Becker, 2011). Plant scientists are usually more interested in how functional properties (like photosynthesis, transpiration, nutrient uptake) or structural properties (like shoot and root architecture, leaf size) of the plant are affected by the environment.

When looking at the genetic setup, bringing about phenotypes, researchers usually discern traits into complex (quantitative) and simple (qualitative) ones (Acquaah, 2007). Flowering time is an example of a simple trait, determined only by a few genes. Whereas, nutrient uptake or yield signify complex genetic traits being spread out over multiple loci on the genome. Plant phenotyping is particularly important to quantify the diversity of phenotypic traits and understand in which social and ecological contexts which genetic setup translates to which phenotypes.

Yield exemplifies how the different actors in the breeding system all have different perceptions and understanding of complex traits. Basic research in biology and plant science contributes to improving yield, by looking at the multitude of plant physiological traits influencing yield. For example, scientists try to understand how photosynthesis works in C3 compared to C4 plants telling us the range of yield in- or decrease in crops reacting to increased levels in CO2 in the atmosphere (Kebeish et al., 2007). These insights serve as theoretic background for pre-breeders.

Pre-breeders make some of these insights from basic research utilizable for breeding. They transfer knowledge about how single plants work to small populations of crops or introduce new genetic resources, for example from wild relatives to more adapted breeding material. They breed crops having advantageous new traits and bring about a yield level comparable to adapted varieties of a specific pedo-climatic region. Varieties are groups of homogenous, distinguishable plants of the same crop (Becker, 2011). Introducing new traits to a gene pool of already adapted varieties demands a lot of effort in pre-breeding (Gerullis, Heckelei, & Rasch, 2021). It is usually undertaken by partnerships between academia and industry (Moore, 2015). Figure 1 shows the different steps of breeding and pre-breeding. Pre-breeders usually focus on selecting for those plants containing targeted traits into a better adapted genetic background with higher yields. This process usually takes years in practice (Gerullis et al., 2021), as complex traits need specific combinations of genes, being spread over the genome, whilst crossing-in new traits abates these efforts. Once new traits have entered an adapted gene pool, applied breeders can take these materials and cross them in with their breeding material (Figure 1 box 1, 5 to 7). They create new varieties containing these new traits, aiming for best performance of all other important traits (higher average yields and qualities) by even better adapting these to a specific region. While applied breeders still include grain yield, seed weight, and resistances when they refer to yield, multipliers and farmers usually talk about yield in terms of tons per hectare.

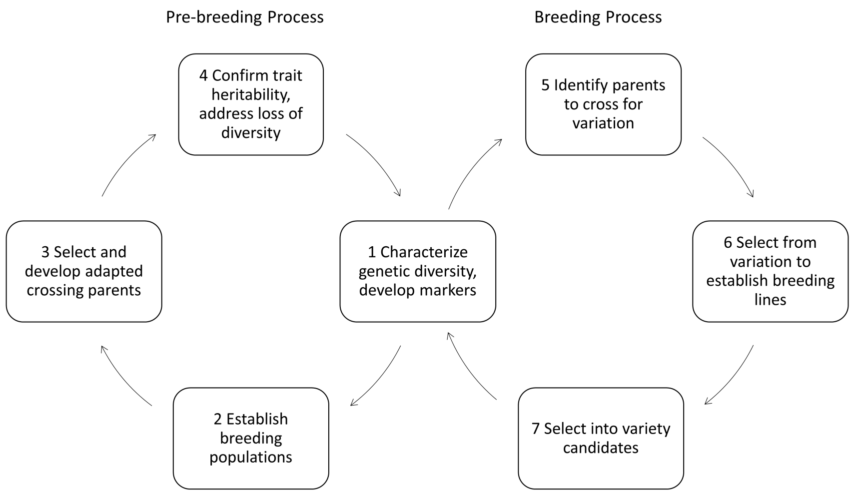

FIGURE 4.1: Pre-breeding and Breeding Processes (adopted and extended from (Watt et al., 2020)

Developing genetic markers for different traits necessitates characterizing genetic diversity (Figure 1 box 1). Phenotyping provides here the necessary information to correlate genetic information with observations on how these genotypes perform under different environmental and management conditions, and how well different traits are inherited (Figure 1 box 2 to 4). Phenotyping is basis for developing of molecular markers and genomics-based selection (Cooper et al., 2014). Automated systems in laboratory and field promise an increase in speed and precision in generating data and thereby accelerating pre-breeding and breeding processes.

Breeding outputs, namely varieties with improved properties, usually focus on improving yields, but also include other qualities, such as flowering colors, baking qualities, resistances to pests, nutrient content, or edibility. These are important to the remaining supply chain of agricultural and other plant-based products. It can take a decade or more to make a new variety of a crop. (Becker, 2011)

Plant breeding maintains and increases global productivity in agricultural products, see Laidig et al. (2017) for the contribution of breeding progress to yields and qualities in German winter wheat. Due to changes in the environment, breeders need to constantly adapt to changing conditions, and therefore maintaining the same yield level facing ever-changing pests can already be considered an improvement (A. L. Olmstead & Rhode, 2008). Yet, as we are going to see in the following plants' efficiency in resource use, their attributes in nutrient cycling and the systemic position cropping takes within the agricultural system determines how sustainable the overall system will be.

4.2.2 Sustainability by plant breeding?

In this section, we define what we mean by sustainable agricultural systems to clarify towards which goals we are heading, if we transform agriculture with mission-oriented governance. For this paper sustainability means that we can ensure the survival and thriving of humanity over an infinite time horizon. Doing so means living within the ecological boundaries of our planet (Rockström et al., 2009) while providing the social means to do so for all – as laid out by the SDGs (Raworth, 2017). Sustainable agricultural systems are social-ecological-technical systems (McGinnis & Ostrom, 2014) in which social, ecological, and technical processes produce food and fiber for the nourishment and fulfillment of the needs of humanity, while staying within the ecological boundaries of our planet (Rockström et al., 2017).

Sustainability of agricultural practices is in question if the current performance cannot be kept up in the long term. Some farming practices may lead to decreasing yields over shorter or longer periods and are as such intrinsically unsustainable. Whereas some are easily recognized in a short time (e.g. onion monoculture, Aragona and Orr (2011)) others involving soil erosion or accumulating salt may not be recognized by the individual farmer (see ancient Mesopotamian agriculture in (Gibson, 1974; Jacobsen & Adams, 1958). Additionally, farming practices relying on resources that are not replenished as fast as they are being used are also non-sustainable. Phosphorus use for fertilizer or water use for irrigation are examples of it. The task of breeding in this context is to provide varieties that allow those agricultural systems avoiding such unsustainable practices.

Whether changes of traits by breeding are an 'improvement' depends on the boundaries of and the specific social-ecological context of the system considered. For example, if we breed plants for a cropping system with higher input of phosphorus, then this has implications not only for crop management but the whole supply chain of inputs related to it. Higher yields may directly impact the nutritional and income status of those growing the crops, yet phosphorus may need to be mined and economic and social conditions of those handling the resource on its way to the farm are impacted (Nesme, Metson, & Bennett, 2018). If we, however, breed new traits into crops to use the phosphorous in the ground more effectively and have a lower phosphate extraction rate (van de Wiel, van der Linden, & Scholten, 2016), maybe some transportation of resources around the globe can be saved and additional extraction activities need not take place (Schipanski & Bennett, 2012). As we can see from this example, what to consider and how different changes in varieties affect sustainability depends on the context.

Breeding goals for future cropping systems should consider context-specific resource-use efficiency, stability, or more generally, sustainability of farm and food system outcomes. Improving the ratio of relevant output to resources used such as land, water, energy, biodiversity, and other environmental pressures.

Crop traits shape crop production and we need to give plant breeding proper consideration in its role towards achieving the mission targets ahead. Hence, we point at new directions that may open up with new technologies and approaches to phenotyping in breeding research to navigate towards the SDGs more effectively. Yet, phenotyping technologies will not solve all challenges in bringing about sustainability and should not be treated as a panacea, as we elaborate in the following section.

4.2.3 Origins of phenotyping - or how to adapt genes to fit environmental conditions

Early forms of phenotyping were already employed in the rudimentary forms of plant breeding appearing when sedentism emerged. Having domesticated plants meant a vital step towards sustaining large-scale societies where agriculture serves using and bundling energy – sunlight – such that human societies can use it for better survival and thriving (Bätzing, 2020). As crops pose very specific demands on climate, soils, pathogens to survive, it is decisive to know which crop functions well in which environment to reliably secure nutrition and allow humans to pursue other purposes. Domesticating wild plant species into early crops through plain eye-sight, intuitive judgment and trial and error was thereby a form of mending the first plant-based biological technologies (Becker, 2011; Maisels, 1993).

Aggregating plants, through mass selection into landraces, can be counted as a process of cultural learning (Henrich & McElreath, 2003). Adapting plants, like the wild relatives of cereals, throughout domestication to the pedo-climatic conditions of the Fertile Crescent (T. A. Brown, Jones, Powell, & Allaby, 2009; Maisels, 1993), is a process of cumulative cultural evolution (Henrich & McElreath, 2003). The most important information of these early days of agriculture was enclosed in the genetic information of saved seed and could be propagated to the next generation by simple mass selection (Purugganan & Fuller, 2009). The accumulation of advantageous traits took several intermediate stages before certain crops were prominent over wider regions (T. A. Brown et al., 2009; Smith et al., 2019).

4.2.3.1 *The advent of scientific plant breeding*

The advent of scientific plant breeding in the late 19th century stimulated more targeted breeding practices compared to the formerly used mass selection (Harwood, 2015; Kloppenburg, 2004). Breeders started to incorporate experimental designs (Mendel, 1866; Wieland, 2004). They generated scientific insights on-farm management and included the first mental models of the influences of genes on farm outputs (Brandl & Glenna, 2017). Breeders selected for more homogenous plant types (Kloppenburg, 2004; Wieland, 2004) and adopted more explicit and precise approaches to the underlying causalities assumed between plant physiological traits and farm outputs. They developed different forms of breeding and introduced the concepts of varieties, as uniform and stably performing groups of plants outperforming landraces in their yield by far (Becker, 2011). Meanwhile, crop genetic diversity reduced in richness (van de Wouw, van Hintum, Kik, van Treuren, & Visser, 2010).

Approaching the management of crops with scientific methods emerged together with the different disciplines within the agricultural sciences (Wieland, 2004). They targeted higher yields by adding synthetic fertilizer and crop protection agents tested with experimental designs. Aiming for control of the natural environment in fields, by suppressing pathogens and weeds (Wieland, 2004). Coinciding, use of machinery increased, labor intensity decreased and productivity of western agricultural systems increased immensely (A. L. Olmstead & Rhode, 2008; Pardey, Alston, & Ruttan, 2010). These scientific developments meant adding "M" to the basic formula of breeding, GxExM. This evolution in the agricultural sciences invoked the impression that the impact of the environment "E" was controllable by management practices (Wieland, 2004). Yet, pests constantly diminished the gains just realized by more targeted breeding (A. Olmstead & Rhode, 2002).

Discovering semi-dwarfed varieties, capable of producing comparatively higher yields, denoted a breakthrough in plant breeding (Pingali, 2012). Scientists, like Norman Borlaug, were capable of reversing a trait (long stems in cereals) brought about by natural selection in crops (R. Denison, 2012). Instead of further fueling individual competition between plants, dwarfing genes lead to plants putting their energy in higher grain yields and low stems, producing even greater outputs if fertilized (R. Denison, 2012). Developments in breeding went hand in hand with farm management advancements.

4.2.4 Genotyping and biotechnology – answers to the pest problem?

Genotyping technologies invented in the 1980s allowed a deeper look into the genome. Breeders and pre-breeding scientists use these technologies to associate specific phenotypic traits, like a certain degree of susceptibility to a pathogen, with different mostly simple traits in the genome of crops (Eathington, Crosbie, Edwards, Reiter, & Bull, 2007). Several genotyping techniques have been invented over the last two decades and have dramatically improved in terms of cost, speed, and accuracy for detecting correlations amongst gene loci and their phenotypic performance in different environments. While modern genotyping technologies permit to find those places in massive amounts of genetic data which bring about complex traits, limited data in phenotypes across different environments is available and hinders scientists to leverage their full potential. The data limitation in phenotypic information poses a bottleneck to advancing insight on how different genotypes perform in different environments (Fiorani & Schurr, 2013; Pieruschka & Schurr, 2019).

Explicitly taking genetic information into account for breeding opened up possibilities for modification. Pairing chemical mechanisms of pesticides with plant physiological traits, rooted in genetic modification (GM), was used to fight pests. Herbicide tolerance means that GM plants will survive a broad-spectrum herbicide where other weeds die (Kishore, Padgette, & Fraley, 1992). Insect resistances for example induced through parts of Bacillus thuringiensis (Bt) genes lead to plants producing insecticidal proteins (Ranjekar et al., 2003). Yet, these alleged solutions to pressing pests are in vain from an evolutionary perspective, as the mechanisms employed to fend off pests are overcome by evolved resistances against these (Carroll et al., 2014; Tabashnik, 2008).

R. F. Denison, Kiers, and West (2003) state that we merely enter an arms race between host plants and pests, but not resolving underlying problems. These cases of GMs represent low-hanging fruit in genetic modification and may even be misdirected in how they approach agricultural systems as a whole in face of natural selection. What seems successful at first produces no long-lasting improvements of agricultural systems. Natural selection caught up with human inventions, as these traits were used in big monocultural setups and pathogens had plenty of room for developing resistances to the employed chemical mechanisms (R. Denison, 2012; Søgaard Jørgensen et al., 2020). Consequently, the targeted plant protection starts to fail. GMs add nothing new than what the application of pesticides and the co-evolving pathogen resistances in conventional agriculture did (Varah et al., 2020).

From an evolutionary perspective, R. Denison (2012) argues that humans are not likely to improve on those traits natural selection has been optimizing for millennia, but chances for improvement lie in redirecting natural selection. As plants themselves face trade-offs in how they use their energy, some traits, stemming from increases in individual plant fitness, but unnecessary to human use, can be reversed for improvements towards human needs. R. Denison (2012) puts forward that for pests, there is no way of winning at the individual level, as plants and pathogens have been in these co-evolutionary cycles for long enough that natural selection developed plenty of strategies implemented in individual organisms to circumvent them. We can only hope to prolong a cycle in the arms race long enough to come up with new ideas of adaptation.

There is, however, a set of strategies aimed at changing agricultural practices on a collective level. When looking at pests from the perspective of an ecosystem, another set of possibilities opens up. Interrupting a pathogens propagation mechanism, for example by eradicating intermediate hosts (A. Olmstead & Rhode, 2002) as done with mulberries to eradicate black rust in wheat. These strategies alter a crop's environment on a higher level. Strategies like these cannot be considered a mere change in management practices of an individual farmer, as they involve targeted collective action by farmers, extension services, and other interest groups on landscape level. The entailed social dilemmas, where incentive structures for individual costs and collective benefits diverge, can be quite complex, but have been achieved before with successful governance– see A. L. Olmstead and Rhode (2008) for more examples of historic accounts from the United States.

The principles and elements of agroecology as suggested by FAO (2018) target integration of social and ecological aspects for design and management of agricultural systems at a higher level (ecosystem level). Yet, R. Denison (2012) warns of false mimicry of whole ecosystems as it may lead to suboptimal outcomes compared to competitively tested systems. Competitive selection pressures of natural selection are not as effective on ecosystem level, as they are on individual (plant) level, as ecosystems usually do not compete for space against each other, opposed to individuals in ecosystems R. Denison (2012). Pest management is such an example, as any pest management strategy is counteracted by individual adaptations of pests.

Yet, within an agroecosystem with homogenous conditions where a single strategy is being scaled up, pests are going to have an easier time for counteraction. Hence management for diversity and smart interaction of strategies needs to be considered.

Independent of detailed strategies in governing agricultural practices, pest management is a good example to show, that aside of the fit between genetics, biological environment, and direct farm management practices, the social system and its governance on a higher level needs consideration when developing targets for innovations in breeding. This will allow achieving relevant individual and whole system-level outcomes (Carroll et al., 2014).

4.3 A governance heuristic for sustainability in plant breeding

Successful breeding demands very high R&D costs, which led to considerable concentration of firms in commercial seed markets (Deconinck, 2020) and the need for wise decision making in how and where public spending is directed. We can learn three things from the cases presented: One, not all traits are created with equal ease. We need to account for this in policy such that hard-to-get traits are developed by public monies, as private actors may be more likely to produce the low-hanging fruits. Two, the direction of genetic development is not open towards all possibilities. We need to account for what traits have been brought about by natural selection and where there is still room for development towards human needs. Three, the pest management examples highlighted above show that interactions of social-ecological dynamics lead to co-evolutionary cycles influencing cropping long-term. Short-term successes must not be overrated, as second-order effects on collective level may turn out to hamper overall systemic performance. We may need to find ways of slowing down arms races on wider systemic levels to have enough time for developing new adaptions.

While words like “social system” or “governance” may strike plant breeders and most crop scientists as a vague notion irrelevant to their work, we want to prevent

Definitions of GxExMxS	
G	"Genetics" – stands for changes on genetic/plant level.
E	"Environment" – denotes biotic (e.g. pathogens) and abiotic (e.g. soil and climate) environment of an agricultural system. It means those parts of the biophysical surroundings of locations where agricultural production or breeding takes place.
M	"Management" – means those activities undertaken by actors directly influencing plant growth in fields and controlled environments.
S	"Social" – implies the wider social system influencing management activities from the collective level but also co-evolving with the wider biophysical environment.

TABLE 4.1: Governance heuristic for plant breeding research

exactly that and add an "S" for social system to the mental model of breeding and create a new heuristic for plant breeding governance:

$$GxExMxS$$

As explained, cropping outcomes rely on interaction of genetics (G), biological environment (E), directly applied management practices (M), and influences from the collective level implemented through governing the social system. Comparable to ecological environments higher-level social systems are complex in themselves. They are usually being structured by institutions (Ostrom, 2006) and entail all prescriptions bringing about individual-level behavioral patterns – usually subcategorized in rules, norms, and strategies, opposed to the laymen notion of an institution being an organization like a ministry. The management practices pointed out above are classical examples of strategies – describing what activities specific actors (e.g. farmers) perform. Norms and rules are usually brought about by different forms of governance systems, like cooperation organizations, lobby groups, or law-making bodies; they specify the conditions and sanctioning mechanisms under which individual strategies may or must (not) be enacted. Incentive alignment between individual strategies and the rules and norms brought about by the governance systems on all scales is key to structuring future breeding and farming systems.

We suggest the GxExMxS formula, see table 1, as a governance heuristic to those people in policy advice and governance specific to plant breeding contexts. It should serve as a gentle reminder of not putting considerations of collective level activities in agricultural systems aside too quickly. For example, when EU project funds are being granted to researchers, funders should have some notion how activities scale up as this will influence the effectiveness of implementing innovations from plant breeding. Meanwhile, we want to encourage economists, who are traditionally good at considering markets and other institutions of governance, to more explicitly include notions of interactions between genetics and environment together with individual management and system-level outcomes.

4.4 Phenotyping technologies

In the following section, we define and introduce automated phenotyping technologies and delineate underlying scarcities these breeding technologies may alleviate and point out bottlenecks they may bring about.

4.4.1 Overview of technologies in early research and development stages

Non-invasive high-throughput phenotyping technologies measure plant growth, structure, and composition with a specific precision in an automated manner, without destroying organs or canopy of the observed plant (Fiorani & Schurr, 2013). Being non-invasive, the new technologies enable observing plant traits without interrupting plant growth. Basic sensors and data processing may also be employed in farming, but plant breeding and pre-breeding pose different demands on these technologies, as they need to process smaller batches and have more heterogeneous tasks to fulfill (Watt et al., 2020). Sensor-based vision goes beyond the spectrum visible to humans' eyes and even below ground, making it possible to observe new traits, only passively accounted for in breeding so far.

Researchers involved in breeding encounter scarcities in phenotypic data due to limited time and person-power. Precision and depth of data are usually an issue in collecting phenotypic data, depending on the physiological plant traits or farming outputs researchers are looking for. For example, daily images of the same plants throughout their growth period can be interlinked mathematically with genotypic information and daily climate data, for inferring how different genotypes may react to various weather conditions. Usually, multiple people need to score these attributes, by hand and eye inspection, while the source of data changes, once the person leaves the field, as plants continue growing. Main advantages of the new technologies are that one can see more, see faster, more precisely and there is no primary data loss.

For plant scientists there is a plethora of automated phenotyping technologies in different stages of development. Table 2 presents an overview of the heterogeneity of phenotyping systems available for (pre)-breeding. All breeders must have some form of implicit or explicit notion about what and how inputs and efforts connect with their (pre)-breeding outputs, called mental models (Kieras & Bovair, 1984). Depending on their technical possibilities for inquiry, breeders use a variety of physical infrastructures for phenotyping: a) controlled conditions, like greenhouses or climate chambers, used alongside b) lean fields using minimal phenotyping equipment, like drones or robots or c) intensive fields using highly equipped for monitoring plants and environments. All physical infrastructure is complemented with d) information systems and e) modeling tools for processing sensor data.

4.4.2 Controlled environments and enhanced vision traits

Controlled environments, in greenhouses and climate chambers, serve to investigate genetic variability in measured plant traits as a response to well-defined environmental conditions (Table 2). Researchers and breeders need to know the functional connection of how individual genes interact with each other as part of a plant and their environments. Most platforms can phenotype shoots throughout their growth period observing plant response when simulating biotic and/or abiotic environments, like temperature, water, nutrient availability, pathogens, etc. (example: PhenoTron in table 2). Predominantly for controlled conditions the platform upon which the sensor system is mounted is fixed and plants are automatically moved to sensors creating observations (Table 2; Yang et al. (2020)). Yet, there are also large installations where plants grow in fixed carriers and are being moved towards sensor systems – e.g., GrowScreen-Rhizo 1 (Nagel et al., 2012). Sensor systems are usually defined by noninvasive imaging measuring time series of dynamic processes such as plant growth. Depending on the trait of interest an entire electromagnetic spectrum can be used for different modes of imaging (Fiorani, Rascher, Jahnke, & Schurr, 2012) usually in fully or semi-automated systems. With the current state of the art, most installations can process plants only until a certain stage in their growth – or only smaller crops and some platforms only permit to scan single plants, which decreases speed of inspection (Fiorani & Schurr, 2013).

Some platforms are capable of phenotyping roots below ground. While breeders have inspected above ground for thousands of years, to judge a plant's quality, it seeing below ground opens up new possibilities to research. Now breeders can select for below-ground traits in a targeted manner. There are a few success stories demonstrating targeted selection of root traits (Watt et al., 2020). Being able to observe root setup without destroying them or their soil habitat over the growth period in an automated manner allows for data improving the speed in selection for root traits. This is essential for traits like water or nutrient use efficiency. These observations allow disentangling the role of root structures and their functional properties such as uptake of nutrients, biotic interactions within the rhizosphere (Watt, Silk, & Passioura, 2006). This brings about insights on genotype-to-phenotype relationships including those related to soil environments. (e.g. flood or drought stress, interactions between microorganisms and roots. We may be able to select entirely new trait types in applied breeding based on roots, where so far only shoot observations were used (Ober et al., 2021). So far, however, simultaneous measures of roots and shoots show that relationships between both are unpredictable, particularly for plant growth traits, like biomass (Nagel et al., 2015). Having more data available will likely give rise to disentangling these relationships.

Applying results from pre-breeding to practical breeding depends on how well genotypes predict intended outcomes, like yield, under field conditions. Yet, there are significant differences between controlled and field conditions in the target environments (Poorter, B Hler, van Dusschoten, Climent, & Postma, 2012) for example regarding light intensities or room for root expansion. It is impossible to fully simulate outdoor environmental conditions in experimental setups due to their complex dynamics (Kumar, Pratap, & Kumar, 2015). Moreover, insight can usually only be gathered for smaller time spells in growth phases of a plant and rarely spans

Own Source. Category of Infrastructure: ▪ Controlled Environments; ▪ Field Sites; ▪ Modelling and Information Systems

FIGURE 4.2: Overview of network for automated phenotyping technologies within research infrastructure

from seedling to harvest. Therefore, correlations between controlled environments and field conditions are generally fairly low (Kumar et al., 2015; Watt et al., 2020).

Controlled environments allow predictions and heritability assessments of yield components where it may not be possible to assess those under field conditions. This allows directly developing insights for plants grown under controlled conditions, as needed for horticulture and vertical farming. However, phenotyping under field conditions is needed to see the performance of farming outcomes of different genotypes of crops farmed in large outdoor spaces.

4.4.3 Field environments and faster data generation

Field phenotyping serves testing plants – or rather their genotypes – under real environmental conditions. Testing plants in as many different environments of future potential relevance reveals the range of environments in which plant candidates perform well. This information can already be used for crop model simulations to scale up the variety's 'spatial reach'(Ersoz, Martin, & Stapleton, 2020; Grassini et al., 2015).

The range of technologies applicable for usage in the field is wide (Table 2; (Araus & Cairns, 2014)). Ensuring adaptability to differences in agricultural practice technologies range from rather low-tech field-bikes, with sensors mounted between two manually pushed wheels, robots looking like moving photobooths for cereals, or drones scanning fields. Most technology combinations of platforms and sensors currently tried out are mobile devices where the sensor is carried to the plants for imaging and can be distinguished by scanning single plants or multiple plots at a time. Some technologies are being developed for specific crops – like grapevines or sugar beet canopies – and therefore have limited flexibility in their technical setup (Schmenner & Tatikonda, 2005). There are trade-offs involved at the technical level. Drones have the advantage of being faster at scanning a whole field than any human, yet resolution in their data is still limited (Burud et al., 2017). Drones do not need to navigate driving lanes or muddy fields nor do they compact soils. Yet, drones have trouble flying in adverse conditions with wind and rain (Chapman et al., 2014). Automated wheel-driven robots can easily produce high-resolution images of individual plants but still, take a lot longer than their human counterparts at scanning a whole field (Vijayarangan et al., 2018).

4.4.4 Socio-technological bottlenecks – data processing and management as the missing link

Scientists and breeders need to have actionable insights they can directly translate into their breeding practice. The knowledge about causal relationships between different factors and the phenotype is key to know what material to use next for breeding actual varieties. Scientists need to communicate these insights for breeders to use. Their experimental set-ups should enhance our understanding of relevant traits and their functional interactions of GxExMxS. Machine Learning is capable of compressing the high-dimensional 'big data' obtained and to produce predictions of phenotypical traits from genetic and environmental features (Minervini, Scharr, & Tsaftaris, 2015; Tsaftaris, Minervini, & Scharr, 2016). To be able to employ machine learning, breeders need training or hire services/employees with the required new skills.

Another challenge is managing data for reusability. In pre-breeding, genotype-to-phenotype data in different environments is scarce, as a low number of candidate plants or seeds contain specific traits limiting repeated measurements. Meta-analyses could support robust insights on quantitative and qualitative traits (Watt et al., 2020). There are challenges involved in facilitating these studies: Data needs to be a) accessible, b) standardized/interoperable and c) worded in a common language (ontology), (d) findable (FAIR principle; Wilkinson et al. (2016)) for describing what is being measured to make data comparable and re-usable across experiments. For meaningful comparison across different environmental contexts, pedo-climatic conditions, pathogen pressures, and other plant growth conditions need to be recorded systematically. Reusable data and replicable results are hard to gain under constantly changing environmental conditions (Massonnet et al., 2010). Ensuring FAIR data needs a collective effort by scientists and breeding practitioners complying with these principles. Several initiatives already exist aiming to harmonize experimental data from phenotyping, like the International Wheat Information System (http://www.wheatis.org/) or MIAPPE (https://www.miappe.org/).

4.5 The future of governing phenotyping technologies in plant breeding

High throughput phenotyping can contribute to sustainable intensification on different scales by shaping and accelerating crop improvements. Automation will influence individual breeding programs as they produce varieties with better traits than before. RIs provide the socio-technical environment and concrete demand-driven services to achieve this.

4.5.1 Implications for applied breeding programs

Breeding programs produce varieties for farmers to use. Private businesses try to recoup their research and development investments through sales of varieties or licenses for multiplication. Breeders are usually faced with the two-fold problem of creating variation of trait expressions in candidate variants and then selecting effectively and efficiently from the variation created for combinations leading to improved farm outputs. The number of varieties admitted for sale and income generated from sales or licenses can be seen as their current measure of success. Yet, these numbers need to be interpreted as relative to the inputs used by a breeding firm. (Gerullis et al., 2021).

Inputs - limiting factors to practical breeders' operations - are nursery space, different locations for having a variety of environments available to test breeding lines under different conditions, genetic variation in their material, and skilled or unskilled person-power producing and evaluating the depth and breadth of data created through the mentioned factors of production. Breeders employ social strategies to work around the physical limits of their firm. Some breeders share and exchange information, nursery space in different locations, and material with their colleagues or co-produce new genetic traits with scientists in pre-breeding programs (Gerullis et al., 2021). Even small breeding programs can be quite successful as such (Brandl, 2018) if they manage their input to output ratio well and produce well-working varieties for different ecological niches.

Adopting high throughput phenotyping as an applied breeder leading a breeding program only makes sense if the technologies alleviate the resource scarcities mentioned and if they help outperform the return on investments necessary for the technologies of the breeding process currently in use. Those firms will be the most successful in employing the technologies that can leverage them for developing wider phenotypic variation and/or then employing the technologies for increased selection pressure, thereby accelerating the breeding process (Brandl, 2018).

Breeders' mental models of the functional connection between crop physiological traits, genotypic information, and the phenotypic observations of varieties and farming outputs under different environments (biological and social) determine what breeders use in their breeding process. It is vital to know for a breeder how and when to inspect signs of a disease, for example, fusarium head blight in late growth stages shows a whitening of wheat ears, to look for resistance of the same (Champeil, Doré, & Fourbet, 2004). They need to know how candidate variants perform under different disease pressures and then relate observable farm outcomes, like toxin levels in wheat harvests if they are susceptible to fusarium.

Sensors employed in high throughput phenotyping can enhance vision beyond plain eye-sight, opening up possibilities for completely new breeding input traits, so far ignored (Watt et al., 2020). Yet, for bringing about improved varieties, breeders' mental models, depicting causal connections in terms of structure and processes of the plant system (Kieras & Bovair, 1984), are decisive. For example, if a breeding goal is to boost plant productivity by introducing crop varieties paired with specific variants of mycorrhizae (Brito, Carvalho, & Goss, 2021), then the tricky part for the pre-breeder is figuring out which plant physiological attributes an applied breeder needs to look out for to bring about improved farm outputs. Breeders need to know what patterns to look for in the images of root structures they gather and what these different patterns mean to formulate expectations of how crops work and how they can gain improvements. Additionally, opportunities arise where interactions of multiple factors come into play. For example, if different root structural patterns allow for a narrower planting on the same space, an increase in yield through interspecies cooperation (e.g. micro-organisms and plants) and variation in field arrangements (Grahmann, Reckling, Hernandez-Ochoa, & Ewert, 2021) allows a push and pull pest control, then all three factors may be combined (R. Denison, 2012). Both examples need new ways of phenotyping and the integration of experimental meta-data into experimental set-ups of applied breeders.

Automation – once established – can bring about more comparable and precise measures of phenotypes across locations. In handicraft breeding, personnel have to hand-inspect and rate every variant plot for multiple time slots throughout growing seasons (Reynolds et al., 2019). There are differences in how individuals rate plots. Breeders usually compensate this by knowing their staffs' style of judgment and triangulating the results for important diseases. Human staff will usually correct their ratings for environmental conditions. Some diseases may not be visible well if another disease already infected big parts of a plant or if only low disease pressure is present. Automated phenotyping and the corresponding image processing algorithms could, once machine learning models employed are trained to compensate for these problems, aid in inspecting and rating over multiple locations saving person power and time (Reynolds et al., 2019). Paired with decision support systems for breeders, which pre-process the data, there is potential for accelerating breeders' work in this approach if robotics and data management systems can be maintained and adapted easily Kuriakose, Pushker, and Hyde (2020). Yet, the additional data in terms of quality and quantity created needs to be processed, standardized and interoperable to work effectively (van Dijk, Kootstra, Kruijer, & de Ridder, 2021).

4.5.2 Bottlenecks in breeding programs and opportunities for new service industries

Depending on their pre-existing socio-technological infrastructures, private breeders face different trade-offs when considering investing in automated phenotyping technologies. The cost and risks of investing in robotics-based phenotyping may be immense for a small breeding firm currently equipped with just the minimum technical setup for instance in wheat breeding – nursery fields, skilled and unskilled labor, and a rudimentary computer system where they store and manage data from plant inspections. The firm would need to invest, in the robot(s) itself, the highly skilled robotics personnel to implement, maintain and improve it and more personnel skilled in computer science for implementing, maintaining, and improving data and knowledge management and analysis (Reynolds et al., 2019). With shifting to new systems, firms run the risk that the new technology will cost more than it adds in value. Similar considerations struck breeding programs 35 years ago when they faced the integration of molecular genetics with plant physiology (Reece & Haribabu, 2007). Some breeding firms outsourced genotyping their seeds and a service industry appeared (Shkolnykova, 2020). This outsourcing generally worked better for some breeding programs, where the initially chosen interdisciplinary collaboration within breeding programs had problems (Reece, 2007; Reece & Haribabu, 2007). Today, smaller breeding programs use genotyping services to scan for specific markers, targeted genetic sequences, of intended breeding input traits and base their selection on the results. Using services for genetic markers in breeding accelerates breeding already.

Having more data from an automated phenotyping process will only increase value-added if the software for processing the new data types enables breeders to integrate their hypotheses into building new ideotypes, i.e. targeted ideal phenotypes. Software needs to be flexible enough to accommodate new insights when new traits are developed (Xu & Crouch, 2008). They need to contain graphical user interfaces, which allow for ample flexibility for the set-up of data processing through the breeder, without having to have a computer science degree (Galitz, 2007). It is important that breeders can individually fine-tune analyses and try out assumptions for different functional models between trait expressions and outcomes. Breeders need to be able to arrange their experimental designs for crossing and selecting according to their wishes. Breeders need to learn how to explicitly transform the “breeders’ eye” (Brandl, 2018) into heuristic computer models. Open question is whether breeders will actively engage in pre-breeding and try to develop different ideotypes, or go for merely applying what pre-breeding research serves to them as new ideotypes and use trial and error in application.

There is ample opportunity for specialized services to develop alongside new breeding technologies. Effortless usage and maintenance of robots and data infrastructures may be provided well by businesses, who arrange their activities around co-producing services for multiple breeders. We specifically say co-production, as these services demand a collective and dynamic learning process, based on research by universities and research institutes, then tailored to different localized social contexts, biological environments, and crops. In other sectors, like banking, the co-creation of technologies with heterogeneous small actors has brought about decentralized organizational structures and kept market concentration at bay (Hannan & McDowell, 1990). Considering how heterogeneous and locally adapted breeding needs to be to produce varieties fit for prevailing environmental conditions, long-run cooperative networks of firms may outperform single players in achieving this goal. Multiple firms may pool resources and share risks in developing software, data management services, and robots focusing on ease of use and flexibility for individual ideas and specific conditions. This way, a diversified approach of adopting the new technologies seems possible for breeders even if they currently possess low-tech infrastructure. As the case of German winter wheat shows (Brandl, 2018), cooperative breeding strategies have led to German wheat breeders outperforming the global competition over the last 100 years in terms of yields (Brandl, Paula, & Gill, 2014). Going for co-production may in the long-term better hedge our bets for societal goals of sustainability overall, as we maintain flexibility and adaptiveness to localized conditions.

Accelerating the breeding process through increased selection pressure may bring about a trade-off over nursery space for short-term variety development and maintaining genetic resources in adapted breeding material (Gerullis et al., 2021). If automated phenotyping provides more precise predictions compared to current selection schemes, breeders will be quicker with selection decisions for dropping material. Meaning that breeders run the risk of dropping material earlier in the breeding process than before, possibly losing too much valuable variation in genotypes. Private incentives led to underinvestment in crop genetic resources in the past already in the USA (Day-Rubenstein, Heisey, Shoemaker, Sullivan, & Frisvold, 2005). Hence, monitoring and evaluating in-situ genetic resources from breeders and their released varieties will be vital to ensure long-term functioning of seed production and needs to be developed alongside the new technologies. In the next section, we will go deeper into how public RIs can support these strategies and promote overall sustainability goals.

4.5.3 Threats and opportunities to effective research infrastructure governance

RIs provide resources and services for research communities conducting research and fostering innovation (ESFRI, 2021). From a mission-oriented perspective, a RI around plant phenotyping serves as an accelerator for developing agricultural systems adapted to existing or upcoming challenges. Developing these sustainable agricultural systems demands governance connecting scientists and all relevant stakeholders, providing physical and mental space to rigorously test different system configurations against each other. Principles of mission-oriented governance (Mazzucato & Li, 2021) necessitate a) defining overall but also intermediate goals, b) entertaining a widespread portfolio of project set-ups so that failures become acceptable, c) involving actors and investment across different scientific disciplines, private and public sectors, d) joined governance, yet, strategic division of labor among involved research sections with well-defined responsibilities for coordination and monitoring.

We put forward GxExMxS as rule of thumb for thinking about how efficiencies in land use, water, energy, ecological impacts due to changes in nitrogen, phosphorous, and carbon cycling are brought about, at different levels initiated and/or complemented by changes in traits of crops. Research programs under the Horizon Europe missions should integrate relevant stakeholders having expertise in different topics. RIs are supposed to function as an organization providing services such as access to facilities, data, resources and could function as an important element stimulating cross-disciplinary interaction and research towards common goals. With their cross-cutting capabilities to reach many different actor groups, RIs are key in shaping how governmental monies spill over to private industry (Mazzucato & Li, 2021). They can deploy mission-oriented organizations, to crowd-in private investment and use knowledge governance for public values, by putting in play conditionalities of public interest (Mazzucato, 2018; Mazzucato & Li, 2021).

Aside from immediate breeding outcomes, the performance on-farm and beyond must be considered as well, potentially already during pre-breeding. High-throughput installations need to be accessible to create high-quality, reusable data sets to yield reliable results for crop model predictions and integration into simulation models over larger spatial scales including different pedo-climatic zones. Basic research on crop improvement needs rigorous testing of different technical systems' performance, necessitating flexibility in where and how different sensors are used. This demands modular installations, sensors, and platforms. Scientific testing and optimization must not stop until new system configurations outperform the best running systems in use on farms, to provide proper proof of concept ready for wider application. On the level of research, this includes from biological insights of symbiotic interactions amongst crops and other organisms to technical inventions developing enhanced vision with machines.

EU funding of RIs together with other fiscal incentive schemes for agricultural research aims at developing innovations for the Green New Deal (Mazzucato & McPherson, 2019) and achieving sustainable development goals with mission-oriented governance (Sachs et al., 2019). The goal is to crowd-in those individuals and organizations, who are willing to innovate for achieving these goals and co-creating new markets for and through sustainable innovations. RIs play a role as enabling scaffold in these overall European goals.

Yet, treating RIs merely as enabling organizations is not enough. Supporting the overall directionality of missions like healthier soils or adaptation to climate change (European Strategy Forum on Research Infrastructures, 2016, 2021) effectively not only requires the development of technological features, like steering software for robots, but collective learning across sectors and disciplines to achieve goals like the SDGs. As reaching the SDGs requires deep structural changes across all sectors of society (Sachs et al., 2019), they include social cooperation problems across multiple scales and amongst different stakeholders discussed in section 2.3. Leading actors in RIs may need to adopt institutional navigation as they pursue the SDG policy goals against a backdrop of complex, polycentric governance, where multiple decision-makers engage in different forms of organization to manage cooperation problems present in agriculture (Lubell & Morrison, 2021).

Facilitating a research environment with learning and high explorative capacity best fits for tackling the mission's challenges (Lubell & Morrison, 2021; Mazzucato, 2015a). High explorative capacity within these organizational structures may be achieved through a social environment where RI staff can welcome uncertainties and long-term competencies are developed (Mazzucato, 2015a). Additionally, staff need to be proactive and entrepreneurial in their role of leading researchers and other actors using the infrastructure and its outputs (Table 2 for examples).

In fiscal terms, this necessitates long-term investment in equipment and human resources (Mazzucato, 2016) (Mazzucato 2016). In RIs for breeding and agricultural purposes, long-term experimentation is important (e.g. considering breeding cycles taking 10 years and more, (Gerullis et al., 2021)). Experimental set-ups need to go beyond the usual 3-year project term and limited field space to bring about useful and accurate long-term results. With the current set-up of phenotyping networks in Europe (see figure 2 for the Emphasis RI) it is possible to leverage multiple locations and installations distributed across Europe even though individual scientists may not have the same access to specialized installations at their home institutions.

Infrastructure category	*Object of interest*	*Basic characteristics*	*Operational modes*	*Limitations/ challenges*	*Examples*
Mental Model	Design of experiment	Denotes the functional and heuristic connections between breeding inputs and outputs	Present in all forms of breeding and pre-breeding practice: • Implicit knowledge • Explicit knowledge	Bound by computational capacity and information storage	• Breeder's eye • Experimental designs and idea funnel
Controlled Conditions	Mostly single plants in pots (up to containers)	• Plant growth: plants are grown in growth chambers, greenhouse • Environment: well controlled environment • Capacity: 100-1000s plans per experiment • Experimental duration: days to weeks	Quantitative plant measurement using: Carrier system for plants PtS • Conveyor belts • Robotic systems Carrier system for sensors StP • Gantry systems Sensor: • Optical sensors (visible light (RGB), near infrared, multispectral, hyperspectral, thermal, fluorescence imaging, tomographic systems)	Often only small to medium sized plants possible	• WIWAM xy; • GrowScreen-Rhizo-1 • Phenotron Lemnatec
Intensive Field	Canopies in plots	• Plant growth: micro-plots usually in natural soil • Environment: Environmental monitoring (Semi-controlled conditions) • Capacity: 100-1000s plots per experiment • Experimental duration: Usually a growth season	Quantitative plant measurements: Carrier systems for sensors: • Fixed (e.g. towers, gantry systems) • Ground based mobile (e.g. phenomobiles) • Airborne mobile (e.g. drones) Sensors: • Optical sensors (visible light (RGB), near infrared, multispectral, hyperspectral, thermal, fluorescence imaging.)	Heterogeneous environment	• Breed-FACE • Pheno3C • Field Scanalyzer Rothamsted
Lean Field	Canopies in plots	• Plant growth: micro-plots usually in natural soil • Environment: Basic environmental monitoring • Capacity: 100s – 1000s of microplots multiple field sites • Experimental duration: Usually one or more growth seasons	Quantitative plant measurements StP Sensor carrier: • Ground based mobile (e.g. phenomobiles) • Airborne mobile (e.g. drones) Sensors: • Optical sensors (visible light (RGB), near infrared, multispectral, hyperspectral, thermal, fluorescence imaging.)	Heterogeneous environment	• Projects with networks of field trials (DROPS)
Modelling	Plants *in silico* (= virtual representation of phenotypes under different conditions)	• Virtual tools: - integrated in phenotyping pipelines (experimental design, image analysis) - interfacing with phenotyping pipelines (develop, validate in silico models)	In silico plant modelling • Process based models (e.g. simulate growth) • Functional structural plant models (e.g. plant architecture and physiology) • Statistical models • Models in phenotyping pipelines (e.g. trait quantification, dissection)	Need for experimental data	• Collection of models: https://www.quantitative-plant.org/
Phenotyping Information Systems	Data (all kinds of images and outcome measures)	• methods and interfaces for interoperability of datasets • manage, share, reuse and visualize heterogeneous, high-throughput plant phenotyping data stemming from different sources	Local information systems • Data base as part of a physical infrastructure for storage, visualisation date etc. Data integration and reusability • Standardisation (data models, metadata)	Implementation of standards	• Data standards: MIAPPE (https://www.miappe.org/) BrAPI (https://brapi.org/)

Source: based on Morisse et al. (2018) for updated list of examples from EU Infrastructure for plant phenotyping – EMPHASIS - see https://emphasis.plant-phenotyping.eu/phenotyping-landscape/infrastructure-map

FIGURE 4.3: Overview on phenotyping technologies

There is a necessity to keep a good portion of scientific expertise within the RI as it needs maintenance and building up expertise for smooth workflows (European Plant Phenotyping Network, 2020; Knowles, Mateen, & Yehudi, 2021). Long-term human resource development must be applied to scientists in the same way it is usually done in private businesses. While high-throughput phenotyping will need the same level of highly trained scientific staff, it will ease the shortage in person-power of technical staff for phenotyping large amounts of plant materials. Yet, technical knowledge on installations being run needs to be maintained over time as well and allowed to evolve further.

Individual scientists need to find an environment fostering collaboration across a wide range of disciplines and working cultures, who need to find new and transdisciplinary ways of solving research challenges (R. R. Brown, Deletic, & Wong, 2015). Transdisciplinary research needs disciplinary specialists and generalists who function as boundary actors between these different disciplines (Poteete, Janssen, & Ostrom, 2011). Hiring and maintaining the right set of people will determine success or failure of these infrastructures. Evaluation criteria for scientists working in research facilities connected to infrastructures determine the type of individuals joining different projects (R. R. Brown et al., 2015), research venues, and the success in using technological installations over longer time horizons. From climate change science we can learn that team science is key in solving complex challenges at hand and one can safely assume that sustainable agriculture is similar (Cundill, Currie-Alder, & Leone, 2019; Ledford, 2015). Likewise, integration of social sciences is vital for tackling research challenges such as social system feedbacks (Viseu, 2015). For example, having a few social scientists that "speak plant" may help elicit unknown areas of knowledge between what breeders have been selecting for with "breeders eye" (Timmermann, 2009) – i.e. implicit knowledge on how breeding input traits translate into farm output traits in plants – and what pre-breeding scientists can see with their new sensors for enhanced vision. Such insights have potential to improve the effectiveness in implementing new breeding strategies, farming practices complementing newly bred plants, and extension services.

On an organizational level, polycentric governance of plant breeding requires RIs to build cooperative relationships amongst different actor groups to ensure effective research towards reaching mission goals (Lubell & Morrison, 2021). Scientists need to co-produce with farmers, breeders, agri-business, and citizens what sustainable traits in crops are and how they manifest in the food and fiber supply chain. Note though that each of these groups needs separate consideration in transdisciplinary approaches (Max-Neef, 2005). Integrating non-scientific actor groups early on spells-out issues usually leading to unforeseen transition risks and lack of adoption (Mazzucato, 2019). An example is the considerable societal resistance in Europe towards GMs and their ban from most agricultural use thereafter (Directive 2001/18/EC). Incorporating a dialogue with stakeholders and the public may lower transition risks and can be used as an opportunity for collective learning and diffusing innovations in public interest. Using and including governmental organizations already in place, such as agricultural extension services should be tried early on in development and testing processes, as it provides a notion of feasibility of traits in farm management practices.

How private businesses are integrated into a phenotyping network providing public services for research will greatly influence the effectiveness of delivering research insights. 'Toxic actors' can have detrimental effects on whole research venues and hamper their effectiveness in delivering research outcomes (Lubell & Morrison, 2021). Including private actors may enhance testing capacities and promote insights if data is shared in a FAIR manner and symbiotic relationships are fostered (Mazzucato, 2015b). Public value creation must be in focus of those taking care of research contracts over new projects for effective long-term risk and reward sharing (Mazzucato, 2015b). Risk and reward sharing needs to be implemented such that they maintain an open innovation culture, which reinvests into further research.

Overall, the success of RIs will depend on how well its staff strategizes over knowledge, relationships, and decisions for implementation towards mission goals (Lubell & Morrison, 2021).

4.6 Conclusions

Mission-oriented governance for research is supposed to be implemented for plant breeding research to fulfill the SDGs and facilitate green growth. Improving crops through plant breeding will be vital for reaching the SDGs associated with agriculture. Crop breeding research shall bring about varieties enabling the necessary transformations to agricultural systems. High throughput technologies for phenotyping are meant to accelerate the plant breeding process and enhance breeders' vision of breeding materials, leveraging innovation pathways. Yet, against the backdrop of complex agricultural systems and polycentric research venues, and agricultural governance, the question remains how to reach these ambitious goals.

We propose a governance heuristic illustrating how mission-oriented governance can work for plant breeding research. We show the current state-of-the-art of phenotyping technologies and draw, based on historic examples from plant breeding, implications for their introduction to individual breeding programs and RIs.

Our core result is that plant breeding is not only about the interaction of genetics (G), environment (E), and farm management practices (M), but that activities at collective level (S) are crucial for the sustainability performance at lower levels of the system. Hence, we propose GxExMxS as a guiding rule of thumb for future governance of plant breeding. This heuristic needs to be interpreted in specific context of application, e.g. when a funder wants to decide if a research project for plant breeding may be justified they may ask how novel plant traits lead to results on a higher level in the social-ecological system.

Additionally, we want to caution that novel phenotyping technologies alone will not bring about sustainable agricultural systems. Integrating robotics, sensors, and information systems meaningfully is necessary to elevate mental models of breeders, scientists, and other actors contributing to crop breeding. This implies a high heterogeneity in potential adoption of these technologies in breeding programs. Concurrently, RIs need to care how they institutionally navigate their role as facilitator and promoter of research to reach mission goals.

4.7 Bibliography

Acquaah, G. (2007). *Principles of plant genetics and breeding*. Malden, MA, USA: Blackwell Publishing.

Alston, J. M., & Pardey, P. G. (1996). *Making science pay: The economics of agricultural r&d policy*. Washington, DC: AEI Press.

Aragona, F. B., & Orr, B. (2011). Agricultural intensification, monocultures, and economic failure: The case of onion production in the tipajara watershed on the eastern slope of the bolivian andes. *Journal of Sustainable Agriculture*, *35*(5), 467-492. doi: 10.1080/10440046.2011.579832

Araus, J. L., & Cairns, J. E. (2014). Field high-throughput phenotyping: the new crop breeding frontier. *Trends in Plant Science*, *19*(1), 52-61. Retrieved from `https://www.sciencedirect.com/science/article/pii/S1360138513001994` doi: https://doi.org/10.1016/j.tplants.2013.09.008

Bätzing, W. (2020). *Das landleben*. München: C.H.Beck.

Becker, H. (2011). *Pflanzenzüchtung*. UTB.

Brandl, B. (2018). *Wissenschaft, technologieentwicklung und die spielarten des kapitalismus: Analyse der entwicklung von saatgut in usa und deutschland*. Springer. doi: 10.1007/978-3-658-18923-5

Brandl, B., & Glenna, L. (2017). Intellectual property and agricultural science and innovation in germany and the united states. *Science, technology & human values*, *42*(4), 622–656.

Brandl, B., Paula, K., & Gill, B. (2014). Spielarten des wissenskapitalismus - die kommodifizierung von saatgut in den usa und in deutschland. *Leviathan*, *42*(4), 539–572. doi: 10.5771/0340-0425-2014-4-539

Brito, I., Carvalho, M., & Goss, M. J. (2021). Managing the functional diversity of arbuscular mycorrhizal fungi for the sustainable intensification of crop production. *PLANTS, PEOPLE, PLANET*, *3*(5), 491-505. Retrieved from `https://nph.onlinelibrary.wiley.com/doi/abs/10.1002/ppp3.10212` doi: https://doi.org/10.1002/ppp3.10212

Brown, R. R., Deletic, A., & Wong, T. H. (2015). Interdisciplinarity: how to catalyse collaboration. *Nature News*, *525*(7569), 315. doi: 10.1038/525315a

Brown, T. A., Jones, M. K., Powell, W., & Allaby, R. G. (2009). The complex origins of domesticated crops in the fertile crescent. *Trends in Ecology Evolution*, *24*(2), 103-109. Retrieved from https://www.sciencedirect.com/science/article/pii/S0169534708003479 doi: https://doi.org/10.1016/j.tree.2008.09.008

Burud, I., Lange, G., Lillemo, M., Bleken, E., Grimstad, L., & From, P. J. (2017). Exploring robots and uavs as phenotyping tools in plant breeding. *IFAC PapersOnLine*, *50*(1), 11479–11484.

Carroll, S. P., Jørgensen, P. S., Kinnison, M. T., Bergstrom, C. T., Denison, R. F., Gluckman, P., . . . Tabashnik, B. E. (2014). Applying evolutionary biology to address global challenges. *Science*, *346*(6207), 1245993. Retrieved from https://www.science.org/doi/abs/10.1126/science.1245993 doi: 10.1126/science.1245993

Champeil, A., Doré, T., & Fourbet, J. (2004). Fusarium head blight: epidemiological origin of the effects of cultural practices on head blight attacks and the production of mycotoxins by fusarium in wheat grains. *Plant Science*, *166*(6), 1389-1415. Retrieved from https://www.sciencedirect.com/science/article/pii/S016894520400072X doi: https://doi.org/10.1016/j.plantsci.2004.02.004

Chapman, S., Merz, T., Chan, A., Jackway, P., Hrabar, S., Dreccer, M., . . . Jimenez-Berni, J. (2014). Pheno-copter: A low-altitude, autonomous remote-sensing robotic helicopter for high-throughput field-based phenotyping. *Agronomy*, *4*(2), 279–301. Retrieved from https://www.mdpi.com/2073-4395/4/2/279 doi: 10.3390/agronomy4020279

Cooper, M., Messina, C. D., Podlich, D., Totir, L. R., Baumgarten, A., Hausmann, N. J., . . . Graham, G. (2014). Predicting the future of plant breeding: complementing empirical evaluation with genetic prediction. *Crop and Pasture Science*, *65*(4), 311–336. Retrieved from https://www.publish.csiro.au/cp/cp14007 doi: 10.1071/CP14007

Cundill, G., Currie-Alder, B., & Leone, M. (2019). The future is collaborative. *Nature Climate Chnage*, *9*, 343–347.

Day-Rubenstein, K. A., Heisey, P. W., Shoemaker, R. A., Sullivan, J., & Frisvold, G. B. (2005). Crop genetic resources: An economic appraisal. (1476-2016-121016), 47. Retrieved from `http://ageconsearch.umn.edu/record/59388` doi: 10.22004/ag.econ.59388

Deconinck, K. (2020). Concentration in seed and biotech markets: Extent, causes, and impacts. *Annual Review of Resource Economics*, *12*(1), 129–147. doi: 10.1146/annurev-resource-102319-100751

Denison, R. (2012). *Darwinian agriculture: How understanding evolution can improve agriculture*. Princeton: Princeton University Press.

Denison, R. F., Kiers, E. T., & West, S. A. (2003). Darwinian agriculture: when can humans find solutions beyond the reach of natural selection? *The Quarterly Review of Biology*, *78*(2), 145–168. doi: 10.1086/374951

DG Research and Innovation. (2020a, 09). *100 climate-neutral cities by 2030 - by and for the citizens - report of the mission board for climate-neutral and smart cities* (Tech. Rep.). Mission Board for climate neutral and smart cities. doi: https://doi.org/10.2777/46063

DG Research and Innovation. (2020b, 09). *Caring for soil is caring for life: Ensure 75 of soils are healthy by 2030 for food, people, nature and climate - report of the mission board for soil health and food* (Tech. Rep.). Mission Board for Soil health and food. doi: https://doi.org/10.2777/821504

DG Research and Innovation. (2020c, 09). *Proposed mission: Conquering cancer, mission possible* (Tech. Rep.). Mission Board on on Cancer. doi: https://doi.org/10.2777/045403

Eathington, S. R., Crosbie, T. M., Edwards, M. D., Reiter, R. S., & Bull, J. K. (2007). Molecular markers in a commercial breeding program. *Crop Science*, *47*(3), 154–163. doi: 10.2135/cropsci2007.04.0015IPBS

Ersoz, E. S., Martin, N. F., & Stapleton, A. E. (2020). On to the next chapter for crop breeding: Convergence with data science. *Crop Science*, *60*(2), 639-655. Retrieved from `https://acsess.onlinelibrary.wiley.com/doi/abs/10.1002/csc2.20054` doi: https://doi.org/10.1002/csc2.20054

ESFRI. (2021, 03). *Making science happen: A new ambition for research infrastructures in the european research area: Esfri white paper 2020* (Tech. Rep.).

European Strategy Forum on Research Infrastructures.

European Plant Phenotyping Network. (2020). *Eppn2020_start.* Jülich, Germany. Retrieved 04.06.2021, from https://eppn2020.plant-phenotyping.eu/

European Strategy Forum on Research Infrastructures. (2016). Strategy report on research infrastructures: Roadmap 2016. Retrieved 03.06.2021, from http://www.esfri.eu/roadmap-2016

European Strategy Forum on Research Infrastructures. (2021). *Strategy report on research infrastructures: Roadmap 2021 public guide*. Brussels.

FAO. (2018). *The 10 elements of agroecology: guiding the transition to sustainable food and agricultural systems* (Tech. Rep.). Retrieved from http://www.fao.org/3/i9037en/i9037en.pdf

Fiorani, F., Rascher, U., Jahnke, S., & Schurr, U. (2012). Imaging plants dynamics in heterogenic environments. *Current Opinion in Biotechnology*, *23*(2), 227-235. Retrieved from https://www.sciencedirect.com/science/article/pii/S0958166911007531 (Food biotechnology - Plant biotechnology) doi: https://doi.org/10.1016/j.copbio.2011.12.010

Fiorani, F., & Schurr, U. (2013). Future scenarios for plant phenotyping. *Annual review of plant biology*, *64*, 267–291. doi: 10.1146/annurev-arplant-050312-120137

Forschungszentrum Jülich, Institute for Plant Sciences. (2021). *Emphasis.* Jülich, Germany. Retrieved 01.07.2021, from https://emphasis.plant-phenotyping.eu/

Galitz, W. O. (2007). *The essential guide to user interface design: an introduction to gui design principles and techniques*. John Wiley & Sons.

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

Gibson, M. (1974). *Violation of fallow and engineered disaster in mesopotamian civilization* (No. 25). University of Arizona Press.

Grahmann, K., Reckling, M., Hernandez-Ochoa, I., & Ewert, F. (2021). An agricultural diversification trial by patchy field arrangements at the landscape level: The landscape living lab “patchcrop”. *Aspects of Applied Biology*, *146*, 385–391. Retrieved from https://www.aab.org.uk/aspects/aspect-146-intercropping-for-sustainability/

Grassini, P., van Bussel, L. G., van Wart, J., Wolf, J., Claessens, L., Yang, H., . . . Cassman, K. G. (2015). How good is good enough? data requirements for reliable crop yield simulations and yield-gap analysis. *Field Crops Research*, *177*, 49–63. doi: 10.1016/j.fcr.2015.03.004

Hannan, T. H., & McDowell, J. M. (1990). The impact of technology adoption on market structure. *Review of Economics and Statistics*, *72*(1), 164–168.

Harwood, J. (2015). Did mendelism transform plant breeding? genetic theory and breeding practice, 1900–1945. In *New perspectives on the history of life sciences and agriculture* (pp. 345–370). Springer, Cham. Retrieved from https://link.springer.com/chapter/10.1007/978-3-319-12185-7_17 doi: 10.1007/978-3-319-12185-7{\textunderscore}17

Henrich, J., & McElreath, R. (2003). The evolution of cultural evolution. *Evolutionary Anthropology: Issues, News, and Reviews*, *12*(3), 123–135.

Jacobsen, T., & Adams, R. M. (1958). Salt and silt in ancient mesopotamian agriculture. *Science*, *128*(3334), 1251–1258. Retrieved from http://www.jstor.org/stable/1754565

Kebeish, R., Niessen, M., Thiruveedhi, K., Bari, R., Hirsch, H.-J., Rosenkranz, R., . . . Peterhänsel, C. (2007). Chloroplastic photorespiratory bypass increases photosynthesis and biomass production in arabidopsis thaliana. *Nature biotechnology*, *25*(5), 593–599.

Kieras, D. E., & Bovair, S. (1984). The role of a mental model in learning to operate a device. *Cognitive Science*, *8*(3), 255-273. Retrieved from https://www.sciencedirect.com/science/article/pii/S0364021384800038 doi: https://doi.org/10.1016/S0364-0213(84)80003-8

Kishore, G. M., Padgette, S. R., & Fraley, R. T. (1992). History of herbicide-tolerant crops, methods of development and current state of the art: Emphasis on glyphosate tolerance. *Weed Technology*, *6*(3), 626–634. Retrieved from http://www.jstor.org/stable/3987224

Kloppenburg, J. R. (2004). *First the seed: The political economy of plant biotechnology, 1492-2000* (2nd ed. ed.). Madison, Wis: University of Wisconsin Press.

Knowles, R., Mateen, B. A., & Yehudi, Y. (2021). We need to talk about the lack of investment in digital research infrastructure. *Nature Computational Science*, *1*(3), 169–171. Retrieved from `https://doi.org/10.1038/s43588-021-00048-5` doi: 10.1038/s43588-021-00048-5

Kumar, J., Pratap, A., & Kumar, S. (2015). *Phenomics in crop plants: Trends, options and limitations*. New Delhi: Springer India. doi: 10.1007/978-81-322-2226-2

Kuriakose, S. V., Pushker, R., & Hyde, E. M. (2020). Data-driven decisions for accelerated plant breeding. In S. S. Gosal & S. H. Wani (Eds.), *Accelerated plant breeding, volume 1: Cereal crops* (pp. 89–119). Cham: Springer International Publishing.

Laidig, F., Piepho, H.-P., Rentel, D., Drobek, T., Meyer, U., & Huesken, A. (2017). Breeding progress, environmental variation and correlation of winter wheat yield and quality traits in german official variety trials and on-farm during 1983-2014. *TAG. Theoretical and applied genetics. Theoretische und angewandte Genetik*, *130*(1), 223–245. doi: 10.1007/s00122-016-2810-3

Ledford, H. (2015). Team science. *Nature*, *525*, 308–311. Retrieved from `http://nspire.nwciowa.edu/wp-content/uploads/2019/05/interdisciplinarity.pdf`

Lubell, M., & Morrison, T. H. (2021). Institutional navigation for polycentric sustainability governance. *Nature Sustainability*, 1–8. Retrieved from `https://www.nature.com/articles/s41893-021-00707-5` doi: 10.1038/s41893-021-00707-5

Maisels, C. K. (1993). *The emergence of civilization: From hunting and gathering to agriculture, cities, and the state of the near east* (1st ed.). Routledge. doi: https://doi.org/10.4324/9780203450642

Massonnet, C., Vile, D., Fabre, J., Hannah, M. A., Caldana, C., Lisec, J., ... Granier, C. (2010). Probing the reproducibility of leaf growth and molecular phenotypes: a comparison of three arabidopsis accessions cultivated in ten laboratories. *Plant Physiology*, *152*(4), 2142–2157. Retrieved from http://www.plantphysiol.org/content/152/4/2142.short doi: 10.1104/pp.109.148338

Max-Neef, M. A. (2005). Foundations of transdisciplinarity. *Ecological Economics*, *53*(1), 5-16. Retrieved from https://www.sciencedirect.com/science/article/pii/S0921800905000273 doi: https://doi.org/10.1016/j.ecolecon.2005.01.014

Mazzucato, M. (2013). *The entrepreneurial state: Debunking public vs. private myths in risk and innovation*. London, United-Kingdom: Anthem Press.

Mazzucato, M. (2015a). *Building the entrepreneurial state: A new framework for envisioning and evaluating a mission-oriented public sector: Working paper no. 824*. doi: 10.2139/ssrn.2544707

Mazzucato, M. (2015b). *Entrepreneurial state: Debunking public vs. private sector myths*. Perseus Book LLC (Ingram). Retrieved from https://books.google.de/books?id=Wro1DgAAQBAJ

Mazzucato, M. (2016). From market fixing to market-creating: a new framework for innovation policy. *Industry and Innovation*, *23*(2), 140–156. doi: 10.1080/13662716.2016.1146124

Mazzucato, M. (2018, 02). *Mission-oriented research & innovation in the european union: A problem-solving approach to fuel innovation-led growth* (Tech. Rep.). European Commission Directorate-General for Research and Innovation. doi: https://doi.org/10.2777/360325

Mazzucato, M. (2019, 06). *Governing missions: Governing missions in the european union* (Tech. Rep.). European Commission Directorate-General for Research and Innovation. doi: https://doi.org/10.2777/014023

Mazzucato, M., & Li, H. L. (2021). A market shaping approach for the biopharmaceutical industry: Governing innovation towards the public interest. *The Journal of law, medicine & ethics : a journal of the American Society of Law, Medicine & Ethics*, *49*(1), 39–49. doi: 10.1017/jme.2021.8

Mazzucato, M., & McPherson, M. (2019). *What the green revolution can learn from the it revolution: A green enterpreneurial state (policy brief 08)*. Retrieved from https://www.ucl.ac.uk/bartlett/public-purpose/sites/public-purpose/files/

final_iipp_policybrief_green_entreprenurial.pdf

McGinnis, M. D., & Ostrom, E. (2014). Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society*, *19*(2). Retrieved from http://www.jstor.org/stable/26269580

Mendel, G. (1866). Versuche über pflanzen-hybriden. verhandlungen des naturforschenden vereines in brünn 4: 3-47. In *Classic papers in genetics.* Prentice-Hall.

Minervini, M., Scharr, H., & Tsaftaris, S. A. (2015). Image analysis: The new bottleneck in plant phenotyping [applications corner]. *IEEE Signal Processing Magazine*, *32*(4), 126-131. doi: 10.1109/MSP.2015.2405111

Moore, G. (2015). Strategic pre-breeding for wheat improvement. *Nature Plants*, *1*(15018). Retrieved from https://www.nature.com/articles/nplants201518 doi: 10.1038/nplants.2015.18

Nagel, K. A., Bonnett, D., Furbank, R., Walter, A., Schurr, U., & Watt, M. (2015). Simultaneous effects of leaf irradiance and soil moisture on growth and root system architecture of novel wheat genotypes: implications for phenotyping. *Journal of experimental botany*, *66*(18), 5441–5452. doi: 10.1093/jxb/erv290

Nagel, K. A., Putz, A., Gilmer, F., Heinz, K., Fischbach, A., Pfeifer, J., . . . others (2012). Growscreen-rhizo is a novel phenotyping robot enabling simultaneous measurements of root and shoot growth for plants grown in soil-filled rhizotrons. *Functional Plant Biology*, *39*(11), 891–904.

Nesme, T., Metson, G. S., & Bennett, E. M. (2018). Global phosphorus flows through agricultural trade. *Global Environmental Change*, *50*, 133-141. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959378017310026 doi: https://doi.org/10.1016/j.gloenvcha.2018.04.004

Ober, E. S., Alahmad, S., Cockram, J., Forestan, C., Hickey, L. T., Kant, J., . . . others (2021). Wheat root systems as a breeding target for climate resilience. *Theoretical and Applied Genetics*, 1–18.

Olmstead, A., & Rhode, P. (2002). *The red queen and the hard reds: Productivity growth in american wheat, 1800-1940.* Cambridge, MA: National Bureau of Economic Research. doi: 10.3386/w8863

Olmstead, A. L., & Rhode, P. W. (2008). *Creating abundance: Biological innovation and american agricultural development, 1700–1960*. New York, USA: Cambridge University Press. Retrieved from https://www.cambridge.org/core/journals/journal-of-economic-history/article/creating-abundance-biological-innovation-and-american-agricultural-development-17001960-by-olmsteadalan-l-and-rhodepaul-w-new-york-cambridge-university-press-2008-pp-xii-467-8000-cloth-2399-paper/ee59df4d7b4796b44f7391162a636de8

Ostrom, E. (2006). *Understanding institutional diversity*. Princeton, NJ: Princeton University Press.

Pardey, P. G., Alston, J. M., & Ruttan, V. W. (2010). The economics of innovation and technical change in agriculture. In B. H. Hall & N. Rosenberg (Eds.), *Handbook of the economics of innovation* (pp. 939–984). Amsterdam: North Holland. doi: 10.1016/s0169-7218(10)02006-x

Pieruschka, R., & Schurr, U. (2019). Plant phenotyping: Past, present, and future. *Plant Phenomics*, 1–6. doi: 10.1155/2019/7507131

Pingali, P. L. (2012). Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences*, *109*(31), 12302–12308. Retrieved from https://www.pnas.org/content/109/31/12302 doi: 10.1073/pnas.0912953109

Poorter, H., B Hler, J., van Dusschoten, D., Climent, J., & Postma, J. A. (2012). Pot size matters: a meta-analysis of the effects of rooting volume on plant growth. *Functional Plant Biology*, *39*(11), 839–850. Retrieved from http://www.publish.csiro.au/fp/fp12049 doi: 10.1071/FP12049

Poteete, A. R., Janssen, M. A., & Ostrom, E. (2011). Working together: Collective action, the commons, and multiple methods in practice. *Journal of Artificial Societies and Social Simulation*, *14*(3), 2. Retrieved from https://hal.archives-ouvertes.fr/hal-02595370/

Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science*, *362*(6417), 1–7. doi: 10.1126/science.aav0294

Purugganan, M. D., & Fuller, D. Q. (2009). The nature of selection during plant domestication. *Nature*, *457*(7231), 843–848. Retrieved from https://

doi.org/10.1038/nature07895 doi: 10.1038/nature07895

Qaim, M. (2020). Role of new plant breeding technologies for food security and sustainable agricultural development. *Applied Economic Perspectives and Policy*, *42*(2), 129–150. doi: 10.1002/aepp.13044

Ranjekar, P. K., Patankar, A., Gupta, V., Bhatnagar, R., Bentur, J., & Kumar, P. A. (2003). Genetic engineering of crop plants for insect resistance. *Current Science*, *84*(3), 321–329. Retrieved from http://www.jstor.org/stable/24107416

Raworth, K. (2017). *Doughnut economics: Seven ways to think like a 21st-century economist.* White River Junction, Vermont: Chelsea Green Publishing.

Reece, J. D. (2007). What enables innovation in the private sector? lessons from the development of salt-tolerant hybrid rice. *Journal of International Development*, *19*(6), 853–863. doi: 10.1002/jid.1397

Reece, J. D., & Haribabu, E. (2007). Genes to feed the world: The weakest link? *Food Policy*, *32*(4), 459–479. doi: 10.1016/j.foodpol.2006.10.003

Reynolds, D., Baret, F., Welcker, C., Bostrom, A., Ball, J., Cellini, F., ... Tardieu, F. (2019). What is cost-efficient phenotyping? optimizing costs for different scenarios. *Plant Science*, *282*, 14-22. Retrieved from https://www.sciencedirect.com/science/article/pii/S0168945217311482 (The 4th International Plant Phenotyping Symposium) doi: https://doi.org/10.1016/j.plantsci.2018.06.015

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. Stuart III, Lambin, E., ... Foley, J. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2).

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., ... Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, *46*(1), 4–17. Retrieved from https://link.springer.com/article/10.1007%252fs13280-016-0793-6 doi: 10.1007/s13280-016-0793-6

Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six transformations to achieve the sustainable development goals. *Nature Sustainability*, *2*(9), 805–814. Retrieved from https://www.nature.com/articles/s41893-019-0352-9 doi: 10.1038/s41893-019-0352-9

Schipanski, M. E., & Bennett, E. M. (2012). The influence of agricultural trade and livestock production on the global phosphorus cycle. *Ecosystems*, *15*(2), 256–268. doi: 10.1007/s10021-011-9507-x

Schmenner, R. W., & Tatikonda, M. V. (2005). Manufacturing process flexibility revisited. *International Journal of Operations & Production Management*.

Shkolnykova, M. (2020). *Firm innovation and industry transformation. the case of german biotechnology*. Universität Bremen. Retrieved from https://media.suub.uni-bremen.de/handle/elib/4526 doi: 10.26092/elib/323

Smith, O., Nicholson, W. V., Kistler, L., Mace, E., Clapham, A., Rose, P., ... others (2019). A domestication history of dynamic adaptation and genomic deterioration in sorghum. *Nature plants*, *5*(4), 369–379. Retrieved from https://doi.org/10.1038/s41477-019-0397-9 doi: 10.1038/s41477-019-0397-9

Søgaard Jørgensen, P., Folke, C., Henriksson, P. J., Malmros, K., Troell, M., & Zorzet, A. (2020). Coevolutionary governance of antibiotic and pesticide resistance. *Trends in Ecology Evolution*, *35*(6), 484-494. Retrieved from https://www.sciencedirect.com/science/article/pii/S0169534720300136 doi: https://doi.org/10.1016/j.tree.2020.01.011

Tabashnik, B. E. (2008). Delaying insect resistance to transgenic crops. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(49), 19029–19030. Retrieved from http://www.jstor.org/stable/25465590

Timmermann, M. (2009). *Der züchterblick: Erfahrung, wissen und entscheidung in der getreidezüchtung*. Aachen, Germany.

Tsaftaris, S. A., Minervini, M., & Scharr, H. (2016). Machine learning for plant phenotyping needs image processing. *Trends in Plant Science*, *21*(12), 989-991. Retrieved from https://www.sciencedirect.com/science/article/pii/S1360138516301613 doi: https://doi.org/10.1016/j.tplants.2016.10.002

van de Wouw, M., van Hintum, T., Kik, C., van Treuren, R., & Visser, B. (2010).

Genetic diversity trends in twentieth century crop cultivars: a meta analysis. *TAG. Theoretical and applied genetics*, *120*(6), 1241–1252. doi: 10.1007/s00122-009-1252-6

van Dijk, A. D. J., Kootstra, G., Kruijer, W., & de Ridder, D. (2021). Machine learning in plant science and plant breeding. *iScience*, *24*(1), 101890. Retrieved from https://www.sciencedirect.com/science/article/pii/S2589004220310877 doi: https://doi.org/10.1016/j.isci.2020.101890

van de Wiel, C. C., van der Linden, C. G., & Scholten, O. E. (2016). Improving phosphorus use efficiency in agriculture: opportunities for breeding. *Euphytica*, *207*(1), 1–22.

Varah, A., Ahodo, K., Coutts, S. R., Hicks, H. L., Comont, D., Crook, L., . . . others (2020). The costs of human-induced evolution in an agricultural system. *Nature sustainability*, *3*(1), 63–71. Retrieved from https://doi.org/10.1038/s41893-019-0450-8 doi: 10.1038/s41893-019-0450-8

Vijayarangan, S., Sodhi, P., Kini, P., Bourne, J., Du, S., Sun, H., . . . Wettergreen, D. (2018). High-throughput robotic phenotyping of energy sorghum crops. In *Field and service robotics* (pp. 99–113). Springer, Cham. Retrieved from https://link.springer.com/chapter/10.1007/978-3-319-67361-5_7 doi: 10.1007/978-3-319-67361-5{\textunderscore}7

Viseu, A. (2015). Integration of social science into research is crucial. *Nature News*, *525*(7569), 291. doi: 10.1038/525291a

Watt, M., Fiorani, F., Usadel, B., Rascher, U., Muller, O., & Schurr, U. (2020). Phenotyping: New windows into the plant for breeders. *Annual review of plant biology*, *71*, 689–712. doi: 10.1146/annurev-arplant-042916-041124

Watt, M., Silk, W. K., & Passioura, J. B. (2006, 03). Rates of Root and Organism Growth, Soil Conditions, and Temporal and Spatial Development of the Rhizosphere. *Annals of Botany*, *97*(5), 839-855. Retrieved from https://doi.org/10.1093/aob/mcl028 doi: 10.1093/aob/mcl028

Wieland, T. (2004). *" wir beherrschen den pflanzlichen organismus besser,...": Wissenschaftliche pflanzenzüchtung in deutschland, 1889-1945*. München, Deutschland.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J. J., Appleton, G., Axton, M., Baak, A., . . . Mons, B. (2016). The fair guiding principles for scientific data management and stewardship. *Scientific Data*, *3*(1). Retrieved from https://www.nature.com/articles/sdata201618 doi: 10.1038/sdata.2016.18

Xu, Y., & Crouch, J. H. (2008). Marker-assisted selection in plant breeding: From publications to practice. *Crop Science*, *48*(2), 391-407. Retrieved from https://acsess.onlinelibrary.wiley.com/doi/abs/10.2135/cropsci2007.04.0191 doi: https://doi.org/10.2135/cropsci2007.04.0191

Yang, W., Feng, H., Zhang, X., Zhang, J., Doonan, J. H., Batchelor, W. D., . . . Yan, J. (2020). Crop phenomics and high-throughput phenotyping: Past decades, current challenges, and future perspectives. *Molecular Plant*, *13*(2), 187-214. Retrieved from https://www.sciencedirect.com/science/article/pii/S1674205220300083 doi: https://doi.org/10.1016/j.molp.2020.01.008

Chapter 5

Seed multiplication decisions in response to pest epidemics†

Abstract:
In crop production social response to abiotic and biotic shocks is needed to fight climate change. Seed multipliers provide varieties resistant to pest epidemics (a biotic shock) to farmers for mitigating changes in their environment. We present evidence of how sensitive seed multiplication portfolios are to pest infestations. We ask whether the seed system is capable of responding quickly through adjusted decision making in seed multiplication areas of resistant varieties. We hypothesize that the supply of resistant seed varieties will increase when there are sudden shocks in pest infestations. A data set that combines Bavarian wheat variety trials with multiplication areas from 2000 - 2019 is used to analyze the effect of pest infestations on the varieties multiplied in seed. We use regression analysis (difference-in-differences) to estimate changes in wheat multiplication area in response to pest shocks. Our main findings are: First, we cannot find evidence that supports a reaction to pest epidemics. Pest shocks bring about little or no additional multiplication area in pest resistant varieties. Second, we find that varieties recommended for specific pedo-climatic zones correlate with increasing multiplication area when pest shocks occur. We conjecture from our findings that the amount of information provided from the trials may not suffice for preparing adequate social responses in breeding directionality, seed provisioning, crop, variety or management choices to climate change mitigation by the seed system.

Keywords: *seed multiplication, biotic shock, pest epidemics, seed system, climate change mitigation, wheat, social factors, plant breeding*

Significance Statement:
Accelerating the adoption and diffusion of new varieties is decisive for agricultural productivity, resilience and adaptive capacity of agricultural systems in response to ecological and social challenges like climate change or social conflicts. Our findings provide evidence for policy makers and the breeding community to improve the governance of seed supply chains. There is a need to maintain and potentially enhance

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†This chapter is a working paper intended for publication in a journal where sections are usually arranged in order introduction, results, discussion, and methods. Further due to the page limit imposed, readers should peel their eyes for appendices corresponding with sections which demand more detail.

region level information provisioning on variety resistances, localized governmental recommendations to plant breeders, seed multipliers, retailers and farmers.

5.1 Introduction

The most hard felt effects of climate change will come to us through the increase in extreme weather events (Coumou & Rahmstorf, 2012) influencing crop production negatively (Asseng et al., 2015; Porter & Semenov, 2005; Trnka et al., 2014) . We usually think of these events as temperature peaks causing droughts (Asseng et al., 2015; Tack, Barkley, & Nalley, 2015) or heavy rains causing floods (Gudmundsson et al., 2021; Markonis, Papalexiou, Martinkova, & Hanel, 2019). As abiotic conditions are changing, however, biotic factors adapt likewise and pose threats to crop production (Blois, Zarnetske, Fitzpatrick, & Finnegan, 2013; Juroszek & Von Tiedemann, 2013). Countering pests and abiotic stressors at the same time demand a smooth and effective diffusion of crop improvements (Feder, Just, & Zilberman, 1985). Diffusing improved varieties to farmers has been a long standing problem (Heisey & Brennan, 1991). Usually farmers choices have been problematized as incomplete, instead of asking whether they are offered appropriate choices in varieties by seed multipliers and retailers (Barkley & Porter, 1996; Dahl, Wilson, & Wilson, 1999; Heisey & Brennan, 1991). If seed multiplication is lacking ability to react to pest shocks[1], as our results suggest, then the resilience of agricultural systems is hampered as adaptive strategies of farmers and extension services will not work out and climate change mitigation policies will be useless having detrimental effects for food security (Acevedo et al., 2018; Challinor et al., 2014).

We present evidence on the biotic effects on climate change together with evidence on the supply side of adapted seed by looking at how sensitive seed multiplication portfolios are to pest incidences. Our underlying notion is that the supply of resistant seed varieties will increase when there are sudden shocks in pest infestations. To make sure these incidences have considerable relevance for profitability, we are focusing on serious pest shocks and not just minor incidences to see if these surprising

[1]pest shocks or epidemic shocks or pest epidemic will be used interchangeably in the following for fungal disease epidemics.

extreme events cause increased supply in resistant varieties by seed multipliers. We use regression analysis (difference-in-differences) to estimate changes in wheat multiplication area as a function of pest incidence, pedo-climatic zone and social variables like institutional information.

Our main findings are: First, an effect of biotic shocks on multiplication area of disease resistant varieties shows only a statistically significant reaction in brown rust. While, diseases like septoria leaf blotch or fusarium show little or perverse effects, as the shocks bring about less or no additional multiplication area in pest resistant varieties. Second, we have empirical evidence that governmental organization and public information spread have a considerable effect on seed multiplication portfolios.

We focus on wheat as it is a major staple crop in Europe, North Africa and West Asia and takes the most crop acreage globally (Acevedo et al., 2018) and supplies 20 percent of global calories(Shiferaw et al., 2013). It is also the most affected by climate change (Mäkinen et al., 2018). Within Europe, Germany has the top five highest comparative yields per hectare, while being amongst the top producers in (FAO, 2021). The state of Bavaria has the most heterogeneous in terms of its pedo-climatic zones within Germany (Jahn, Wagner, & Sellmann, 2012) and produces the largest portion of cereals production area and amongst the highest per hectare yields in Germany (with 69 $dtha^{-1}$ five year average *Ernteberícht 2021 – Mengen und Preise* (2021)).

With climate change showing increasing frequencies of extreme events, we need to ask ourselves, how well we can react to biotic shocks, like pest epidemics, which are going to change in coming years (Juroszek & Von Tiedemann, 2013). If frequency and size of epidemics amplifies over years, then immediate and potent reactions through variety adoption in fields are a must for farming to counter pests of the future. We ask ourselves how we currently react to sudden pest shocks. We want to see how well our social response, the immediate adjustment in multiplication area, works. Having a well established research and extension system, it is public information on varieties which farmers in Bavaria trust and rely on (Gerullis, Heckelei, & Rasch, 2021). This attribute makes up a major contribution of this paper. We show that governance recommendation of varieties has a considerable effect on multiplication portfolios. This also exemplifies social system response to extreme environmental events as we are going to expect with climate change in the future.

Our empirical approach combines variety-specific data from Bavaria's wheat state trials for variety performance and combines them with state seed multiplication areas. We use regressions with a difference-in-difference approach to find out whether there are any reactions to suddenly occurring pest shocks. In the quasi experimental set-up of a difference-in-difference (DiD) design we want to see whether resistant varieties, our treated group, are given an increase in multiplication areas compared to non-resistant varieties, our control group, when faced with pest shock. We ran separate regressions for each wheat disease to see how pest shocks impacted multiplication area of the varieties with resistances against these. Pest shocks are all those occasions when we encounter grave infestations of a wheat disease at a testing site, where pest infestations are so grave that spraying would not make a difference in outcomes anymore relative to the level of resistance present in the average set of varieties in this year. Yet, we ran into a staggered adoption problem (Goodman-Bacon, 2021) of having multiple shocks in consecutive years in some diseases and used an approach described by Callaway and Sant'Anna (2021) to come up with unbiased results for our DiD selecting shock years with clean leap and lag years.

This permits two major advantages for estimating the relationship between location-specific pest incidence and variety multiplication: 1) we are able to identify graduated pest shock measures based on trial data, which are comparable over the years as they can be established as relative measures 2) allows us to control better for staggered adoption in estimations 3) describe how to integrate variety trial data into a social-ecological regression analysis.

5.2 Results

5.2.1 A lack in reaction to biotic shocks

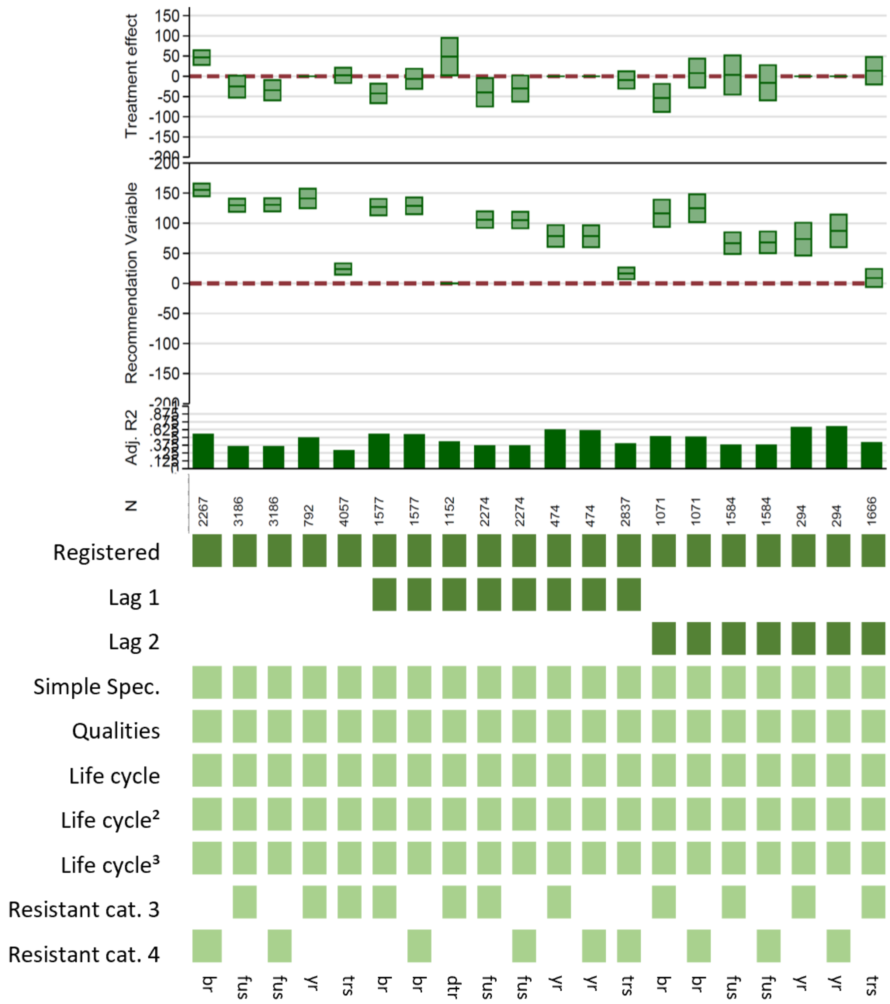
Our regression results for the treatment effects in different diseases show, with one exception in our model specification for brown rust, negative estimates or estimates which are not statistically significantly different from zero, see the corresponding 95 percent confidence intervals of the treatment effects in figure 5.1. This means that there is no immediate response towards an increase in resistant varieties in multiplication area portfolios due to pest shocks. We wanted to see whether pest shocks lead to a c.p. increase in multiplication area of resistant varieties and hypothesized that there is no effect ($H_0 : \beta_1 = 0$) we cannot find support to refute this hypothesis. The results show that there are no or perverse effects in action for fusarium, yellow rust, and septoria leaf spot, see figure 5.1. Looking at the corresponding regressions using multiplication area lagged by one or two years as outcome variable, we see the very similar null or perverse results, see figure 5.1.

We observe only one exception of a a positive estimate: Brown rust pest shocks have a statistically significant effect increasing registered multiplication area on average by 46 ha c.p. in the same year after a pest shock event. The effect size of this equates to roughly 0.01 percent of the entire Bavarian multiplication area on average.

We checked our results for robustness of the treatment variable by using two different thresholds for a variety as being considered resistant and observe the same null or negative results for different measures of resistance, see bottom of figure 5.1. Where resistance category 3 is a more conservative measure for observing a varieties resistance to a pest (Moll, Flath, & Sellmann, 2009).

Corresponding with our geographic focus to Bavaria Pallauf (2018) conducted interviews with seed multipliers. They gave the impression, that their focus in allocating multiplication area lies on the life cycle of a variety. Depending on how a variety performed the previous year wheat seed multipliers said they continue with a similar amount of multiplication area increasing and decreasing multiplication area according to a varieties age. In the same interviews, however, multipliers mentioned that the potential for a multiplication area overall was oriented on governmental recommendations of varieties for specific regions and that any decision for multiplication area was taking place within the respective baking quality category. We included baking qualities and life cycle stage (also squared and cubed) as controls into our models.

FIGURE 5.1: Results from DiD regressions of different diseases



Treatment estimates for regressions per disease with all controls - including multiplication area lagged by one and two years. Only models which passed parallel trends testing are displayed. Green box plots indicate 95 percent confidence intervals around the mean estimate for each specification. 'Recommendation variable' is the estimates for the dummy if a variety is being recommended in a region. Bar plots directly below represent the adjusted R^2 and indicate a goodness of fit of the model. N marks the number of observation for each specification. Light and dark boxes below graphs provide information about the characteristics of each econometric model shown above. Outcome variables are marked in dark green. The 'simple specification' follows the underlying specification of equation 5.4.2 without controls. Qualities are dummies for German baking qualities E, B and C (A is reference category). 'Resistant cat.' denotes 3 or 4 as threshold in infestation resistance to a disease, see appendix E. Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot.

5.2.2 Role of governance in tackling biotic shocks

With our results we see how governmental recommendation for varieties has a considerable effect on multiplication areas during years of pest shocks. The estimates show on average a c.p. increase of 156 ha for brown rust, 139 ha for fusarium, and 141 ha for yellow rust, see figure 5.1, all recommendations estimates are statistically significantly different from zero with a 95 percent confidence interval. Even in tan spot where the effect is only 24 ha in size it is still statistically significantly different from zero. If we look at lagged years of multiplication area as outcomes, the estimates decrease in size and become less sharp, see wider confidence intervals in figure 5.1, and statistically significantly different from zero.

These results tell us that public information signalling works with high efficacy in Bavaria during the observed years with high infestations. Bavarian variety trial conductors hold meetings with representatives of multiplication organizations and report their results early after the growing season is over. Our results indicate that this has a considerable effect on multiplication area portfolios. As the effects carry on into lagged years - even if decreasing - recommending varieties increases multiplication area also in years following after a shock.

5.3 Discussion

Climate change has major impacts on the productivity of food, fiber, and fuels (Stocker, 2014). The impacts it will have on wheat are severe and relevant due to its importance for food security in interaction with being amongst the most climate change affected crops (Ortiz-Bobea, Ault, Carrillo, Chambers, & Lobell, 2021; Tack et al., 2015). From an agronomic perspective the effects of pests are relevant, as extreme weather events and climatic changes will bring about new diseases, which have not been observed yet. Effective mitigation of pest shocks can only be taking place if there is an appropriate reaction in variety choice (Feder et al., 1985), crop management adaptions and infrastructure (Tack et al., 2015). It is not only important to understand and forecast merely the biological and ecological processes, but also to react appropriately and in line with our common goals. As societies we want to govern human processes such that we meet the needs of all (Raworth, 2017) while staying in the limits of our planetary boundaries (Rockström et al., 2009).

The insights of this paper provide an argumentation for governing officials to spend more effort and budget on generating information influencing multiplication and farm variety choice, and better support extension services towards multiplication agents.

5.3.1 Information provisioning to tackle climate change

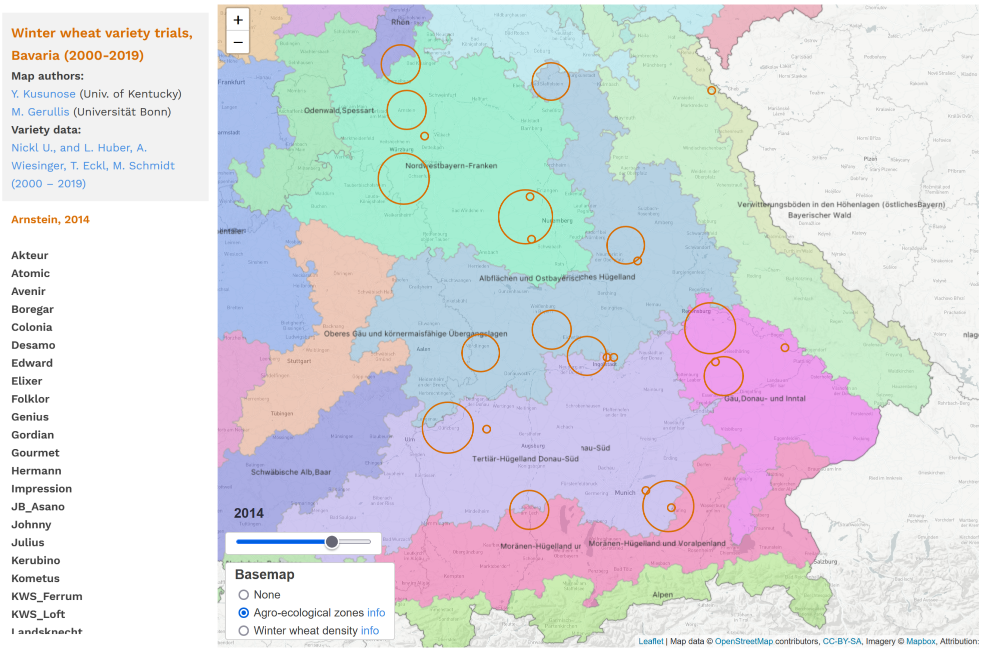
In Bavaria the governmental trial conductors publish the results from their trials open access to farmers on the internet. The open access information of variety performances contains recommendations of varieties for the different regions where variety trial testing sites are. They are distributed over the pedo-climatic zones as the interactive figure Kusonose and Gerullis (2021, available under https://ykusunose.github.io/bavaria$_{w}heat_{t}rials_{2}/)$ shows, see figures 5.2 and figure 5.3.

Having trial sites spread out over the different regions and in proximity to those areas with the most intensive cropping density for winter wheat, ensures that farmers have reliable information as to how varieties perform in their region under current pedo-climatic conditions (Gerullis et al., 2021). It is a way of giving farmers a benchmark of their own cropping performance relative to other varieties. Farmers are more likely to switch and try out better performing varieties thereof. Overall this indirectly ensures that regional yield levels can be maintained.

Trial conductors will recommend specific varieties which perform well in terms of yield, plant health and quality classes within specific pedo-climatic zones, based on their yearly trial results. Variety trial conductors organize expert meetings where recommendations will be discussed with multiplication organizations. These influence which varieties multipliers will multiply (Pallauf, 2018). Multipliers expect a higher demand of a variety if it is recommended for a region (Pallauf, 2018).

From our presented results we can see that governance mechanisms, as the targeted communication with multiplication organizations, can have a high efficacy for determining variety multiplication portfolios. While the pest shocks themselves

FIGURE 5.2: Screenshot of interactive map of study area with pedo-climatic zones and trial sites showing 2014



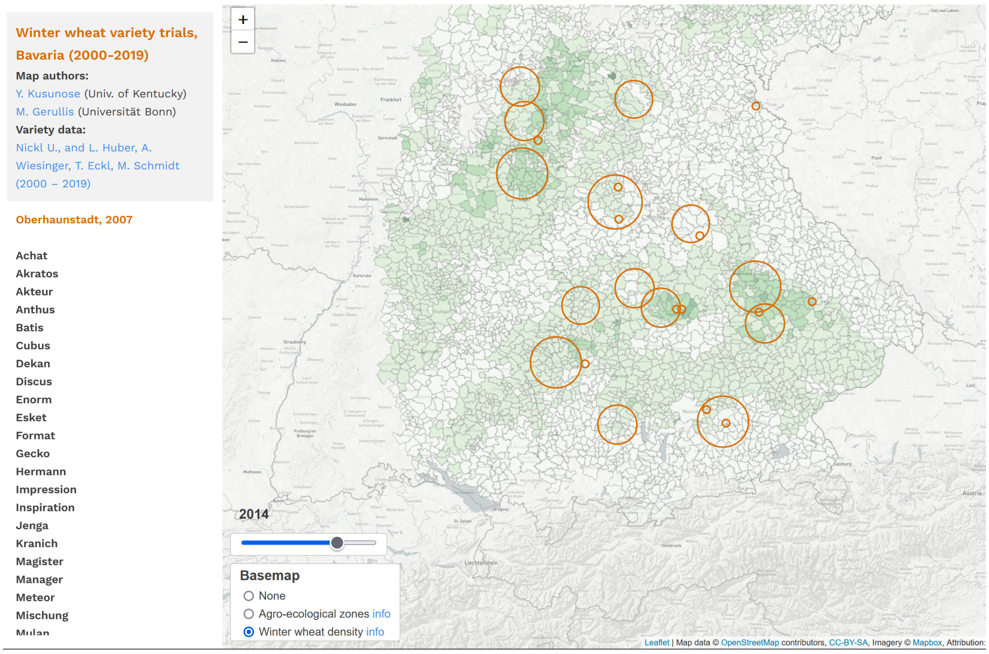
In the interactive version of this figure from Kusonose and Gerullis (2021, available under https://ykusunose.github.io/bavaria$_{w}heat_{t}rials_{2}/$) we can see for the years of observation, where testing sites are. Bubbles show the size of the trials in each location. Varieties planted will popup on the left when hovering over a site with the mouse.

did not have any impact increasing disease resistant varieties, recommendations did have an effect on the multiplication areas. Hence, it is important to make sure that governmental recommendations are based on reliable and trustworthy data for it to remain effective (Gerullis et al., 2021).

Yet, reliability is in question for some of the regions within Bavaria, where variety trials have been reduced in size or whole sites have been cut completely. We can see from the interactive map, see figure 5.3, areas with high cropping density have bigger trial sizes.

We observe that Eastern Bavarian regions have been cut from trials completely. Testing sites there did not lie in the areas with high production intensity for wheat. Further figure 5.3 shows decreasing numbers of varieties being tested at places with low cropping density over the years, (also compare figure 5.4). This means we

FIGURE 5.3: Screenshot of interactive map of study area with cropping density and trial sites showing 2014



In the interactive version of this figure from Kusonose and Gerullis (2021, available under https://ykusunose.github.io/bavaria$_{w}heat_{t}rials_{2}/)$ we can see for the years of observation, the distribution of wheat cropping density and trial sites. Bubbles show the size of the trials in each location. Varieties planted will popup on the left when hovering over a site with the mouse.

have reliable information available to those farmers in the most cropping intense regions, but not for those with more marginal conditions. Farmers will have harder time reaching a conclusion what varieties may work best under their conditions if they want to crop wheat in a marginal region. Likewise, multipliers will have lower incentives to multiply varieties, which have a smaller market and marginal regions may be left astray due to this lack of economic incentives.

These results have implications for mitigating climate change: Reliable, scientifically valid and applicable information on variety performance needs to be produced continuously by public agencies. These agencies conduct the trials and pass these information on to farmers and multipliers ensuring targeted and immediate reactions to changing cropping conditions. Governments maintained efforts and budgets for all pedo-climatic zones in terms of conducting trials is important. This means running trials at decent sizes with proper sets of available varieties, enough repetitions, different treatments and controls for management practices and enough person power to score disease pressures multiple times throughout a growing season to gain reliable data points and insights (Becker, 2011; Miedaner, 2011).

Cutting down on information generation in marginal regions may have another potentially fatal, yet, not apparent consequence: Marginal regions have the potential to bring about valuable results for the expertise of 1) governmental researchers and practitioners, like trial conductors, in public organizations and 2) breeders, who create new varieties. As growing conditions in these regions are usually harsher (droughts, less sufficient soils etc.) they might better depict the growing conditions under climate change than the places where we currently focus variety trial efforts. There is a high potential that we could learn a lot from continued efforts of setting up variety trials specifically for climate change mitigation efforts. Trying out different mitigation strategies in terms of variety specific cropping. Also targeting breeding efforts in marginal regions means that we diversify our efforts in plant breeding for more challenging abiotic and biotic conditions. This may ensure that the governmental system providing the public information to multipliers, is not myopic. Researchers, practitioners in extension, and breeders need to see the challenges ahead of us and adapt their work accordingly. Likewise the system of information provisioning needs to be altered accordingly by public organizations when faced with the need to have varieties available, which are capable of performing well even under more extreme conditions.

5.3.2 Relevance of pedo-climatic zones for seed production and cropping

Multiplication agents take the prevalence of different crop diseases in different regions into account when planning their multiplication areas (Pallauf, 2018; Thiel, 2014). Hence, some variation in our outcomes may be explained due to some varieties fitting specific pedo-climatic zones and the yield effects derived from this fit to an ecological niche.

Judging the economic relevance of diseases for crop production is tricky. Experimental plant research has the tendency to over report potential yield losses, due to using especially susceptible varieties in their experimental designs as control group (Duveiller, Singh, & Nicol, 2007). This will lead to higher estimates than what actual yields with newly adopted varieties in farmers fields encounter in terms of actual yields losses (Duveiller et al., 2007). This not withstanding some diseases have due to some biological mechanisms potential for complete yield loss, like black rust (Singh et al., 2008). Plant breeding - bringing about the resistant varieties - is done in anticipation of countering pests (Zetzsche, Friedt, & Ordon, 2020). Yet, extreme biotic shocks are what drives the calculation of their yield losses (see Jahn et al. (2012) for Germany and Bockus et al. (2001) for Kansas for the positively skewed distributions) and hence they are of economic interest to us, as we expect these extreme events to occur with even higher frequencies in the future (Juroszek & Von Tiedemann, 2013).

The yield losses from pathogens for Germany from 2000 - 2008 are reported by Jahn et al. (2012) and vary between 1,9 $dtha^{-1}$ on average for fusarium and 10,2 $dtha^{-1}$ on average for septoria leaf spot. The first classifies as rather low loss, while the latter can would mean a 13 percent decrease for average yields (*Ernteberícht 2021 – Mengen und Preise*, 2021; Jahn et al., 2012). Brown rust likewise categorizes as a pathogen with sizeable losses of up to 10 percent in actual yield losses (*Ernteberícht 2021 – Mengen und Preise*, 2021; Jahn et al., 2012) and we see this reflected in our results, where multiplication area for brown rust resistant varieties increases on average during a shock year.

Tan spot has a low effect on in incurred yield losses in Germany of 0.6 dt ha^{-1} (Jahn et al., 2012), and hence is very likely to not be considered a major problem by farmers and multipliers. Fusarium with a 2,5 percent in losses per ha may seem like there is no damage done, but while the percentage of actual yield loss seems low, fusarium will produce toxins in wheat, that make is useless to the farmer if it appears in high concentrations. Deoxynivalenol (DON) is a mycotoxin and occurs due to moisture at the time of flowering and the timing of rainfall (Figueroa, Hammond-Kosack, & Solomon, 2018). High DON levels do not negatively impact the yield in itself, they deem whole batches of grain useless due to their toxicity. Fusarium has a high frequency in pedo-climatic zone 115 the Southern Danube and Tertiary Hills region see for example figure E.18. Yet, most of these pest occurrences are not salvageable for our empirical approach, as they are all in consecutive years and do not dispose singular shock events.

The Gaeu, Danube and Inn Valley region yields for shows a wide range of disease pressures, see figures E.25 , E.26, and E.27. However, brown rust spikes have an unremitting pattern over the last 20 years and seem to put together most of those observation generating the effect in brown rust, that we observe on a state level.

In the Southern Danube and Tertiary Hills regions septoria leaf spot is the predominant problem with medium to high infestations in consecutive years. There are no conclusive results to be gained from for this region for our analysis, as one can see from figures E.16, E.17, E.18, E.19, E.20, E.21, E.22, E.23, and E.24.

The predominant effects of sparingly observable brown rust epidemic strikes in the region of the Swabian Jura and Eastern Bavarian Foothills (Pedo-climatic zone 114) contribute to the brown rust results, which we observe on state level, see figures E.10, E.11, E.12, E.13, and E.14. Powdery mildew is a problem for the the Swabian Jura and Eastern Bavarian Foothills, however, does not pass our criteria for parallel trends testing for the region, see figures E.10, E.11, E.12, E.13, and E.14.

Northwestern Bavaria does not yield any conclusive results for its wide range of disease pressures and consecutive infestations of pest shocks, see figures E.3, E.4, E.5, E.6, E.7, E.8, and E.9.

The pedo-climatic zone of Eastern Bavaria (112) and Swabian Jura does not have enough observations in general, due to the mentioned cut in trials.

Overall those small effects we see in our state wide results stem from individual regions with the area where pedo-climatic conditions stipulate the needs of taking care of specific diseases for farmers and multipliers.

5.4 Methods

5.4.1 Data

The data include wheat multiplication area on state level matched by variety with performance outcomes of variety trials. In the sample are 25 testing sites over the years 2001 - 2019 where between 6 to 66 varieties are being tested per testing site; totalling 209 varieties see figure 5.4. This makes this sample high resolution for a geographically heterogeneous state with 70 tsd sq kms compared to for example Tack et al. (2015) with 200 tsd sq km in Kansas and only 11 locations, allowing us to go deeper into the issue of response diversity towards climate change as examined e.g. by Kahiluoto et al. (2019).

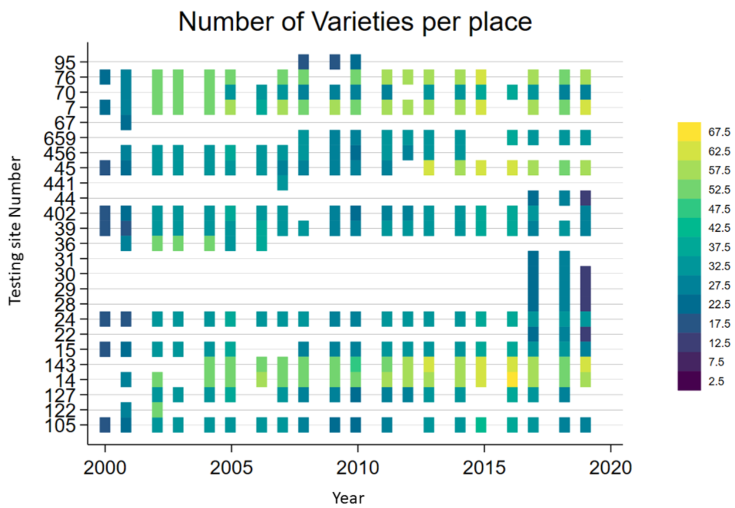


FIGURE 5.4: Number of varieties over the years plotted by testing sites

Field testing data were taken from the Bavarian State Research Center for Agriculture. Disease grades are scored throughout the growing season for each plot. Variant plots are 2m x 0.5m in each place. The original data set contained over 56 000 variant plot observations of 206 varieties from 2000 to 2019. There were usually between 3 to 4 repetitions per variety and treatment or control group, to avoid attrition due to random damage and we worked with averages over the repetitions to account for this. Variety trials usually do include not only those varieties which are on the market already, but also those used to assess the performance of lines which are submitted for admission in the national variety lists. From the initial observations 10 000 had to be dropped, as they were lines still under assessment for market admission whose performance could not influence the choice of multiplication area.

Details on how scores are produced for pests can be found in appendix E. Pest shocks were constructed based on the notion that crop and pest build a host-pathogen relationship, which produce a realized ecological niche, as termed by Hutchinson (1957). Modern approaches on crop-pathogen population dynamics support this, see the review of Brown, Tellier, et al. (2011).

Shock events make up between 4 to 19 percent of the observations depending on the disease. While pest occurrences show reoccurring patterns of the same diseases on the same sites, there is substantial variation between the testing sites, see figures in appendix section E.28 E.26 to E.13. Pest shocks were constructed as relative measures, where we constructed shocks with the underlying intuition that on average resistance of varieties in a place were breached such that spraying did not help their score performance anymore relative to the performance of the non-sprayed plants (see appendix E.28 for details on how we constructed epidemic shocks). We developed this approach based on scoring practices by applied plant breeders. Plant breeders construct their nurseries such that they can evaluate pest shocks measures relative to the intensity of occurrence in the most susceptible variety over the years (Miedaner, 2011, corresponding field notes from Gerullis et al. (2021)). As such we implemented a measure relative to the most susceptible variety on a yearly basis, which exploited the original agronomic design of experiments.

Multiplication area data were provided by the Federal Plant Variety Office, and measured in ha. They are aggregated on state level, so we took only those for data from the state of Bavaria, to only compare matching geographic areas and pedo-climatic zones. We used the multiplication area for of the certified seed only as they represent the area of varieties which can actually be sold to German farmers.

Variety trial data is in general non-orthogonal data, where each year varieties will enter and leave testing as their agronomic performance stays or decreases over the years. The underlying data generation mechanism attributed to variety multiplication area follows a technology adoption life-cycle (Barrett & Just, 2021), where multiplication area varies between 3 and 985 ha.

5.4.2 Regression Models

Our empirical logic follows a difference-in-difference approach, see Angrist and Pischke (2009) and Angrist and Krueger (1999) for methodological introduction. We want to know what the average treatment effect of pest epidemic shocks on multiplication area portfolios is for different diseases. We want to see if the amount multiplication area attributed to resistant varieties increases or decreases after a shock. We have the $H_0 : \beta_3 = 0$ for our treatment effects.

Resistant varieties are our so-called treated group. We exploit variety-level variation of multiplication area and variety trial testing data to do so. Yet, the fact that pest shocks can occur in consecutive years pose a staggered adoption problem, described by Goodman-Bacon (2021). We would compare already shocked places and their varieties to those who are being shocked anew, which can distort the calculated treatment effect (Goodman-Bacon, 2021). Our empirical approach leans on the underlying notion of Callaway and Sant'Anna (2021), who take care of the staggered adoption problem for their framework of estimating DiD average treatment effects under multiple time periods, variation in treatment timing and where parallel trends assumptions holds potentially only after including observed covariates. As all of these conditions are the case for us, we have followed their notion of identifying disaggregated causal parameters, which they call group-time average treatment effects. A "group" at time t is identified by the time period when the units are first treated. In the canonical DiD setup with two periods and two groups (called $2by2$) these parameters reduce to the average treatment effect (Angrist & Pischke, 2009). We follow their notion of identifying times and places with shock hitting a trial site with clean (no shock) lag and lead years and then aggregating these groups of $2by2s$ for estimating the average effect of a shock in a disease. Our general estimation of the treatment effect for each disease is the following regression setup:

$$ma_{it} = \beta_0 + \beta_1 Resistance_i + \beta_2 Aftershock_t \\ + \beta_3 Resistance_i \times Aftershock_t + \\ + \beta_4 Control_{1i} + \cdots + \beta_n Control_{ni} + \varepsilon_{it} \quad (5.1)$$

In this equation $Resistance_i$ denotes a dummy which turns equal to 1 if the variety is a resistant variety, and 0 if not. $Aftershock_t$ denotes a dummy for the year after a shock, that will turn 1 for all observations in a place that experienced a pest shock and for those observations 0 in the same place which do not have the resistance trait to serve as counterfactual group. Hence, t does not denote a year in its classical sense, like "2016", but merely represents the year after a shock, $T1$, see figure E.2 in the appendix for further explanations, for a specific testing site. As a shock will take place only in a specific location at a point in time, we rearranged shocks from multiple time-places into before and after treatment years.

Following the rational of Callaway and Sant'Anna (2021) we went about this in multi-step process: First, we identified the time-location combinations of pest shock occurrences. Second we threw all those observations out of our respective sample for each disease, where multiple shocks occurred in consecutive years to ensure that we had clean $2by2$ shock occurrences within the the data from the testing sites that we look at.

The coefficient β_3 denotes the change in multiplication area between a shock and its year for resistant varieties relative to the change in non-resistant varieties. A positive value of β_3 implies that a pest shock is associated with a relative increase in multiplication area for varieties with resistances. If the coefficient is zero then we do not have an association between the two, and we may say that multipliers do not adjust their behavior for more resistant varieties in reaction to a shock. If we encounter a negative coefficient in β_3 then we can interpret this as multipliers reacting perversely to the pest shock, by putting more susceptible varieties into the overall variety portfolio.

β_3 coefficient can be interpreted as the causal effect of pest shocks under the assumption that varieties with and without resistances were on parallel trends with respect to the unobserved determinants of multiplication area. To test this assumption, we conducted parallel trends tests, by estimating the same specification for the "lead" years - T_{-1} and T_0 see figure E.2 in the appendix -, where the $BeforeShock$ dummy turns 1, for observations from a place where shocks take place in the following year (T_0) and turns 0 for observations from a place where shocks take place in the year after the following year. Hence the analogous specification to conduct parallel trends testing is for each disease:

$$
\begin{aligned}
ma_{it} = \gamma_0 + \gamma_1 Resistance_i + \gamma_2 BeforeShock_t \\
+ \gamma_3 Resistance_i \times BeforeShock_t + \\
+ \gamma_4 Control_{1i} + \cdots + \gamma_n Control_{ni} + \varepsilon_{it} \quad (5.2)
\end{aligned}
$$

If our results were driven by nonparallel time trends, we would expect the lead coefficient in equation 5.4.2 to be significantly different from zero. Hence, for our analysis we considered only those results that were within the 95 percent confidence interval around zero for further consideration of results. Results from parallel trends testing can be found in appendix E.3. Overall, brown rust, fusarium, yellow rust and septoria leaf spot passed testing. The parallel trends testing eliminates specifications for further consideration of results, as one can see in appendix figures 5.5 , nearly half of the possible regression results do not suffice during parallel trends testing. However, as some of the results are very close to zero some diseases yield different results, when looking at whether we draw the thresh-hold for resistance at grade 3 or grade 4 (example: appendix figures E.3 for fusarium) and hence we have reported all treatment estimates in context of their specifications and $adjustedR^2$ in the appendix. 3 is the more conservative measure and but there is no clear tendency as some breeders will also take 4 as threshold, hence, we looked at both.

Patterns in parallel trends testing change after conditioning on observed covariates see appendix figures E.7, E.4, E.5, and E.6, reassuring us again in taking the approach suggeted by Callaway and Sant'Anna (2021), which show that results are valid nonetheless. The full specifications see figure 5.5 have the highest values for the $adjusted R^2$ compared to all other specification groups, hence we took these as main results.

For each disease we ran our model specification with different sets of controls to see which one had the best fit to the observed data. Controls were:

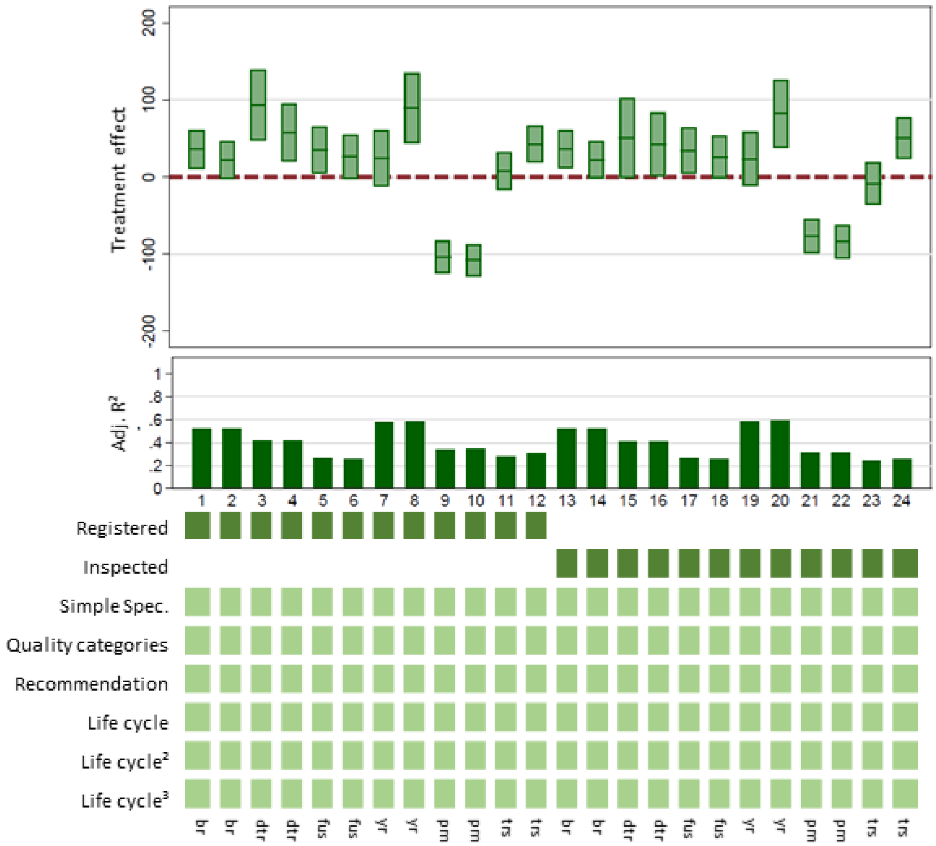
- Recommendation variable: A dummy for all varieties being recommended by trial conductors for different regions.
- Qualities: Dummies for different quality categories according to official quality classification of varieties (Nickl & Schmidt, n.d.)
- Life-cycle variables: Variables for the years since admission of a variety, in plain squared and cubed form to depict the adoption life-cycle of varieties.

5.4.3 Limitations

The main limitation is that we have not yet looked into whether we encounter an identification problem between the recommended varieties and the biotic shocks. If biotic shocks and recommended varieties are correlated then our empirical approach would produce biased results for the treatment effects. In general, however, this would mean that recommendations work as intended by the government. Meaning that the governmental recommendation of varieties for different regions, works well for biotic shocks. Farmers and multipliers would receive and be recommended those varieties which fit their pedo-climatic zones, especially after biotic shocks taking place.

An open question remains whether the control observations to our treated units should be weighted further. So far we have not done this, but deem this worthwhile trying in future to see whether results are going to be notably different in effect size or precision of effects.

A clear drawback on using the approach of (Callaway & Sant'Anna, 2021), is that the use of only clean lead and lag years around a treatment, can lead to too much



Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specifications follows the underlying specification of equation 5.4.2 just without control; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE 5.5: Results from parallel trends testing for full specification

attrition of data. So much data may be lost, that we loose validity compared to the overall process - as we can see in our yellow rust case, where we were left with not enough observations.

Inquiring more into the variation in organizational aspects of governance across different states strikes us as an interesting route for future research. Main limitation for this is the geographic scope of our study. Bavaria is a fairly big and heterogeneous state in Germany in terms of its pedo-climatic conditions, and testing sites are well spread across these. Yet, better insight would have been gained if data from other states would have been available as well, as this would have made it possible to see effects of different governance mechanisms.

5.5 Bibliography

Acevedo, M., Zurn, J. D., Molero, G., Singh, P., He, X., Aoun, M., ... others (2018). The role of wheat in global food security. In *Agricultural development and sustainable intensification* (pp. 81–110). Routledge.

Angrist, J. D., & Krueger, A. B. (1999). Empirical strategies in labor economics. In *Handbook of labor economics* (Vol. 3, pp. 1277–1366). Elsevier.

Angrist, J. D., & Pischke, J.-S. (2009). *Mostly harmless econometrics: An empiricist's companion*. Princeton university press.

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., ... others (2015). Rising temperatures reduce global wheat production. *Nature climate change*, *5*(2), 143–147.

Barkley, A. P., & Porter, L. L. (1996). The determinants of wheat variety selection in kansas, 1974 to 1993. *American Journal of Agricultural Economics*, *78*(1), 202–211.

Barrett, C. B., & Just, D. R. (2021). *Handbook of agricultural economics: Volume 5*. Elsevier.

Becker, H. (2011). *Pflanzenzüchtung*. UTB.

Blois, J. L., Zarnetske, P. L., Fitzpatrick, M. C., & Finnegan, S. (2013). Climate change and the past, present, and future of biotic interactions. *Science*, *341*(6145), 499–504.

Bockus, W. W., Appel, J. A., Bowden, R. L., Fritz, A. K., Gill, B. S., Martin, T. J., ... Eversmeyer, M. G. (2001). Success stories: Breeding for wheat disease resistance in kansas. *Plant Disease*, *85*(5), 453–461.

Brown, J. K., Tellier, A., et al. (2011). Plant-parasite coevolution: bridging the gap between genetics and ecology. *Annual review of phytopathology*, *49*(1), 345–367.

Callaway, B., & Sant'Anna, P. H. (2021). Difference-in-differences with multiple time periods. *Journal of Econometrics*, *225*(2), 200-230. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0304407620303948` (Themed Issue: Treatment Effect 1) doi: https://doi.org/10.1016/j.jeconom.2020.12.001

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S., Smith, D., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature climate change*, *4*(4), 287–291.

Coumou, D., & Rahmstorf, S. (2012). A decade of weather extremes. *Nature climate change*, *2*(7), 491–496.

Dahl, B. L., Wilson, W. W., & Wilson, W. W. (1999). Factors affecting spring wheat variety choices: Comparisons between canada and the united states. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *47*(3), 305–320.

Duveiller, E., Singh, R. P., & Nicol, J. M. (2007). The challenges of maintaining wheat productivity: pests, diseases, and potential epidemics. *Euphytica*, *157*(3), 417–430.

Erntebericht 2021 – mengen und preise. (2021). Bundesministerium für Ernährung und Landwirtschaft).

FAO. (2021). Faostat crop production statistics.
(data retrieved from FAOSTAT, `https://www.fao.org/faostat/en/#data/QCL` on July 12th 2022)

Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic development and cultural change*, *33*(2), 255–298.

Figueroa, M., Hammond-Kosack, K. E., & Solomon, P. S. (2018). A review of wheat diseases—a field perspective. *Molecular plant pathology*, *19*(6), 1523–1536.

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

Goodman-Bacon, A. (2021). Difference-in-differences with variation in treatment timing. *Journal of Econometrics*, *225*(2), 254–277.

Gudmundsson, L., Boulange, J., Do, H. X., Gosling, S. N., Grillakis, M. G., Koutroulis, A. G., ... others (2021). Globally observed trends in mean and extreme river flow attributed to climate change. *Science*, *371*(6534), 1159–1162.

Heisey, P. W., & Brennan, J. P. (1991). An analytical model of farmers' demand for replacement seed. *American Journal of Agricultural Economics*, *73*(4), 1044–1052.

Hutchinson, G. (1957). Population studies: animal ecology and demography: concluding remarks. cold spring harbor symp. *Quant. Biol.*, *22*, 425–427.

Jahn, M., Wagner, C., & Sellmann, J. (2012). Ertragsverluste durch wichtige pilzkrankheiten in winterweizen im zeitraum 2003 bis 2008–versuchsergebnisse aus 12 deutschen bundesländern. *Journal für Kulturpflanzen*, *64*(8), 273–285.

Juroszek, P., & Von Tiedemann, A. (2013). Climate change and potential future risks through wheat diseases: a review. *European Journal of Plant Pathology*, *136*(1), 21–33.

Kahiluoto, H., Kaseva, J., Balek, J., Olesen, J. E., Ruiz-Ramos, M., Gobin, A., ... others (2019). Decline in climate resilience of european wheat. *Proceedings of the National Academy of Sciences*, *116*(1), 123–128.

Markonis, Y., Papalexiou, S., Martinkova, M., & Hanel, M. (2019). Assessment of water cycle intensification over land using a multisource global gridded precipitation dataset. *Journal of Geophysical Research: Atmospheres*, *124*(21), 11175–11187.

Miedaner, T. (2011). *Resistenzgenetik und resistenzzüchtung*. DLG-Verlag Germany.

Moll, E., Flath, K., & Sellmann, J. (2009). Schätzen der befallsstärke-(k) ein problem. *Journal für Kulturpflanzen*, *61*(12), 440–442.

Mäkinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K., Nendel, C., ... Kahiluoto, H. (2018). Sensitivity of european wheat to extreme weather. *Field Crops Research*, *222*, 209-217. Retrieved from `https://www.sciencedirect.com/science/article/pii/S0378429017310572` doi: https://doi.org/10.1016/j.fcr.2017.11.008

Nickl, L. H. A. W. T. E., U., & Schmidt, M. (n.d.). Versuchsergebnisse aus bayern 2017 faktorieller sortenversuch winterweizen. *Landessortenversuch Winterweizen*.

Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G., & Lobell, D. B. (2021). Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change*, *11*(4), 306–312.

Pallauf, M. (2018). *Planning and decision-making by seed trading companies for* *winter wheat (triticum aestivum) multiplication: A mixed-methods analysis for bavaria* (Masterthesis).

Porter, J. R., & Semenov, M. A. (2005). Crop responses to climatic variation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *360*(1463), 2021–2035.

Raworth, K. (2017). *Doughnut economics: Seven ways to think like a 21st-century economist*. White River Junction, Vermont: Chelsea Green Publishing.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. Stuart III, Lambin, E., . . . Foley, J. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2).

Shiferaw, B., Smale, M., Braun, H.-J., Duveiller, E., Reynolds, M., & Muricho, G. (2013). Crops that feed the world 10. past successes and future challenges to the role played by wheat in global food security. *Food Security*, *5*(3), 291–317.

Singh, R. P., Hodson, D. P., Huerta-Espino, J., Jin, Y., Njau, P., Wanyera, R., . . . Ward, R. W. (2008). Will stem rust destroy the world's wheat crop? , *98*, 271-309. Retrieved from https://www.sciencedirect.com/science/article/pii/S0065211308002058 doi: https://doi.org/10.1016/S0065-2113(08)00205-8

Stocker, T. (2014). *Climate change 2013: the physical science basis: Working group i contribution to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge university press.

Tack, J., Barkley, A., & Nalley, L. L. (2015). Effect of warming temperatures on us wheat yields. *Proceedings of the National Academy of Sciences*, *112*(22), 6931–6936.

Thiel, W. (2014). *Praxishandbuch saatgutvermehrung* (W. Thiel, Ed.). Erling Verlag.

Trnka, M., Rötter, R. P., Ruiz-Ramos, M., Kersebaum, K. C., Olesen, J. E., Žalud, Z., & Semenov, M. A. (2014). Adverse weather conditions for european wheat production will become more frequent with climate change. *Nature Climate Change*, *4*(7), 637–643.

Zetzsche, H., Friedt, W., & Ordon, F. (2020). Breeding progress for pathogen resistance is a second major driver for yield increase in german winter wheat at contrasting n levels. *Scientific reports*, *10*(1), 1–17.

Appendix A

Second-tier SESF components for provisioning and appropriating genetic and varietal diversity

Appendix 1

Figure A1.1: Second-tier SESF components for provisioning and appropriating genetic diversity in German winter wheat

Pre-breeding system (PB-RS) †		Governmental resource system (G-RS) †			Breeding firms resource systems (BF-RS) †		Governance system (GS) †	
PB-RS1	Public and private seed sector	G-RS 1	Public sector		BF-RS1	Seed sector	GS1	Breeders rights
PB-RS2	No clear boundaries	G-RS 2	Clear boundaries		BF-RS2	Heterogenous by firm	GS2	Germany as part of EU
PB-RS3	Big	G-RS 3	Testing sites		BF-RS3†	Heterogenous size of nurseries	GS3	All plant breeders
PB-RS4	Nurseries and screening facilities	G-RS 4	Nurseries and facilities for evaluation of trials		BF-RS4†	Facilities for phenotypic and genotypic evaluation	GS4	Democratic
PB-RS5	-	G-RS 5	All Varieties on DVL	Lines in VCU testing	BF-RS5	Number of lines submitted for approval	GS5	Legislative branch of government (EU-level/National legislation); Lobbying organizations
PB-RS7	-	G-RS 7	-	-	BF-RS7	Fairly predictable	GS6	Operational-choice rules and collective-choice rules under constitutional-choice rules
PB-RS8	Medium	G-RS 8	Not existent	Not exsistent	BF-RS8	Medium	GS7	Private and common property side by side
PB-RS9	Globally spreadout	G-RS 9	-	6 trial sites over Germany	BF-RS9†	Heterogenous by firm locations in Germany and worldwide	GS8	Multiple norms and strategies within community

Pre-breeding Material (PB-RU) †		DVL Varieties (G-RU)	Approved (G-RUa) †	Pre-approved (G-RUb) †	Breeding Firms' Systems (BF-RU) †		Breeders (B-A) †	
PB-RU1	-	G-RU1	Mobile	Immobile with exceptions	BF-RU1	Immobile with exceptions	B-A1	19 winter wheat breeders
PB-RU2	-	G-RU2	Number of new varieties per year	Number of submitted lines per year	BF-RU2	Heterogenous per firm	B-A2†	Heterogenous depending on firm size
PB-RU3†	High	G-RU3†	Low - medium	High	BF-RU3†	High	B-A3	Experiences with own material and varieties important for usage
PB-RU4	Very high; invaluable	G-RU4	-	-	BF-RU4	Heterogenous per variety	B-A4	Heterogenous locations in Germany and worldwide
PB-RU5	Heterogenous	G-RU5	All varieties in DVL	Number of lines in VCU testing	BF-RU5	Heterogenous per firm	B-A5	Enterpreneurial
PB-RU6	Heterogenous	G-RU6†	Name of variety; DUS results	VCU testing results of lines submitted	BF-RU6	Labels applied within nursery	B-A6†	Partially very strong trust & reciprocity relationships
PB-RU7b	Programs in Germany & worldwide	G-RU7b	Spread over Germany	VCU testing sites in Germany	BF-RU7b†	Material within nurseries	B-A7	Heterogenous mental models per breeder determined by incomplete information
PB-RU7a	Since 1960's	G-RU7a	Number of varieties approved each year	Three years of VCU testing	BF-RU7a	Each year resown according to plan	B-A8	Very high resource dependent
							B-A9†	Hetergenous per firm

Action situations appropriation and provision of genetic diversity

Interactions (GD-I)		Outcomes (GD-O)	
GD-I1†	Levels of usage of material	GD-O1 †	Efficient use of genetic traits
GD-I2a†	Information sharing	GD-O2 †	Sustained German gene pool
GD-I2b†	Material sharing	GD-O3	-
GD-I2c†	Nursery space sharing		
GD-I5†	Investments in joined R&D projects		
GD-I7 / GD-I8 †	Networking - common activities in R&D projects		

Source: Own depiction of second-tier variables adopted from McGinnis and Ostrom (2014), with alternative variables for the governance system. As there are multiple resource systems with resource units and actor groups these variables are preceded by an abbreviation for the respective group. Individual variables not found relevant to the case are tagged with '-'. VCU denotes value of cultivation and use testing. DVL means the Descriptive Variety List. DUS denotes distinctiveness, use and stability testing. Relevant sources for the included variables were mainly interviews 1, 2, 3, 7, 8, 10, 12-15, 17-20, 22, 24-30, and 32; see list appendix 2 table 1. † marks those variables used in the main text.

Figure A1.2: Second-tier SESF components for provisioning varietal diversity in German winter wheat

	Governmental resource system (G-RS)			Breeding firms resource systems (BF-RS)		Multiplication system (M-RS)		Governance system (GS)
G-RS1	Public sector		BF-RS1	Seed sector	PB-RS1	Seed sector	GS1 †	Breeders rights and Seed regulations
G-RS2	Clear boundaries		BF-RS2	Heterogenous depending on firm	PB-RS2	Clear boundaries	GS2	Germany
G-RS3	Testing sites and respective sites for testing available		BF-RS3	Heterogenous size of nurseries	PB-RS3	Size of multiplier	GS3 †	All plant breeders and multiplication organisations, multiplying farmers and certification organisations for seed
G-RS4	Nurseries and facilities for evaluation of trials		BF-RS4	Heterogenous facilities for phenotypic and genotypic evaluation	PB-RS4	Fields multiplication	GS4	Democratic
G-RS5	All varieties on DVL	Lines in VCU testing	BF-RS5	Number of lines submitted for approval	PB-RS5	Propagation area for the crop	GS5	Legislative branch of government
G-RS7	Predictable variety performance		BF-RS7	Fairly predictable	PB-RS7	Heterogenous per variety	GS6	Operational-choice rules and constitutional-choice rules
G-RS8	-	-	BF-RS8	Minimal	PB-RS8	Medium	GS7 †	Private property system
G-RS9 †	State variety trials in different regions	6 trial sites over Germany	BF-RS9	Heterogenous locations in Germany and worldwide	PB-RS9	Hetergenous within regions	GS8	Multiple norms and strategies

	DVL Varieties (G-RU) Approved (G-RUa) †	Pre-approved (G-RUb) †		Breeding Firms' Systems (BF-RU)		Multiplied Material (M-RU)		Breeders (B-A)		Multipliers (M-A)
G-RU1	Mobile	-	BF-RU1	Mobile	M-RU1	Mobile	B-A1	19 Winter wheat breeders	M-A1	Oligopoly to polypoly
G-RU2	Number of new varieties per year	Number of submitted lines per year	BF-RU2	Heterogenous per firm	M-RU2 †	For winter wheat the multiplication factor is 1:40	B-A2	Heterogenous depending on firm size	M-A2	Heterogenous depending on firm size and type
G-RU3	-	-	BF-RU3	-	M-RU3	-	B-A3	Experiences with own material and varieties important for usage	M-A3	Experiences with kinds of varieties sold
G-RU4	Predictable if in state trials		BF-RU4	Heterogenous per variety	M-RU4	Heterogenous per variety	B-A4	-	M-A4	Located in different regions
G-RU5	All varieties in DVL	Number of lines in VCU testing	BF-RU5	Heterogenous per firm	M-RU5	Heterogenous per multiplier and region	B-A5	Entrepreneurial	M-A5	Entrepreneurial
G-RU6	Name of variety & DUS results	VCU testing results of lines submitted	BF-RU6	Variety names applied to lines	PB-RU6	Variety names; VCU qualitities	B-A6	-	M-A6	-
G-RU7b	-	VCU testing sites in Germany	BF-RU7b	-	M-RU7b	-	B-A7	Heterogenous mental models per breeder determined by incomplete information	M-A7	Mental models of SES and heuristics for devising multiplication areas
G-RU7a	Varieties approved each year	Three years of VCU testing	BF-RU7a	-	M-RU7a	Propagation each year	B-A8	High resource dependence	M-A8	High resource dependence
							B-A9	-	M-A9	-

Action situations for providing varietal diversity

Interactions (PV-I)		Outcomes (PV-O)	
PV-I1 †	Levels of usage of varieties in propagation	PV-O1 †	Supply of diverse varieties fitting farmers preferences
PV-I2a	Public provision of information on trial results	PV-O2 †	Ecological Performance – outcomes of VCU and FSV trials in different regarding yield and other qualities of a variety
PV-I3	Heuristic deliberation of multipliers	PV-O3	-
PV-I5 †	Investment in promising varieties		
PV-I10	Multipliers evaluate VCU and state trials results; are being quality checked		

Source: Own depiction of second-tier variables adopted from McGinnis and Ostrom (2014), with alternative variables for the governance system. As there are multiple resource systems with resource units and actor groups these variables are preceded by an abbreviation for the respective group. Individual variables not found relevant to the case are tagged with '-'. Relevant sources for the included variables were mainly interviews 1, 2, 3, 4, 6, 8, 9, 14, 21, 23, and 33; see list appendix 2 table 1. † marks those variables used in the main text.

	Farming system (F-RS)		Multiplication and retailing system (M-RS)		Governance system (GS)
F-RS1	Agricultural sector/ wheat cropping	M-RS1	Seed sector	GS1 †	Seed regulations
F-RS2	Per farm clear boundaries	M-RS2	Clear boundaries	GS2	Germany
F-RS3	Heterogenous per farm	M-RS3	Heterogenous	GS3 †	Multiplication organizations, multiplying farmers and certification organizations for seed, all agricultural retailers
F-RS4	Fields and grain storage facilities	M-RS4	Fields multiplication, storage facilities for seed	GS4	Democratic
F-RS5	Harvest per hectare	PB-RS5	Heterogenous per propagation area for the crop/variety	GS5	Legislative branch of government
F-RS7	Dependent on biotic and abiotic factors & variety	PB-RS7	Heterogenous per variety	GS6	Operational-choice rules and constitutional-choice rules
F-RS8	Usually available	PB-RS8	High	GS7 †	Private property system
F-RS9	Spread throughout Germany	PB-RS9	Heterogenous within regions	GS8	Multiple norms and strategies

	Seed (F-RU)		Multiplied material (M-RU)		Farmers (F-A)		Multipliers and retailers (M-A)
F-RU1	Mobile	M-RU1	Mobile	F-A1	Polypoly	M-A1	Oligopoly
F-RU2	1:40 reproduction coefficient	M-RU2	Heterogenous per variety	F-A2	Heterogenous depending on firm size	M-A2	Heterogenous depending on firm size and type
F-RU3	-	M-RU3	-	F-A3	Experiences with varieties	M-A3	-
F-RU4	Heterogenous per farm (EU avg 50€/ha)	M-RU4	Heterogenous per variety	F-A4	Spread over different regions with various density	M-A4	Located in different regions
F-RU5	-	M-RU5	Heterogenous per multiplier and region	F-A5	Entrepreneurial	M-A5	Entrepreneurial
F-RU6	Heterogenous attributes per variety and per field	M-RU6	Variety names; public trial results	F-A6	-	M-A6	-
F-RU7b	Varieties in farmers fields	M-RU7b	Multipliers fields within regions; local storage facilities of retailers	F-A7	Heterogenous mental models per farmers determined by different heuristics and social networks	M-A7	Mental models of SES and heuristics for devising multiplication areas
F-RU7a	Depending on crop rotation schemes	M-RU7a †	Each year propagation according to predicted demand	F-A8	High resource dependence	M-A8	High resource dependence
				F-A9	Heterogenous per farm	M-A9	-

Action situations for appropriating varietal diversity

	Interactions (AV-I)		Outcomes (AV-O)
AV-I1	Varieties being bought / farm-saved with license	AV-O1 †	Sustained farming with appropriate varieties; economic and social viability of farm
AV-I2 †	Information provided by federal/ state variety trials	AV-O2 †	Farmers find appropriate variety for their biotic and abiotic circumstances
AV-I3 †	Deliberation on future variety performance by farmers	AV-O3	Externalities - agricultural system in terms of soil qualities (N), biodiversity outcomes (affected by pesticide/herbicide use), water quality
AV-I5 †	Choice of farm-saving or buying certified seed		
AV-I7 /I8	Networking with farmers and between farmers informs variety choice		
AV-I9	Farmers monitor their variety performance individually		
AV-I10	Farmers evaluate their variety performance individually		

Figure A1.3: Second-tier SESF components appropriating varietal diversity in German winter wheat

Source: Own depiction of second-tier variables adopted from McGinnis and Ostrom (2014), with alternative variables for the governance system. As there are multiple resource systems with resource units and actor groups these variables are preceded by an abbreviation for the respective group. Individual variables not found relevant to the case are tagged with '-'. Relevant sources for the included variables were mainly interviews 4, 5, 9, 11, 8, 16, 21, 23, 31, and 33; see list appendix 2 table 1. † marks those variables used in the main text.

Appendix B

Listing of interviews and participatory observations

Appendix 2

Table A2.1 Listing of interviews and participatory observations

Number	Kind	Position / Organization / Occasion	Topic	Time
1	OI	Head of breeding program (private)	Breeding business overview	Feb 16
2	OI	Head of breeding program (private)	Breeding business overview	Apr 16
3	OI	Product manager	Selling seed to multipliers	Apr 16
4	SI	Multiplying farmer / farmer	Variety choice and farming	Apr 16
5	OI	Farmer	Plant protection	Apr 16
6	PO	Meeting sales management btw. breeding and multiplication firm	Selling seed to farmers	Mar 17
7	PO	Plant breeders' rights admission meeting	Plant breeders' rights admission	Mar 17
8	PO	Head of breeding program/head of sales	Variety admission	Mar 17
9	OI	Public breeder	State Variety Trials	Mar 17
10	PO	Plant breeders in training	Plant breeding general	Apr 16
11	PO	Farmer	Inspecting winter wheat	Apr 16
12	OI	Public breeder	Prebreeding	Apr 16
13	PO/OI	Public breeder	Back-crossing	Apr 16
14	PO	Public breeder	Hybrid breeding	Jun 16
15	PO	Plant breeders in training	Double-haploids	Jun 16
16	S	DLG-Field days	Farming winter wheat and plant protection strategies	Jun 16
17	PO	Public breeder	Field inspection	Jun 16
18	PO	Plant breeders in training	Tubers and mutation breeding	Jun 16
19	PO	Breeding assistant (private firm)	Crossing	Jun 16
20	PO	Plant breeders in training	Field inspection	Jun 16
21	PO	Plant breeders in training	Seed certification	Jul 16
22	OI/PO	Public breeder	Population breeding	Jul 16
23	PO	Meeting state variety recommendation announcements	State variety recommendation announcements	Aug 16
24	SI	Scientific plant pathologist from a University	Resistances, farming behavior and breeding	Mar 16
25	SI	Public breeder	Worldwide prebreeding	Jun 19
26	PO	Public breeder	Selection early generations	Jul 16
27	PO	Head of breeding program (private)	Planning of crosses	Feb 17
28	PO	Public breeder	Field inspection prebreeding	Jun 16
29	PO	Private breeders	Field inspection and new technologies	Jun 19

30	PO	Head of breeding program	Selection of later stage generations	May 17
31	PO	Talk in expert panel for breeders	Farmers demands on breeding goals	May 17
32	OI	Researcher at LFL	Maintenance breeding	Apr 16
33	SI*	Head of breeding program (private)	Variety pricing	Dec 17
34	SI*	Head of breeding program (private)	Variety pricing	Dec 19
35	PO	Farmer	Plant protection heuristics	Jun 19
36	OI	Cereal researcher at LFL	Breeding system	Mar 16
37	OI	Researcher in crop pathology	Host-pathogen-human interactions in cereal cropping	Sep 16
38	OI	Researcher at Julius-Kühn Institut	Resistance breeding wheat diseases	Mar 17
39	OI	Researcher at Julius-Kühn Institut	Phytopathology	Jan 16

OI = Interview; SI = Semi-structured Interview; PO = participatory observation; S = survey

*Brief conversation with only field notes available

Appendix C

Stepwise guide to using our diagnostic process to diagnose SES/NAASs of interest

In this document, we provide the rationale and a detailed explanation towards each step of using our diagnostic process upon the SESs of interest. This guide draws upon the process we have articulated within the main manuscript through Figures 2a, 2b, and 2c. Our diagnostic process is divided into three sections, each aimed at unpacking a specific aspect of the complexity relating to SESs under question. The three sections are as follows:

- Section 1: Identifying research questions and characterizing the system of interest (Figure 2a in main manuscript)
- Section 2: Unpacking action situations relevant to the research question (Figure 2b in main manuscript)
- Section 3: Delineating NAASs and associated SES outcomes (Figure 2c in main manuscript)

We now proceed to unpack each of these sections in greater detail.

C.0.1 Section 1: Identifying research questions and characterizing the system of interest

For a researcher wishing to understand the complexity of SES they are investigating, it is important to first articulate their research question in relation to the SES of interest. The following questions guide the researcher in this process.

1.1 What is the broad SES challenge that is being investigated?

Every piece of research begins with the articulation of a broad challenge that the researcher wishes to investigate. This could be as diverse as an attempt to understand the impacts of climate change upon complex SESs or to understand the dynamics of collective action operating within the context of natural resource governance. Articulating this broad research objective is the starting point of our diagnostic process.

Note: We acknowledge that there may be a wide range of incentive structures within natural resource governance and these can include forms of cooperation, conflict, or indifference (Bruns and Kimmich, 2021 characterise incentive structures through a game theoretical approach as win-win, discord, and threat, with exchange, coordination, and independence as their primal archetypes) and it remains up to the researcher to determine the nature of incentive structure associated with the SES challenge they are investigating.

1.2 Do I have a) one SES challenge or b) multiple ones?

Starting with the challenge identified in 1.1. consider whether it may be neatly defined with specific and single outcomes, or whether they can be split into multiple related subcomponents. For example, in researching the impacts of climate change upon an SES, we must consider multiple related elements to the problem such as those related to adaptation, vulnerabilities, technology and infrastructure involved, global politics, etc. On the other hand, if the challenge being investigated relates to institutional arrangements influencing forest cover, we have one clearly defined SES challenge relating to a specific outcome, namely forest cover.

1.3 What is the research question that relates to the identified SES challenge?

Moving from the broad challenge into the specifics of the case being investigated, the analyst must now articulate the research question that guides their work. Research questions are specific and explain other elements of the research design including the articulation of outcomes as envisaged through the project (Cox 2015). For example, what are the institutional arrangements sustaining forest cover in tropical deciduous forests of central India?

1.4 What is/are the outcome/s as envisaged through the research question?

Drawing on 1.3, the analyst must now reflect upon the kinds of potential outcomes arising from the research question they have articulated. In the example given above, there can be multiple SES outcomes. Certain institutional arrangements can act to sustain forest cover in the forests concerned, while others may act against sustaining it. The normative or desired outcome as envisaged through the research question, however, is that forest cover remains sustained and that it is brought about through a certain configuration of institutional arrangements.

1.5 Do the outcomes prioritize a) biophysical outcomes; b) combination of social and biophysical outcomes; or c) social outcomes?

Potential outcomes as envisaged by the researcher are subjective and may relate to their specific positionalities. Accordingly, a researcher might prioritize only a) biophysical outcomes (for example when the desired outcome is defined only by improved ecological parameters such as biodiversity or water quality) or b) a combination of social and biophysical outcomes (for example socially just institutions resulting in improved biodiversity or water quality), or c) only social outcomes (for example if the desired outcome is envisaged as being composed of socially just institutions alone). Our diagnosis concerns itself with b) namely the combination of social and biophysical outcomes, which alone proceed into the next question. If the analyst is looking at either only ecological or only social parameters, they may exit the diagnosis at this stage.

1.6 What are the main social and ecological components of the system that the research question relates to?

Following from 1.5, as this diagnostic process relates to social and ecological systems, it follows that the analyst must identify the social and ecological components of their system of interest. For example, in the research question articulated above relating to institutions that sustain forest cover in India, we can identify both social and ecological components that form the system. Social elements involve actor groups and the various institutional arrangements that may be formed by these actor groups. The forest itself and everything it contains within (such as rivers, trees, fauna etc) represent the ecological component of the system.

1.7 What is the SES the research question relates to and what are its boundaries?

Once we have the social and ecological elements relating to our question and system of interest identified, we now need to define the specific boundaries of the SES based upon our responses to 1.5 and 1.6. In the example above, our SES comprises of tropical deciduous forests in central India and because we are interested in institutional arrangements associated with them, we may delineate our boundaries using jurisdictional markers around the forest. Other ways of defining system boundaries may also exist and delineating these depend strongly upon how the analyst articulates responses from 1.1 – 1.6 and what they are specifically interested in.

1.8 a. Is the SES a single well-defined SES? Or b. Does the system consist of multiple interacting entities, each of which can function independently as an SES (= NRS)?

Once the SES has been delineated, the analyst would next need to identify whether the SES as contained within the boundaries they have identified is discrete and well defined (such as a single aquifer) or whether the SES contains multiple nested entities each of which can function independently as an SES on its own i.e., whether the SES is in fact an NRS. In the example, we have been working with, a forest can be considered an NRS – it can comprise not just of the well-defined tree dominated entity we identify as a forest, but also rivers, lakes, or grasslands within that are equally capable of forming discrete SESs on their own.

1.9 a. What is the RS and RU within that system or b. If system is an NRS, what is the broad NRS and what are the individual subsidiary RSs in that system?

If the SES is discrete and well defined, it follows that we can delineate specific Resource Systems (RS) and Resource Units (RU) from it. For example, if we were considering a single aquifer as our RS, it stands to follow that the groundwater obtained from it would be our RU. On the other hand, if the SES is characteristic of an NRS, then it is next time to delineate what the broad NRS is and what individual subsidiary RSs exist nested within it. In the example of forests that we have been using, our broad NRS is represented by the tropical deciduous forest – our system of interest. Entities within it such as rivers or grasslands, may be considered subsidiary

RSs as each of them can produce discrete RUs on their own (for example water from a river flowing within that forest)

C.0.2 Section 2: Unpacking action situations relevant to the research question (The following questions in the diagnostic protocol are relevant to both SES and NRS cases)

2.1 What are the direct and indirect benefits obtained from the RS/NRS?

Once the analyst determines whether the system, they are engaging with is an RS or an NRS, they will need to identify the direct and indirect benefits that are obtained from the system of interest, that are relevant to the research question. Direct benefits from our example above may be provisioning benefits (such as measurable and quantifiable benefits like timber, non-timber forest products etc), while indirect benefits can include cultural benefits (like spiritual practices), regulating benefits (microclimate regulation), or supporting benefits (such as nutrient cycling). We suggest the terminology adopted by the Millennium Ecosystem Assessment (MEA 2005) to characterise ecosystem services into provisioning, regulating, supporting, and cultural services, is particularly valuable in this context. It is also important to note that the RS/NRS may provide multiple benefits that need to be considered in relation to the research question being investigated.

2.2 Who are the actors (A) that obtain benefits from the RS/NRS?

Benefits are usually accrued by actors who engage directly or indirectly with landscapes represented by the RS/NRS. Therefore, for each benefit identified, the analyst must identify the actors who are involved. For example, timber from a forest may be obtained for fuel/subsistence/commercial purposes by local communities living near it, or by loggers representing the interests of large companies wishing to benefit from the resource.

2.3 What are the activities supported by the RS/NRS relevant to the research question?

Relating to these benefits and closely linked to the idea advanced by Hinkel et al. 2015 that subtractability and excludability within a CPR problem are linked directly to activities supported by the system (and are not intrinsic properties of the system by themselves), the analyst must now identify the various activities supported by the RS/NRS. An example of activities occurring in our exemplary forest would be logging, farming, harvesting non timber forest products, fishing etc.

2.3a How are the activities regulated?

Each activity undertaken is likely to be regulated in some manner and identifying and articulating these regulations forms the next step of our diagnostic process. For example, fishing from the river in our forest can be commercial or subsistence based. It may be that in the system of interest, commercial fishing is regulated through a structured tender based process, while subsistence fishing is unregulated, making them two distinct activities occurring within our RS/NRS.

2.3b. Are these activities excludable?

In the next step of the diagnostic process the analyst should examine whether the activities they have described are excludable – is it possible to exclude actors from participating in the activity? In the example given in 2.3a, tender based commercial fishing by virtue of its own characteristics can exclude actors who do not participate in the tendering process, while on the other hand, it is difficult to exclude actors from the more unregulated subsistence-based fishing activity.

2.4a What are the RUs involved in creating the benefits (from 2.2)?

Benefits from an RS/NRS are always linked to RUs obtained from it. Therefore, in this next step to our diagnostic process, it is important to characterise the RUs involved in creating the benefits. For example, provisioning benefits may be linked to specific RUs such as water or fish from a river, or timber from the forest.

2.4b Are the RUs in relation to the activities subtractable? (if no to 2.3 or 2.4 a or b, exit)

We know from Hinkel et al. 2015 that activities conducted around a system are important towards understanding whether RUs are subtractable or excludable.

Subtractability refers to the idea that the amount of RU available to subsequent users may diminish each time it is extracted from within the RS/NRS. For example, if our activity relates to harvesting the non-timber forest product of wild honey, the associated RU would be the limited number of beehives in the forest. The total number of beehives available to harvesters will decrease each time honey is extracted from one of them. Analysts using our diagnostic process must now reflect upon whether the RUs extracted in relation to various activities occurring within their system are similarly subtractable or not. If the analyst determines that the RUs are neither excludable nor subtractable in relation to the activities being examined within their system of interest, the remainder of this diagnostic process is not applicable to the case in question as this diagnostic procedure relates specifically to CPR problems.

2.5 How excludable are actors performing/conducting activities in relation to the RU (high, low, variable) ?

Once the analyst determines that the RUs are in fact excludable in relation to the activity being performed, they may now proceed towards analysing the gradient of exclusion involved as being high, low or variable. For example, if we consider two activities from our example namely commercial tender-based fishing and subsistence fishing, excludability is high in the former, and low in the latter. On the other hand, if an activity within the system is regulated by means of collectively designed institutions (for example spiritual beliefs around a system), the extent of exclusion may become unclear. It may be that the activity is open to everyone except specific members of the community as designated by the rules governing the activity. This would mean that exclusion is high with respect to the members of the community being actively excluded from the activity, but low with respect to everyone else. In cases such as these, we propose that the analyst assumes excludability as being variable.

2.6 How subtractable are the RUs through different activities (high, low, variable)?

Just as with exclusion, the subtractability of an RU is also activity dependent. We propose that an analyst identifies whether the degree of subtractability of RU in relation to activities is high, low, or variable. For example, the subtractability of fish as an RU is highly variable dependent upon the nature of activity involved. It can be high if fishing is conducted as a commercial activity or low if it is a case of subsistence fishing by local forest dependent communities. Seasonal changes to fish populations can also affect the relative subtractability of fish populations. This is quite different from say an activity such as collecting wild honey, where the subtractability of beehives within the forest is clearly very high.

2.7 Type of governance

The next step within our diagnostic process is to articulate the kind of governance regime operating across each activity within the system of interest. This is important because while the RS/NRS as a whole may be governed through one form of governance (such as a centralized state-based mechanism), specific activities within it may be governed differently. For example, while the forest in question may be subject to state led regulations, access to spiritual benefits from specific regions of that forest may be subject to collective ones, that may or may not intersect with that governing the broader forest.

2.8 Type of action situation – ecological AS, social AS, or social ecological AS. (Only SEAS proceeds to next)

Once activities and their various associations have been delineated, the analyst would need to identify the nature of action situation (AS) involved around these activities. ASs may be of different kinds, namely social AS, ecological AS, or social-ecological ASs (SEAS). Given that we are explicitly interested in coupled social ecological outcomes, it is important at this stage to only list SEAS. As Schluter et al. 2019 define it SEAS involve interactions between human actors, ecological entities, their capacities, as well as the institutional arrangements that govern this complex of interactions. These SEAS can be of two kinds – provisioning AS or appropriation AS. The analyst now identifies which activity may be designated a provisioning AS and which may be exemplary of an appropriation AS. For example, the drawing of water from a river to meet irrigational purposes is an example of an appropriation AS, while the AS associated with governing and providing recreational spaces within the forest may be examples of provisioning ASs.

C.0.3 Section 3: Delineating NAASs and associated SES outcomes

3.1a If system is single and well-defined how many ASs are there? Do the different ASs interact or create adjacencies, thus NAASs?

If (through 1.8a), the analyst has identified that they have a single and well-defined SES, it is now time to recognize the number of ASs of relevance to the research question being investigated. Further, what are the different interactions that occur between these ASs? Do the outcomes of one AS influence another AS thereby creating adjacencies and therefore NAASs? Going back to our example of the forest, ASs guiding activities such as hunting and poaching can potentially influence ASs involving the creation of rules governing the entire forest, and therefore exert influence on social ecological outcomes.

3.1b If SES is representative of an NRS, where in the NRS do the ASs occur? In the subsidiary RSs? Between the subsidiary RS? Between the subsidiary RS and the broader NRS? (Then link to questions in 3.1a)

If (through 1.8a), the analyst has determined that they are in fact working with an NRS, then the next step would be to identify where in the NRS do specific ASs occur. Do they occur within the subsidiary RS (for example, fishing in a river flowing within the forest), or between subsidiary RSs (for example, livestock grazing on the fertile banks of the river flowing within the forest), or between the subsidiary RS and the broader NRS (for example, ASs involving the use of fertile soil within the forest that has been irrigated by water from the river flowing within the forest)? Once this spatiality has been determined, the analyst next proceeds to the questions identified in 3.1a to identify the various NAASs operating within the NRS across these spatial differences.

3.2 What are the external ASs influencing the NAASs?

At this stage of the diagnostic process, the analyst must now ask what external ASs influence the NAASs that have thus far been delineated. These external ASs could take the form of ASs relating to other CPR arrangements influencing the system and question of interest, those relating to broader social-ecological contexts (for example, the influence of external ecosystems or socio-political arrangements that influence the system of interest).

3.3 How do these interactions contribute to social-ecological outcomes?

Once NAASs and factors influencing these NAASs have been identified, the analyst must now reflect upon the complex of interactions that have been teased out through this process and the kinds of social-ecological outcomes that emerge. Depending upon whether the system under consideration is representative of an SES/NRS, these outcomes can either relate to the SES as a whole or to the broad NRS or individual subsidiary RSs. It is important to note that there may be multiple outcomes relating to each AS/NAAS occurring within the system. An example of a social-ecological outcome in our exemplary forest would be an effort to sustain the forest through stringent centralized governance regimes in response to poaching alongside more collectively managed institutional arrangements relating to access and appropriation of non-timber forest products.

3.4 How do diagnostic outcomes relate to the original normative assumptions posed by the research question (see 1.3)?

The final two questions of our diagnostic exercise relate to linking our case study to the original motivations behind doing the exercise. In this penultimate step of the procedure, we ask the analyst to reflect upon how social-ecological outcomes, as unpacked through this stepwise decomposition of the SES/NRS relate to the original assumptions posed by the research question (from 1.3). Further, if the case relates to an NRS, does unpacking NAASs across the various spatial elements of the NRS provide additional nuance towards understanding the case being investigated?

3.5 What do these outcomes imply for the broad SES challenge/s (see 1.1)?

In the last step of our diagnostic process, we ask the analyst to reflect upon how these outcomes (as unpacked through our diagnostic tool) have implications for the broad SES challenge/s identified through 1.1.

Appendix D

Diagnostic characteristics of the two cases- networked lakes in India and German winter wheat breeding systems

A. Diagnostic characteristics of the two cases- networked lakes in India and German winter wheat breeding systems

Section 1: Identifying research questions and characterizing the system of interest

Q No.	Diagnostic question	Networked lakes in Bengaluru	Winter wheat breeding in Germany
1.1	What is the broad SES challenge that is being investigated?	Drivers of coproduction in urban water commons	Provisioning and appropriation of genetic diversity: *insitu* and *exsitu*
1.2	Do I have a) one SES challenge or b) Multiple ones	Multiple challenges relating to social and ecologically just forms of coproduction	Multiple social dilemmas: providing genetic diversity along a supply chain of scientists, breeders, seed multipliers and farmers
1.3	What is the research question that relates to the identified SES challenge/s	What drives inherently heterogeneous communities to come together and invest in the resource collectively? What motivates co-production in the networked lake system of Bengaluru?	What governance challenges arise from provisioning genetic diversity?
1.4	What is/are the outcomes as envisaged through the research question?	To understand the factors that could potentially enable heterogeneous actor groups to successfully engage in coproduction of lakes within the networked lake system	To understand what type of coordination mechanisms are used to channel seed material and corresponding information on agronomic performances and material quality
1.5	What nature of outcomes are being prioritized?	Combination of social and biophysical outcomes. Here the social-ecological outcomes envisaged would be heterogeneous actors successfully coming together towards an inclusive co-production effort that result in sustainable rejuvenation of individual lakes as well as the entire system that they are a part of.	Combination of social and biophysical outcomes **Social-ecological outcomes**: Breeders creating varieties maintaining their long-term genetic pool; Subcontracting and selling varieties, such that farmers' needs and preferences are being met and manifest in ecological outcomes of varietal diversity; Choosing varieties according to their own preferences and societal considerations by the farmer.
1.6	What are the main social and ecological components of the system that the research question relates to?	**Social components:** Resource user groups (Farmers, fishermen, recreationalists, urban foragers, etc), Institutional arrangements (civil society, RWAs, local bureaucracies, rules, norms etc), property rights regimes, Socio-cultural diversity and traditions (Heterogeneities among actors, cultural and religious beliefs or practices associated with the lake) **Ecological components:** the lakes (quality), water, fish, biodiversity (both flora and fauna), soil and silt, supporting and regulating ecosystem services	**Social components**: scientists, breeders, multipliers,agricultural retailers, farmers, institutional arrangements (Lobbying groups, breeders rights, intellectual property rights) **Ecological components**: genes snippets, seed, plants, field variants, fields, genetic diversity; regulating ecosystem services (groundwater quality, soil quality, maintaining biodiversity, agro-climate zones, growing regions)

		(groundwater recharge, local microclimate regulation, maintaining biodiversity)	
1.7	What is the SES the research question relates to and what are its boundaries?	SES relates to the entire network of lakes within the city of Bengaluru. This network formed by individual lakes connected to each other via channels, which constitute a single chain enabling unidirectional water flow forms the boundaries of this system.	The SES relates to the entire chain and use of genetic material, being used from pre-breeding (research projects bringing in foreign genetic material for localized breeding) to farming.
1.8	Is the SES single and well defined or is it an NRS?	The system is representative of an NRS	The system is representative of an NRS
1.9	What is the broad NRS and what are the individual subsidiary RSs within that system?	Broad NRS = entire network of lakes Subsidiary RS = individual lakes in that network	Broad NRS = entire chain of activities using seed material Subsidiary RS = individual types of material usage in breeding nurseries, seed multiplication and on farm usage as varieties.

Section 2: Unpacking action situations relevant to the research question

Q. No	Diagnostic question	Networked lakes in Bengaluru	Winter wheat breeding in Germany
2.1	What are the direct or indirect benefits obtained from the RS/NRS	**Provisioning ecosystem services** (Water for various domestic and commercial activities), Fish, urban forage, pasturage, silt, etc) **Cultural ecosystem services** (Support for cultural, social, or religious traditions and practices – *ashwathkattes* (raised platforms containing a combination of Neem and Peepal trees *(Azadirachta indica, Ficus religiosa* respectively), carrying cultural significance to local communities), sacred forests, temples, cemeteries associated with the water bodies) **Regulating ecosystem services** (microclimate regulation, pollination, flood control etc, groundwater recharge) **Supporting ecosystem services** (Biodiversity maintenance, nutrient recycling, etc)	**Economic benefits:** income generated from variety licensing and subcontracting, income generated from selling seed, income generated from other inputs accompanying seed (crop protecting agents, fertilizer, machinery), income from selling yields, security from stable yields and incomes; future value of a genetically diverse system **Non-economic benefits**: nutrient cycling, groundwater quality, pollination, biodiversity maintenance

The remaining questions of section 2 and question 3.1 are addressed in the following tables for each case

2.2 Actors	**2.3 Activities supported by the system**	**2.3a Regulation of activity in relation to RU**	**2.3b Excludability of actors from activity**	**2.4aStock of (RU) involved**	**2.4bSubtractability of RU with respect to activity**	**2.7 Type of governance**	**2.8 Action situation**	**3.1b Where in the NRS do the AS occur**
Fishermen	Catching fish	Tender based, Access and appropriation rights	Easy	Fish stock	Variable	Undefined	Appropriating fish and spaces to fish within	Individual lake (fishing activity), influx from lake network
Recreational fishermen	Catching fish	None, Access and appropriation rights	Difficult	Fish stock	Low	Public		Individual lake (fishing activity), influx from lake network)
	Occupying a location for undisturbed fishing		Difficult	All available fishing locations	High	CPR		
Farmers	Drawing out water by means of electric pumps from the lake for irrigation	Collective rules Access, appropriation rights	Variable	Water	Variable	Undefined	Appropriating water and other inputs for irrigation	Individual lake, influx from lake network, Network of lakes
	Occupying a location to place electric pumps or other water drawing equipment		Variable	All available locations on bank of lake	High	Undefined		Individual lake

Urban foragers	Collecting green leafy vegetables growing on the banks of the lake	None, Access and appropriation rights	Difficult	Greens	High	CPR	Appropriating urban forage for subsistence	Individual lake
Gated communities	Making use of prime real estate that offers 'lake view' apartments/houses for a premium	Toll, Access, appropriation and management rights	Easy	Land, Water	Low	Toll/Club	Appropriating land around lake for real estate purposes and forming Residents Welfare Associations for management	Individual lake; however ecological quality of water body affected by that of larger network
Nodal agencies	Maintaining water body for public use	State regulated, Access, appropriation, management, and exclusion rights	Difficult	Entire lake	Low	Public	Provisioning water, Managing and regulating most activities associated with lake	Entire network of lakes but individually considered
Private Institutions (such as corporate groups or information technology parks)	Maintaining the water body and drawing recreational benefits for their employees	Private rules Access, appropriation, and management rights	Easy	Entire lake	Low	Toll/Club	Providing aesthetic and recreational spaces through PPP arrangements	Individual lake, however quality of the waterbody is affected by the larger network it forms a part of
Livestock owners	Livestock grazing	Open access Access and appropriation rights	Difficult	Grass on bank of lake or shallow waters	High	CPR	Appropriation of grass from lake banks	Individual lake

		State regulated Access and appropriation rights	Easy		High	Private		
		Private rules Access and appropriation rights	Easy		High	Private		
	Livestock washing	Open access Access and appropriation rights	Difficult	Water from the lake	Low	Public	Appropriation of water from lake	Individual lake; influx from lake network
		State regulated Access and appropriation rights	Easy		Low	Toll/Club		
		Private rules Access and appropriation rights	Easy		Low	Toll/Club		
	Providing drinking water for livestock	Open access Access and appropriation rights	Difficult	Water from the lake	Low	Public		Individual lake; influx from lake network
		State regulated Access and appropriation rights	Easy		Low	Toll/Club		
		Private rules Access and appropriation rights	Easy		Low	Toll/Club		

Dhobies – commercial washerfolk	Washing clothes on the banks of the lake	Open access Access and appropriation rights	Difficult	Water from the lake	Low	Public	Appropriating water and spaces around the lake for washing	Individual lake; influx from lake network Network of lakes
		State regulated Access and appropriation rights	Easy		Low	Toll/Club		
	Finding appropriate places to set up washing stones and other equipment	Open access Access and appropriation rights	Difficult	All available locations for washing	High	CPR		Individual lake
		Collective choice rules Access and appropriation rights	Variable		High	Undefined		
		State regulated Access and appropriation rights	Easy		High	Private		
Urban recreationalists	Jogging, running, walking, sitting, playing music, swimming, exercising	Open access Access and appropriation,and management rights	Difficult	Water body and its banks	Low	Public	Appropriating the water body and its surroundings for recreation, collaborating for lake maintenance	Individual lake; however quality of water body is influenced by that of the larger network
		State regulated Access and appropriation, and management rights	Variable		Low	Undefined		

		Private Access and appropriation, and management rights	Easy		Low	Toll/Club		
Urban residents	Performing religious rituals	Open access Access and appropriation rights	Difficult	Water	Low	Public	Appropriating water, space, and mud for spiritual purposes	Individual lake, lake network
			Variable	All available locations for conducting rituals	High	Undefined		Individual lake
			Difficult	Mud/Clay	Low	Public		Individual lake

Case 2: Winter wheat breeding systems of Germany

Actors	Activities supported by the system	Regulation of actors / activitiy in relation to RU	Excludability of actors from activity	Stock of RU	Subtractability of RU Stock inro	Types of Goods	Action Situations	Level at which action situation occurs	Social outcomes	Ecological outcomes
Breeders	pre-breeding	Internationally regulated	variable	Rest of primary genepool	variable	undefined	breeders providing genetic diversity and appropriate genetic diversity from	molecular; plant	access to choosing preferred traits (option value); information flow	directing gene flows
		State regulated	easy	adapted breeding material to temperate German climate	variable	undefined		plant; field		

	creating /maintaining /improving inhouse variation	State regulated	easy	Lines submitted to VCU trials	low	Toll good	different RU Stocks for their breeding activities	field	information flow	on nursery genetic diversity
		Collective-regulation							collaboration between breeders	
		Open Acess	difficult	All available varieties on DVL	low	Public good		field		
		Private rules	easy	diversity of genotypes & knowledge about internal lines within individual breeding firm	high	Private good		molecular, plant, field	breeding activities	
	selecting from inhouse variation	Private rules / Heuristics	easy		high	Private good		molecular, plant, field		
	subcontracting varieties to multipliers/ agricultural retailers	State regulated	variable	Total expenditure of agricultural retailers / multipliers	variable	undefined	Provisioning of varieties by retailers	landscape	income from licencing fees and subcontracting	varieties being multiplied
Multipliers	Selling certified seed to agricultural retailers	State regulated	variable	Total expenditure of agricultural retailers	variable	undefined		landscape	income from selling seed	spread of different varieties across different geo

	Multiplying seed for breeders	State regulated	variable	Total expenditure of breeders for licensed activities	variable	undefined		landscape	income from licences	graphical regions
Agricultural Retailers				multiplied seed	low	undefined		landscape	income from selling seed	
	Selling certified seed to farmers	State regulated	easy		low	private good	Farmers appropriate seed = they buy or farm-save seed and use them for farming	landscape	seed becoming accessible to individual farmers	spreading different varieties in a specific area
				farmers total expenditure	low	private good		farm	income from selling seed	insitu variation of varieties (e.g. usage of resistant varieties); soil quality, biodiversity, water quality
	Selling fertilizers and pesticides matching the respective seed	State regulated	easy		variable	undefined		farm	income from selling other inputs	
		State regulated		all available seed	high	private good		landscape	saving seed for resowing	
Farmers	conventional/organic winter wheat cropping	State regulated	variable		low	undefined		field		
				Other inputs to farming	variable	undefined		field landscape	undefined	

Section 3: Delineating NAASs and associated SES outcomes

Q. No	Diagnostic question	Networked lakes in Bengaluru	Winter wheat breeding in Germany
3.2	How many ASs are there? Do the different ASs interact/create adjacencies, thus NAASs?	13 ASs may be delineated. Yes, NAASs are created through adjacencies across the various ASs.	3 ASs may be delineated. Yes, NAASs are created through adjacencies across the various ASs.
3.3	What are the external ASs influencing the NAASs?	This is a community that has historically engaged in coproducing its waterscape, and therefore this can serve as an incentive system (see for instance Unnikrishnan et al., 2021), size of the lakes (smaller lakes have easier boundaries to manage), sewage inflows into individual lakes affecting water quality, city and state level sewage discharge, pollution, and wetland regulation policies (which require greater engagement and strategic negotiation between state bureaucratic structures, and the communities engaged in coproduction).	International policy regulating access and benefit sharing of seed internationally, supra- and -national organization of variety testing and monitoring.
3.4	How do these interactions contribute to social-ecological outcomes?	Only four user groups (nodal agencies, gated communities, private institutions, and urban recreationalists) possess all the following attributes: ● Access, appropriation, management and/or exclusion rights ● Their activities define the RS as being public, toll, or undefined goods ● Despite being affected by larger lake network, tend to operate at the level of individual lakes ● Access to stakeholder collaboration and information flow ● Ability to directly influence the form and function of the ecosystem, while accessing only cultural ecosystem services This means that power to influence the social ecological system is monopolized by these groups of actors, allowing them to engage in co-production efforts towards the resource. Ecologically, this means that efforts are not systemic but targeted only to individual lakes, meaning that the entire social ecological system is not sustainably rejuvenated. Other actor groups (who only have access and	While scientists and breeders mainly contribute to provisioning and appropriating genetic diversity within seed material on a genetic and plant level. Seed multipliers, agricultural retailers, farmers appropriate crop genetic diversity in form of appropriating varieties.

		appropriation rights, are more diverse, who depend mostly on provisioning ecosystem services, and who in some cases draw meaning from the systemic nature of the resource) cannot influence the condition of the resource or be involved in decision making processes around it.	
3.5	How do diagnostic outcomes relate to original normative assumptions posed by the research question (see 1.3)	Given that decision making powers around the system of lakes rest only with a few groups of actors interacting with the SES, it follows that other actors do not have sufficient incentive to engage in co-production efforts, even though their uses of the resource can range from a public goods dilemma to a CPR situation. Further, despite the networked nature of the system, actors with the ability to modify the ecosystem only act at the level of individual lakes, while user groups who explicitly make use of the networked character (such as farmers) are excluded from decision making action situations. There is a need to consider the systemic character of this lake system, and that can only be done through inclusive decision making. Note: Exceptions to the case exist where management rights are given to each stakeholder involved in the co-production process, but these are too few and far in between.	The earned income and expectation of income gain incentivizes the different actors to undertake the activities. The information flows on the different agronomic performances of individual biological material (genetic snippets, lines, varieties) direct the concrete genetic material to its purpose and concrete positions within the whole system, leading to the different ecological performance measures. Three individual social dilemmas in networked action situations need to be overcome for not encountering negative environmental impacts on the overall system level: Breeders need to invest collectively in quantitative resistance traits to have these in their varieties. Multipliers need to be willing to subcontract these resistant varieties and forego income from accompanying plant protection agents, so that farmers may sow varieties with stable resistances against pests and spray less. In all three of these action situations, however, the incentives each actor group is faced with points in different directions.
3.6	What do these outcomes imply for the broad SES challenge?	The success of urban coproduction around blue commons seems intimately linked to how inclusive the process is to diverse stakeholders of the resource system.	Failure in reducing ecological impacts through spraying can be traced back to the conflicting interests in incentive structures along the seed chain/ resource system.

Appendix E

Seed multiplication decisions in response to pest epidemics

E.1 Pest performance ratings per trial site displayed by year

On the following pages we plotted out the intensity of the occurrence of different diseases per year. Each testing site has an own radar chart, where we plotted from 0 to 9 the intensity of occurrence of a pest on that site for each of the spokes. On the spokes we have brown rust, tan spot, yellow rust, eye spot septoria nodorum blotch, powedery mildew, septoria leaf spot, fusarium , and brown rust. 0 means that there was no occurrence of a pest while 9 represents the highest form of occurrence of a pest. The rating takes place according to the usual practice in accordance with federal field variety testing standards (Bundessortenamt, 2000; Moll, Flath, & Sellmann, 2009). The individual lines in black represent the variety performance of a variety under treatment with fungicides.

Nomenclature: On each of the following appendix pages we show for each place per year the concurrent occurrence of different diseases with one radar plot each. The first number above the radar plot denotes the year and the digits after each represent the testing site.

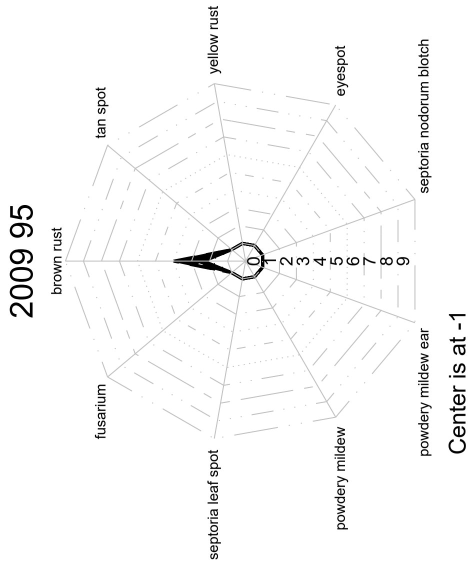
The scores for disease infection

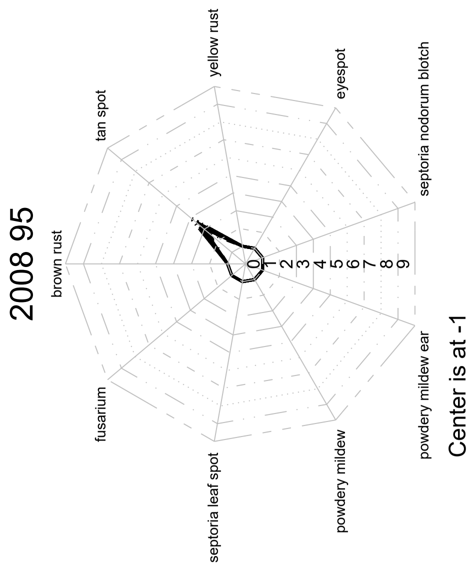
- 1 very little to no infestation
- 2 very little to low infestation
- 3 low infestation
- 4 low to medium infestation
- 5 medium infestation
- 6 medium to strong infestation
- 7 strong infestation
- 8 strong to very strong infestation
- 9 very strong infestation

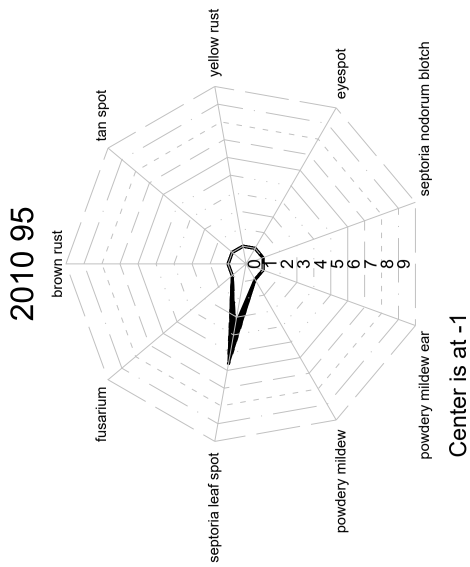
TABLE E.1: List of testing site by pedo-climatic zone

Pedoclimatic Zone	Testing site number	Name
112	95	Oschwitz
113	105	Arnstein
113	122	Buchschwabach
113	143	Greimersdorf
113	22	Aspachhof
113	29	Herzogenaurach
113	30	Seligenstadt
113	45	Giebelstadt
114	127	Hartenhof
114	402	Bieswang
114	456	Reimlingen
114	67	Sommertshof
114	70	Wolfsdorf
115	14	Günzburg
115	15	Landsberg
115	24	Feistenaich
115	31	Mallersdorf
115	36	Desching
115	44	Feldkirchen
115	441	Oberhaunstadt
115	659	Buxheim
115	76	Osterseeon
115	77	Kirchseeon
116	28	Irlbach
116	39	Reith
116	7	Köfering

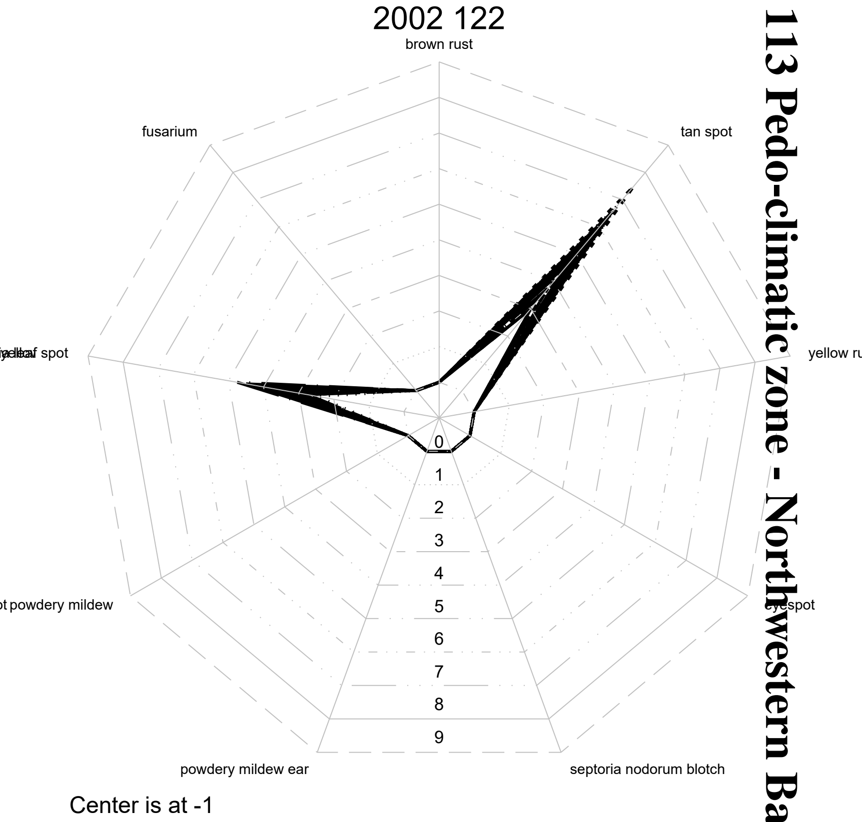
E.2 112 Pedo-climatic zone - Eastern Bavaria







E.3 113 Pedo-climatic zone - Northwestern Bavaria



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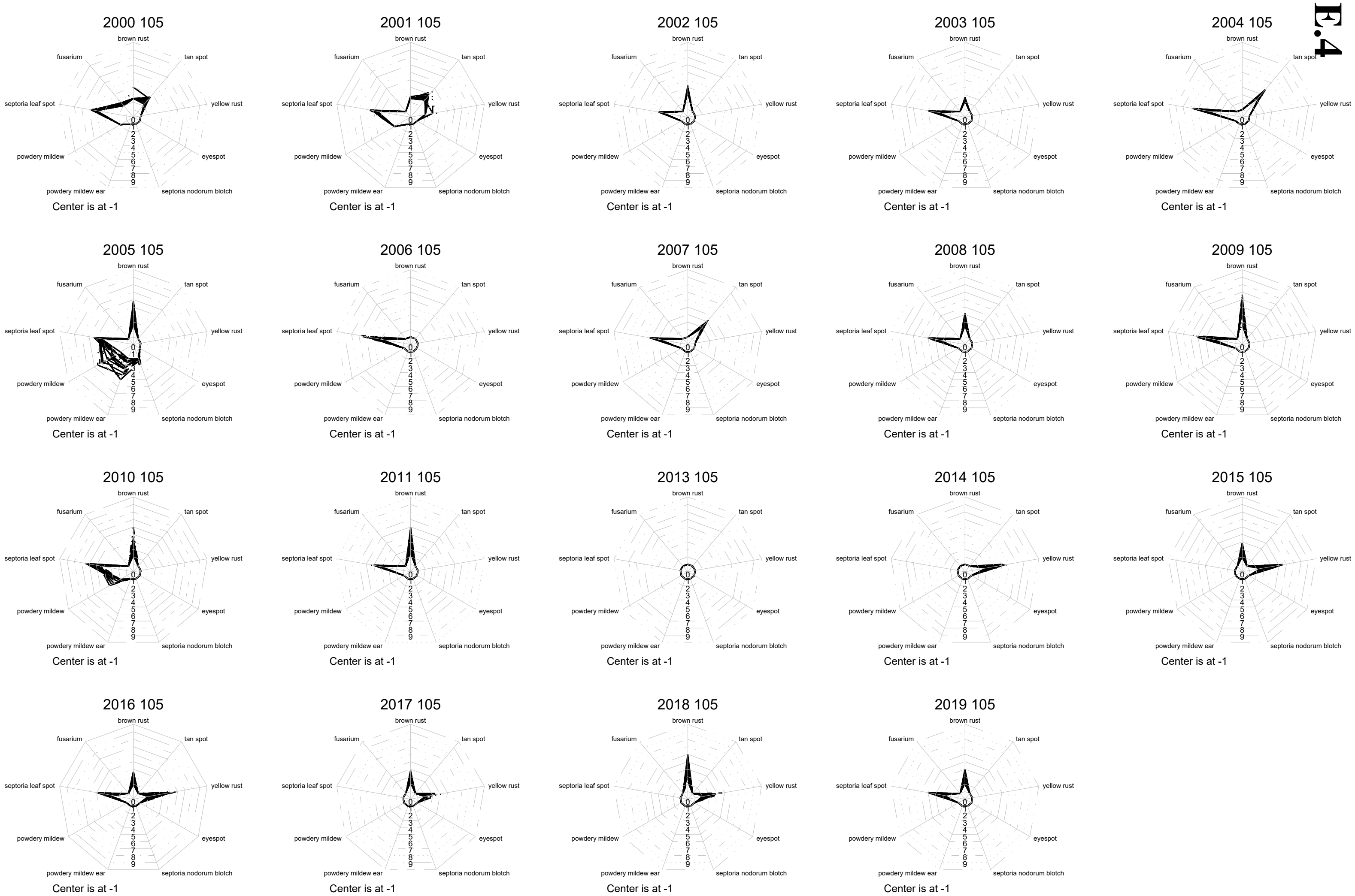
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2007 105
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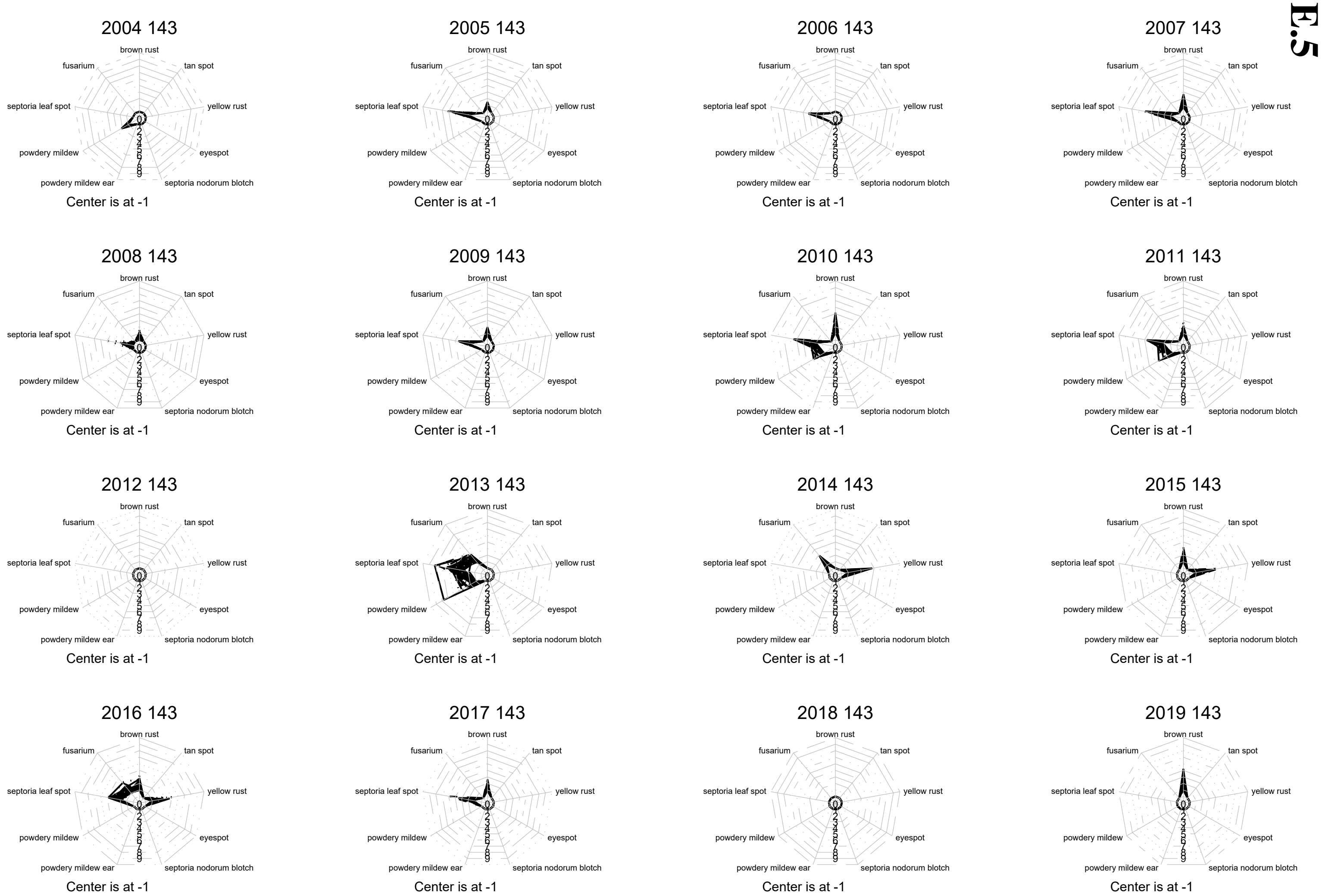
2015 105
2016 105
2017 105
2018 105
2019 105
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
0 1 2 3 4 5 6 7 8 9
Center is at -1

E.5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2008 143
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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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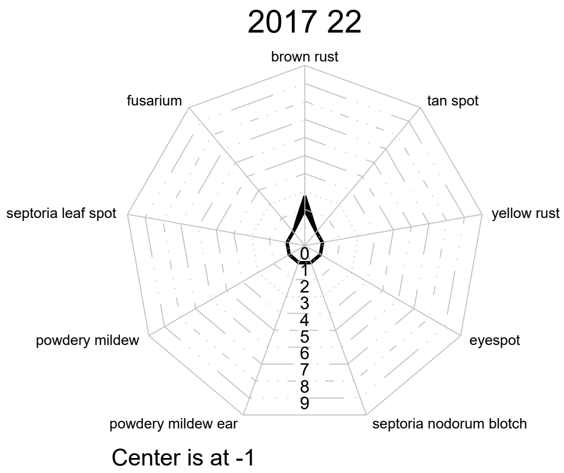
8
9
Center is at -1

E.6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eyespot
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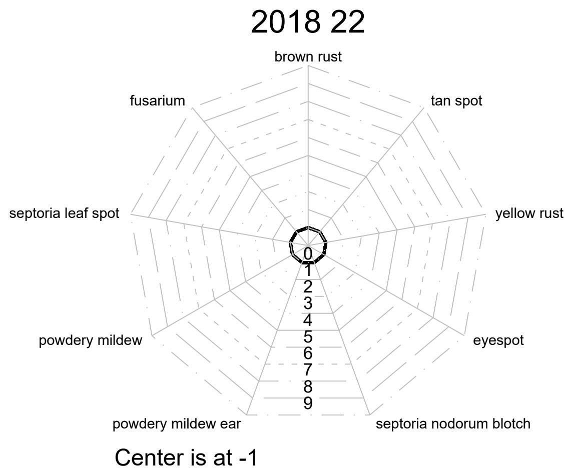
Center is at -1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yellow rust
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septoria nodorum blotch
powdery mildew ear
powdery mildew
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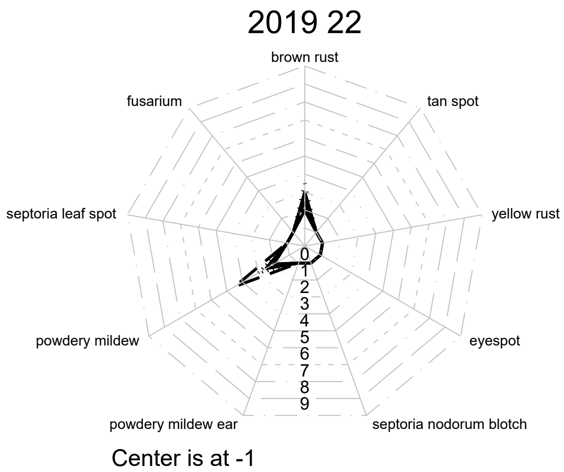
Center is at -1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powdery mildew ear
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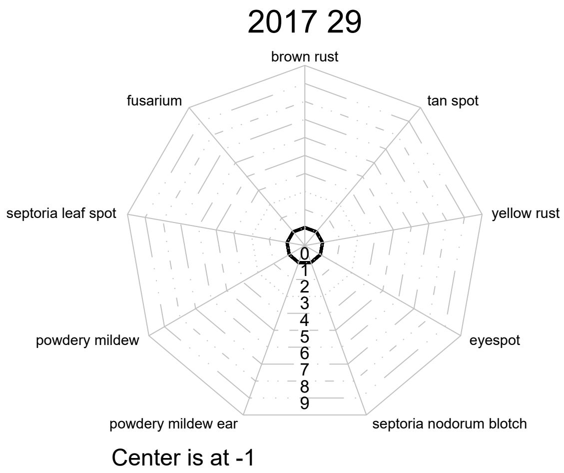
Center is at -1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yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
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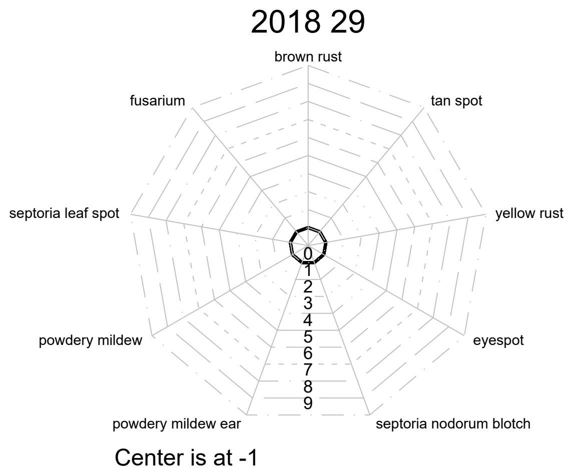
Center is at -1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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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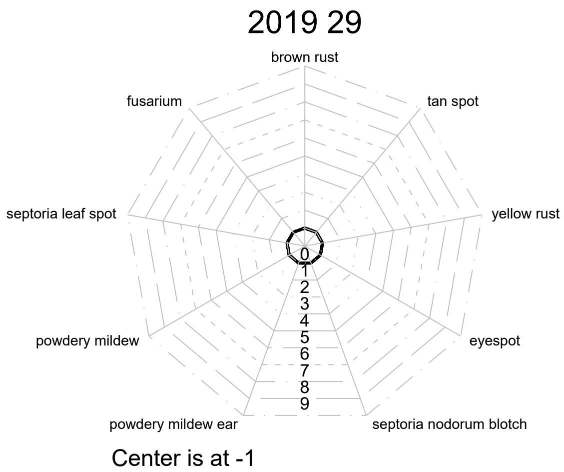
Center is at -1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tan spot
yellow rust
eyespot
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powdery mildew ear
powdery mildew
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fusarium
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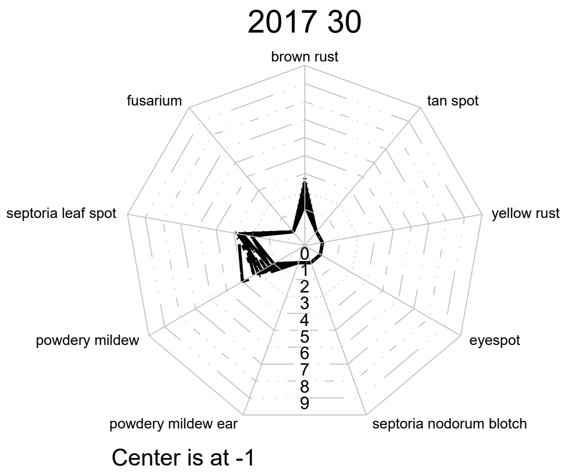
Center is at -1

E.8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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
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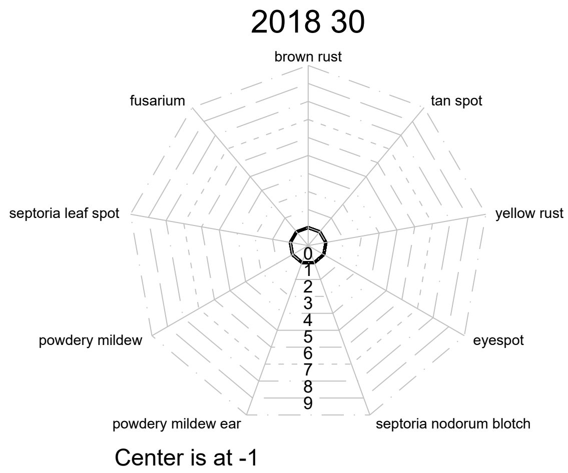
Center is at -1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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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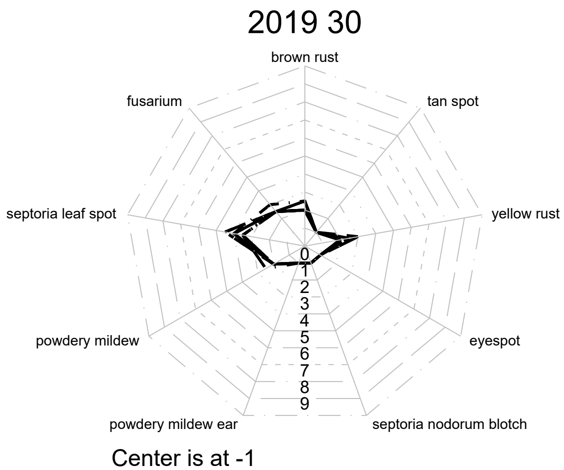
Center is at -1


2019 30
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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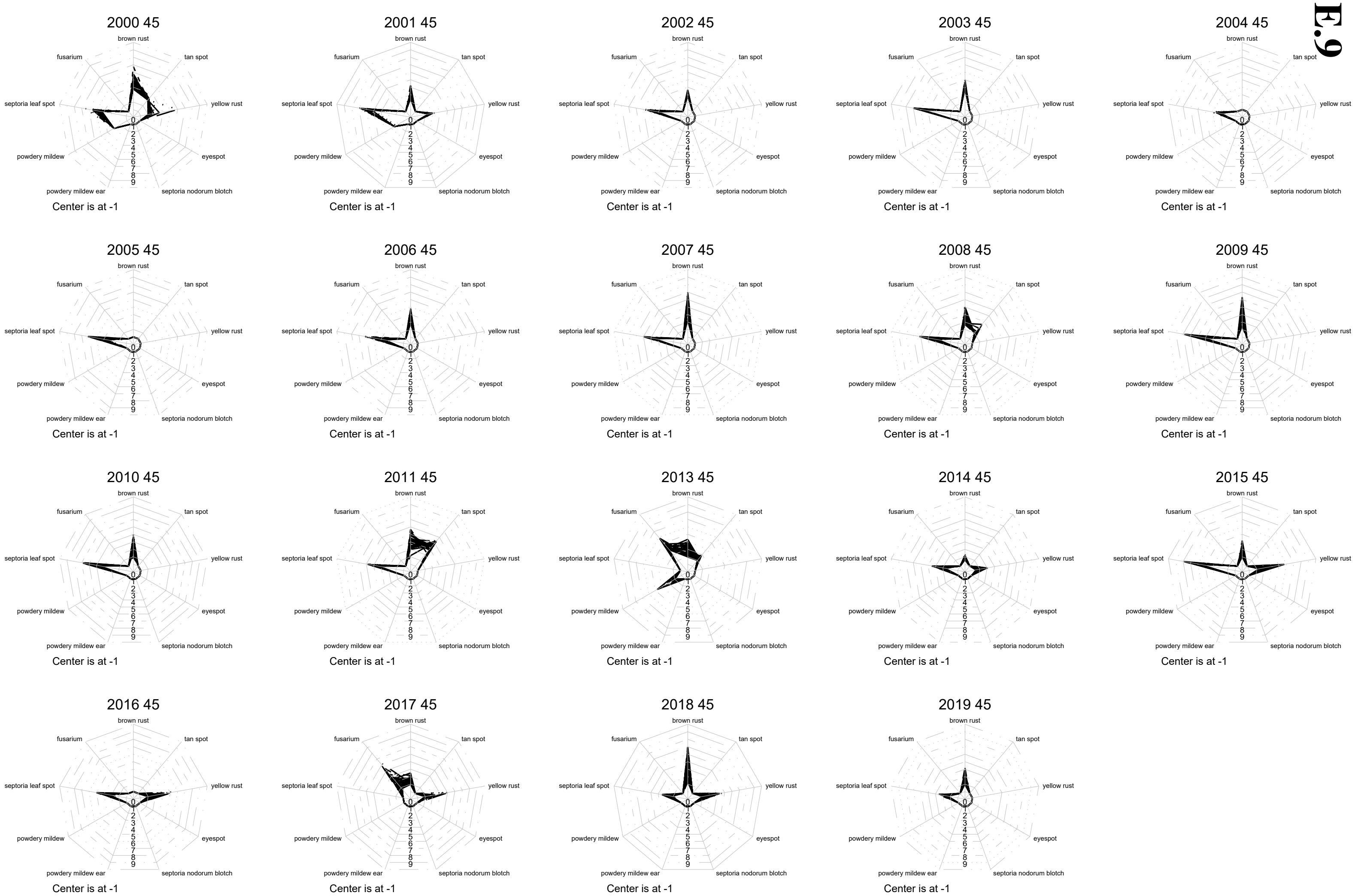
Center is at -1

E.9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brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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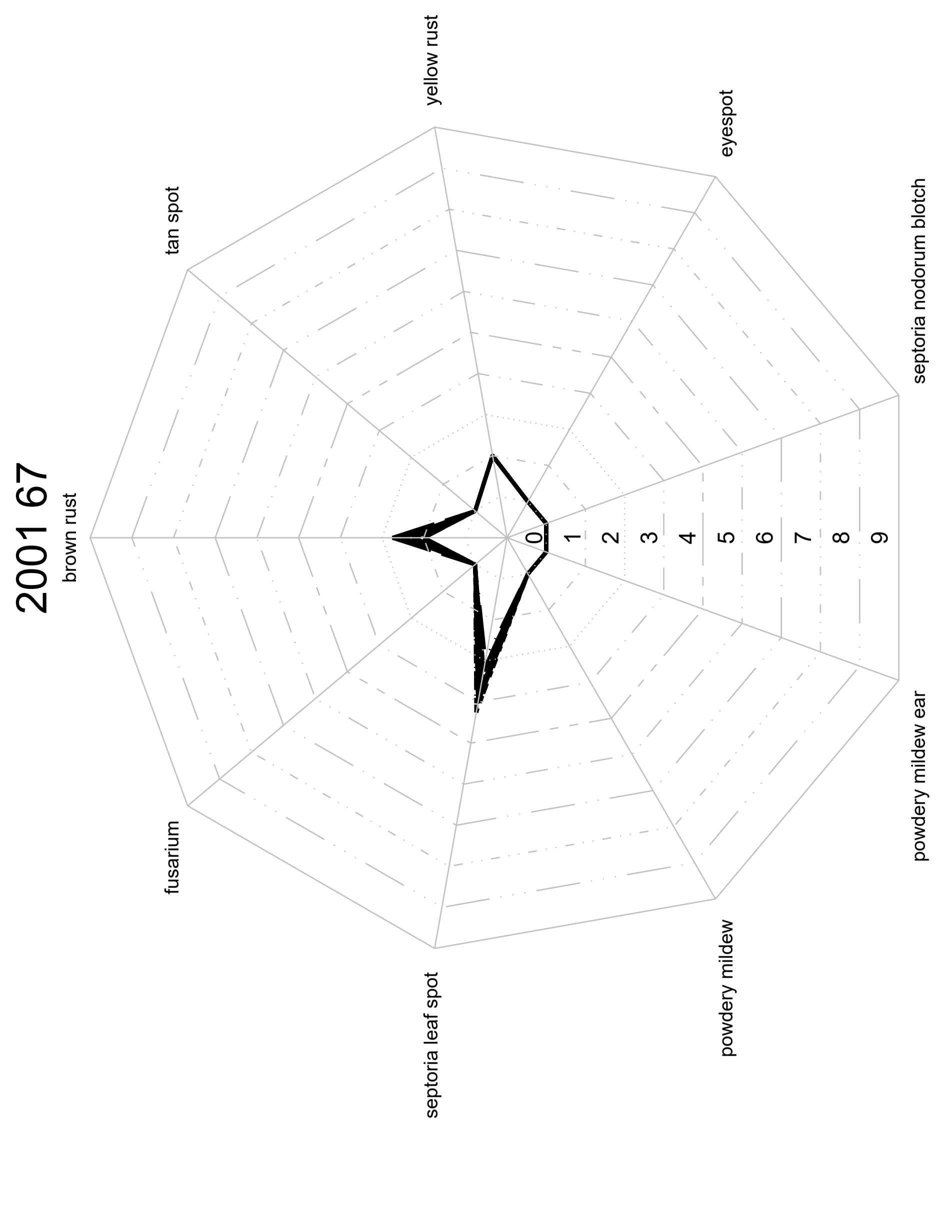
Center is at -1

E.10 114 Pedo-climatic zone - Swabian Jura and Eastern Bavarian Foothills



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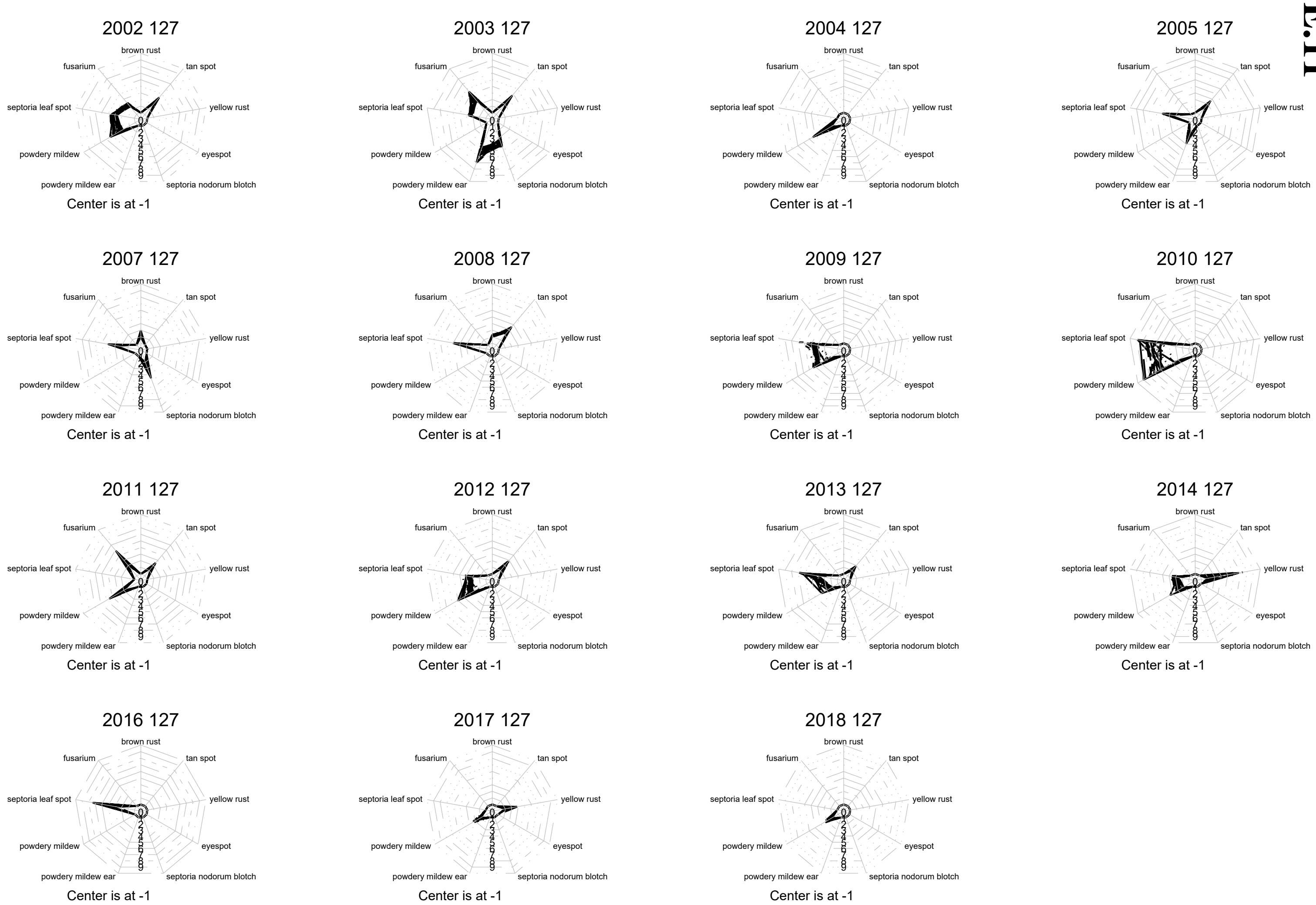
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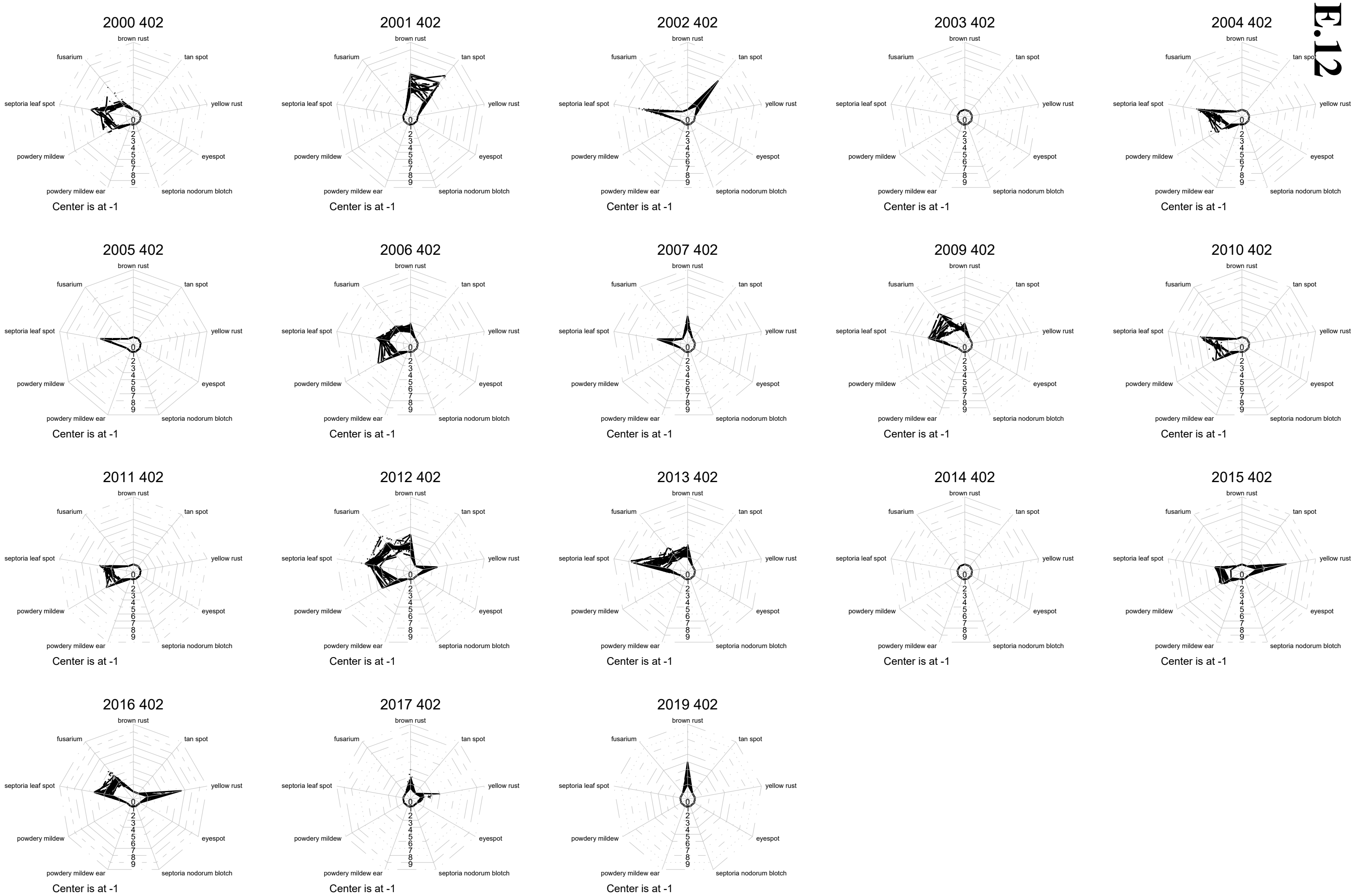
fusarium
Center is at -1

E.12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septoria leaf spot
fusarium
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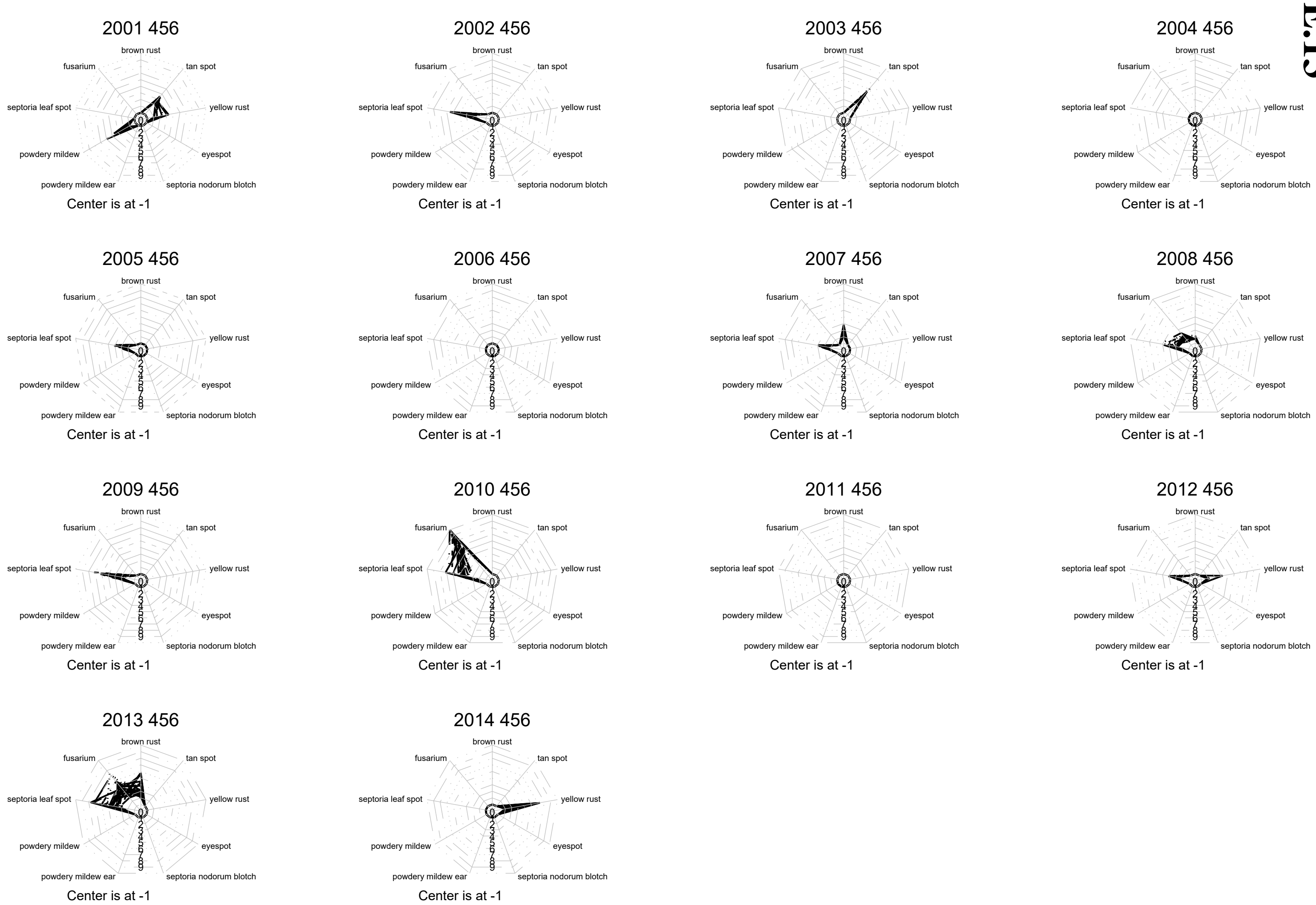
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eyespot
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powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2002 456
Center is at -1
2003 456
Center is at -1
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Center is at -1
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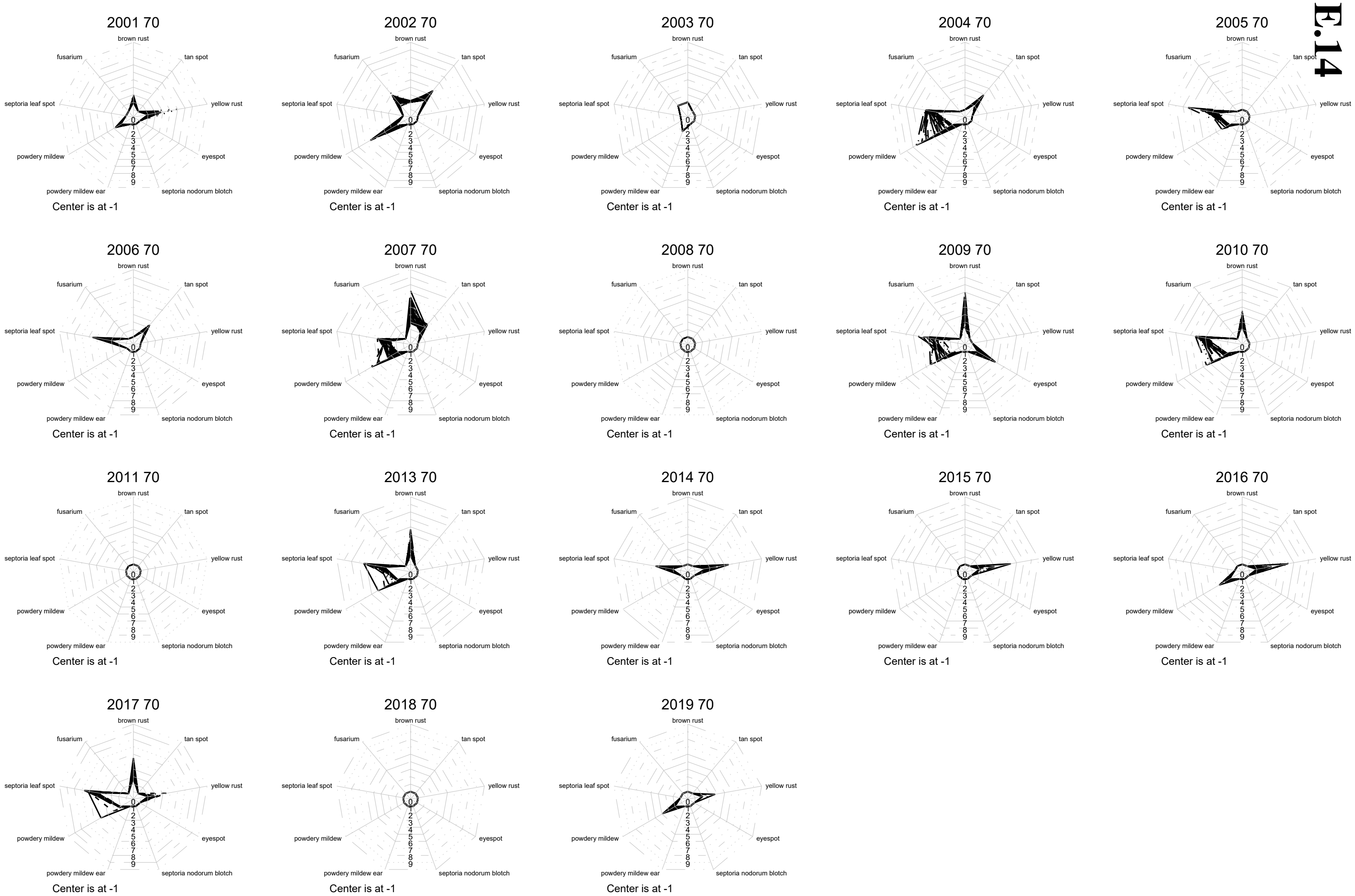
E.14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brown rust
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eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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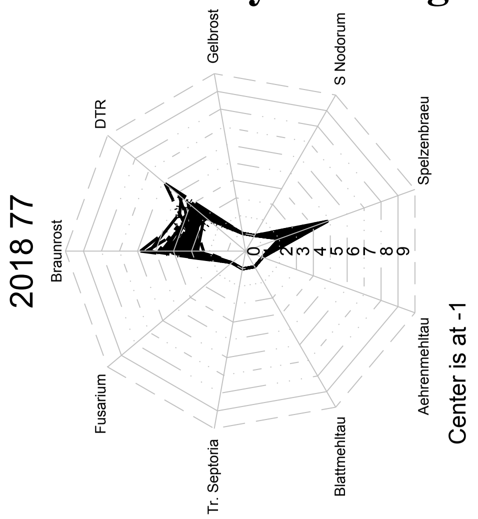
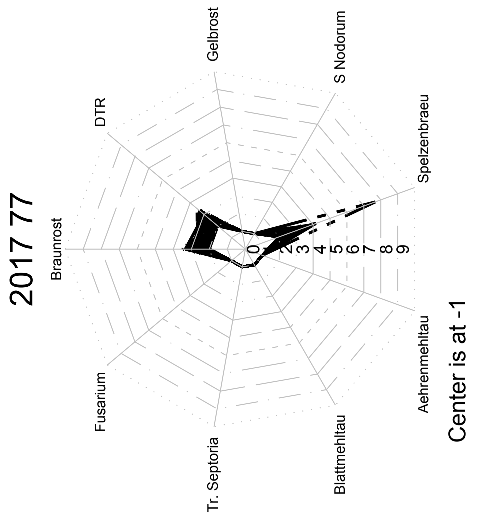
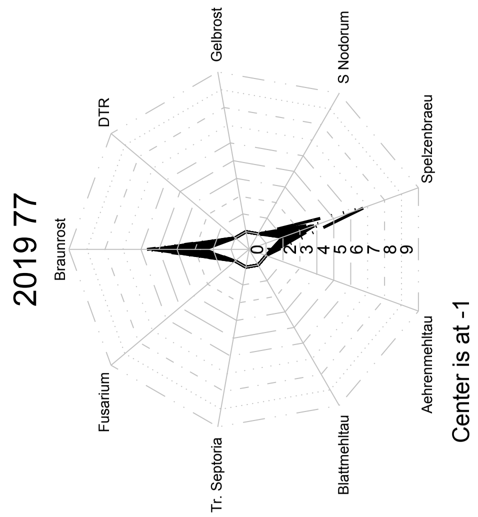
Center is at -1

E.15 115 Pedo-climatic zone - Southern Danube and Tertiary Hills regions







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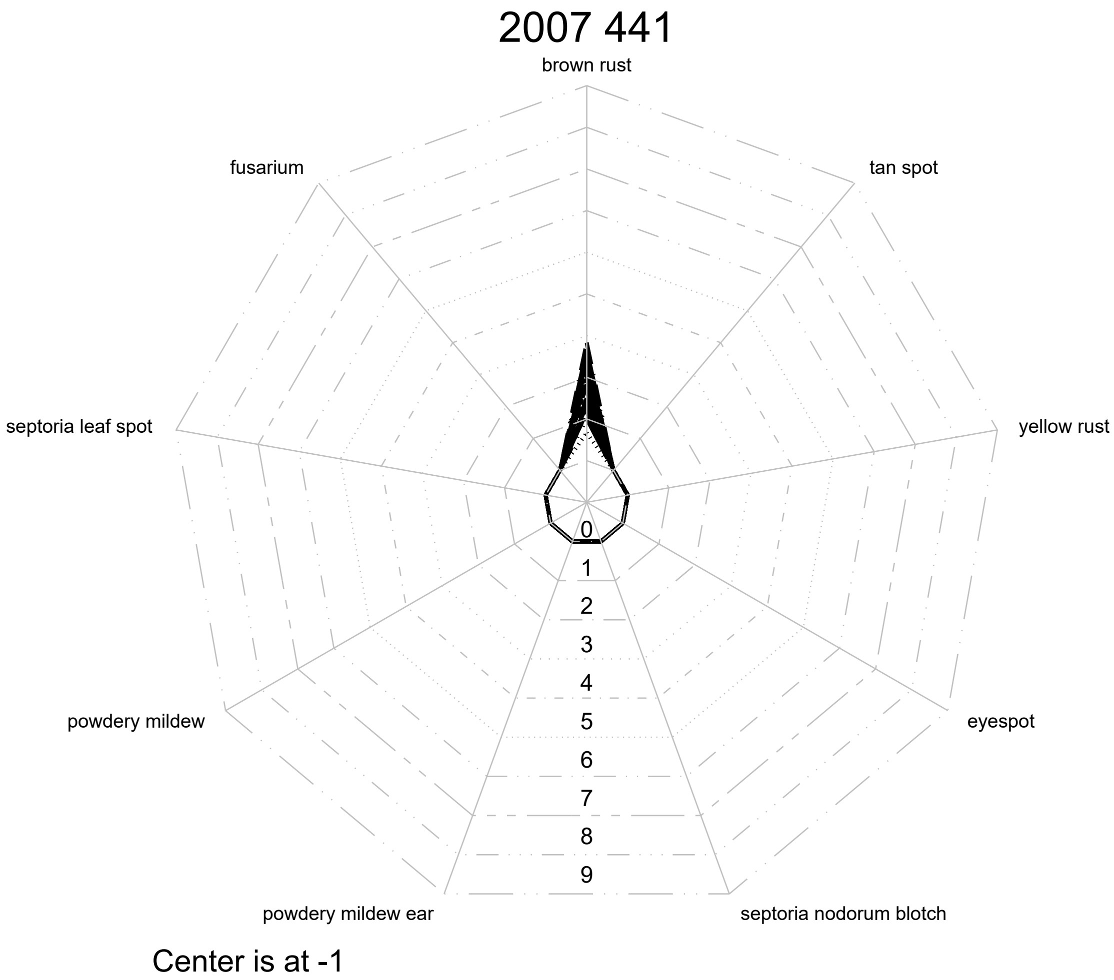
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Center is at -1

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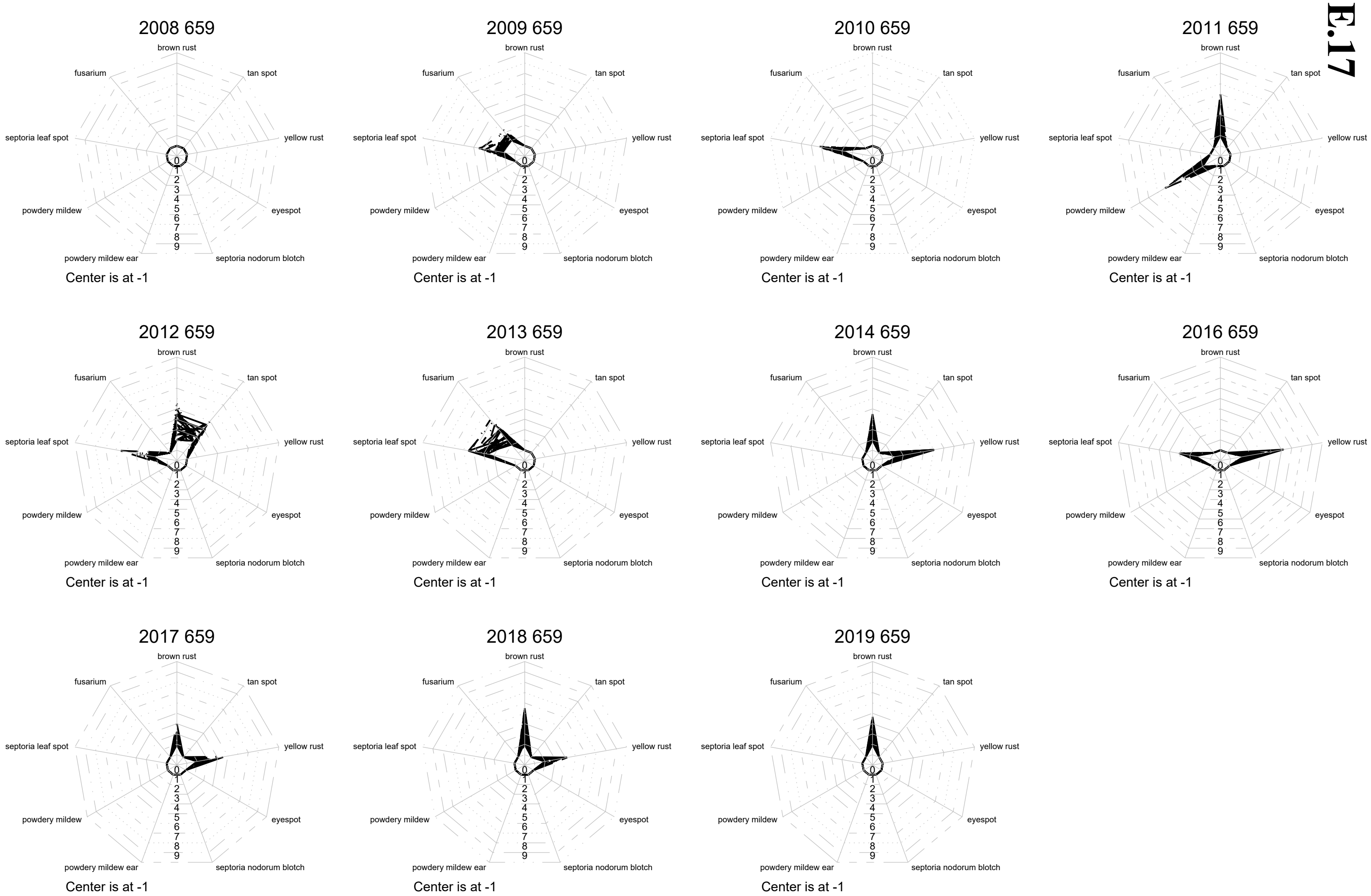
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eyespot
septoria nodorum blotch
powdery mildew ear
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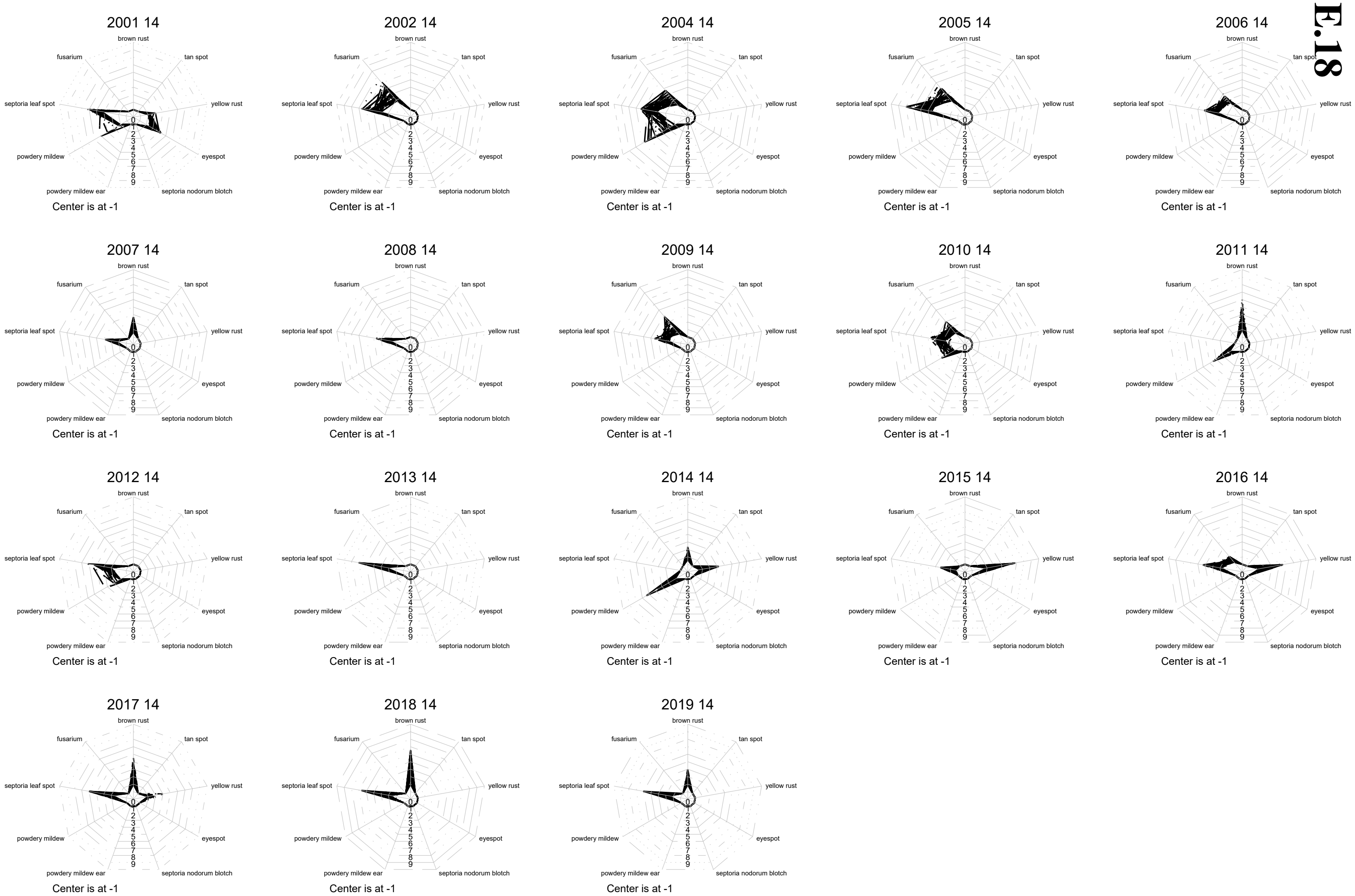
Center is at -1

E.18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2019 14
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
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fusarium
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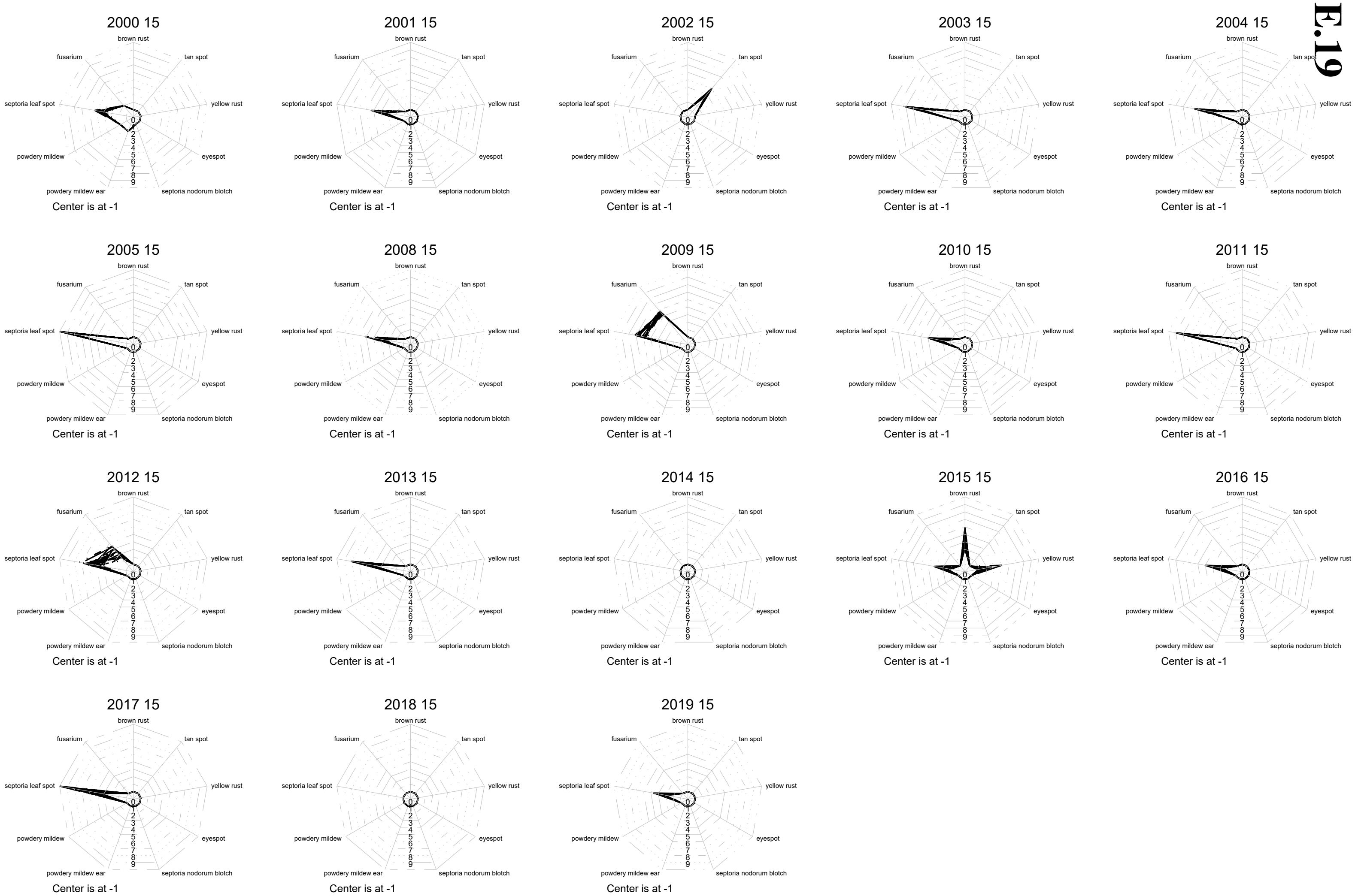
Center is at -1

E.19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2018 15
2019 15
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
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fusarium
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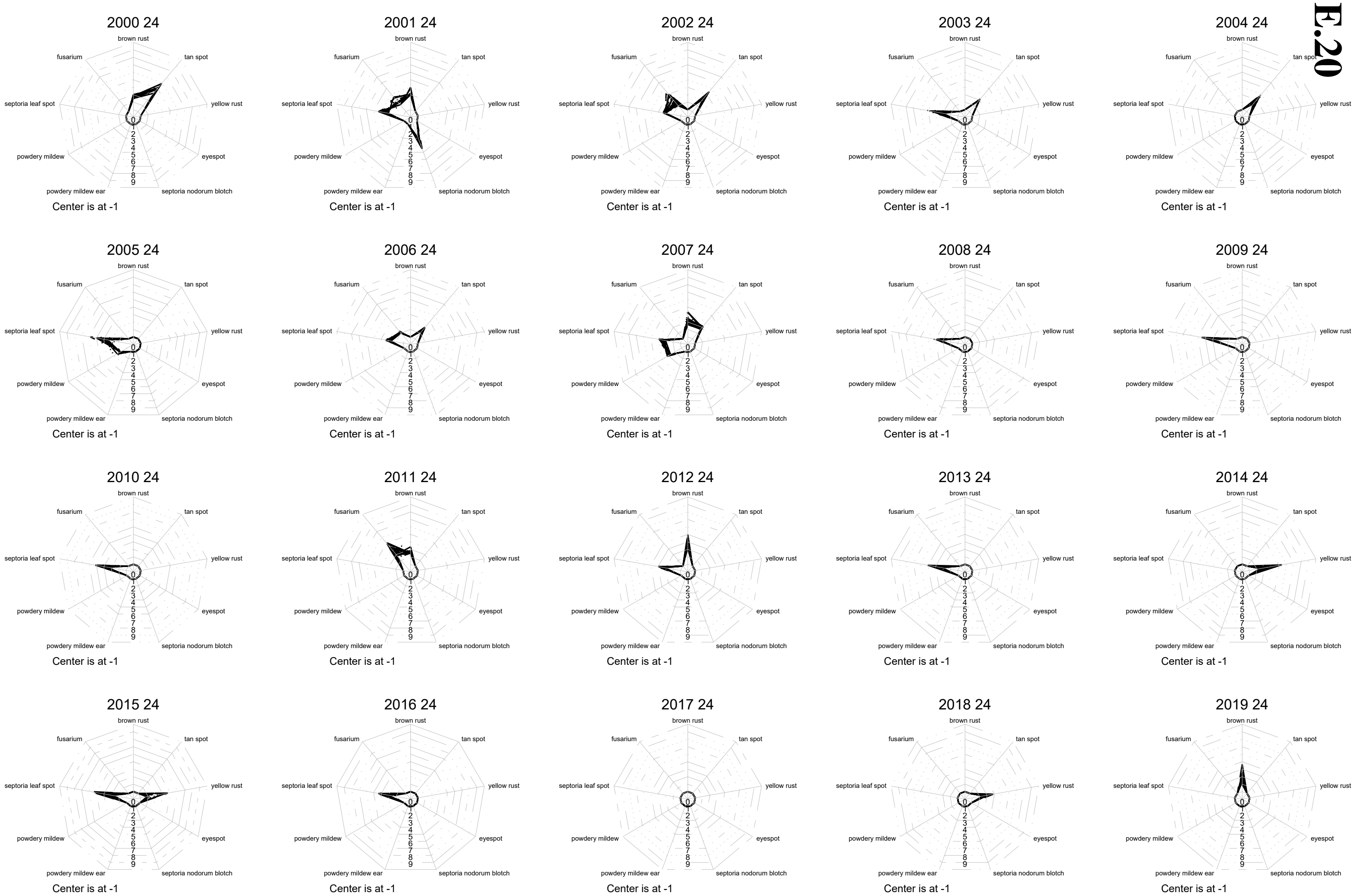
Center is at -1

E.20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2019 24
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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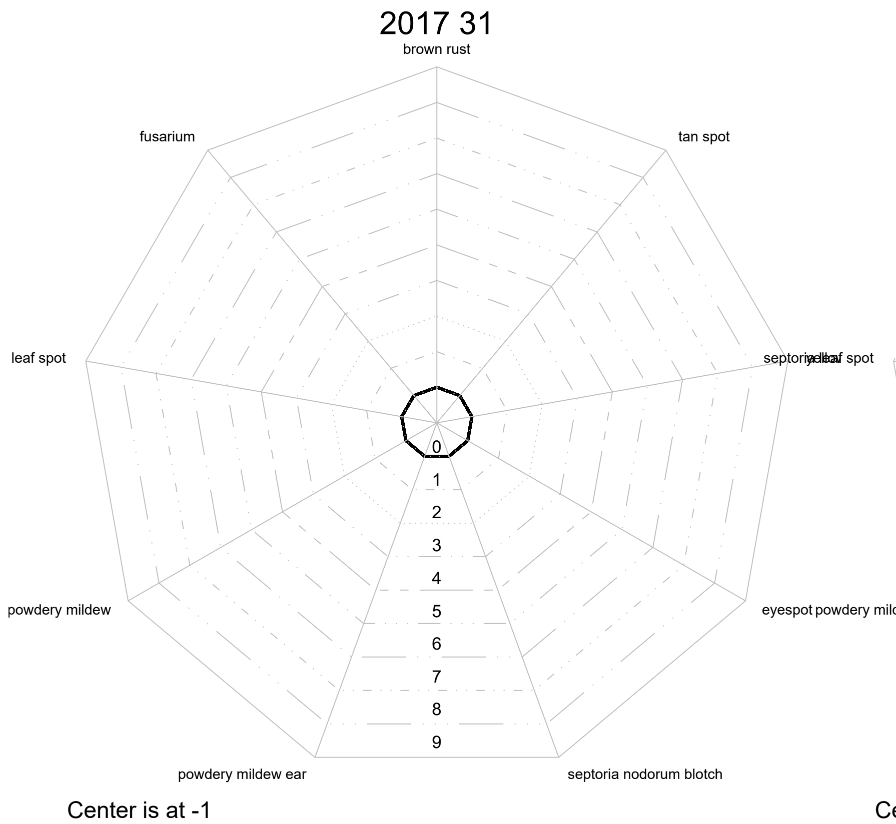
Center is at -1

E.21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eyespot
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leaf spot
fusarium
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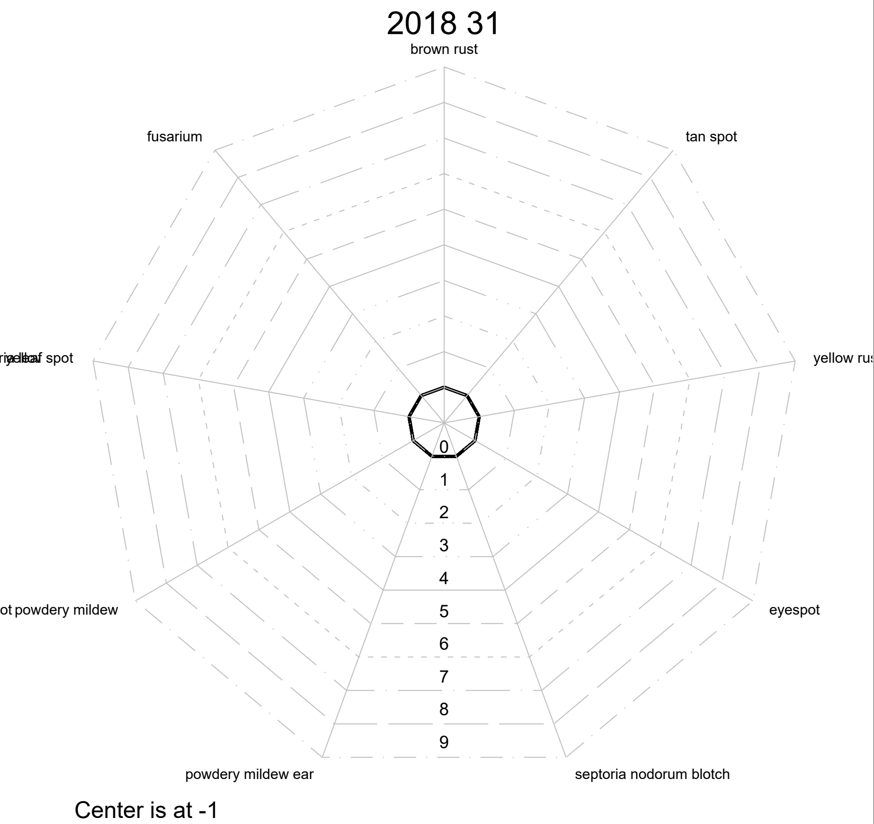
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eyespot
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powdery mildew
fusarium
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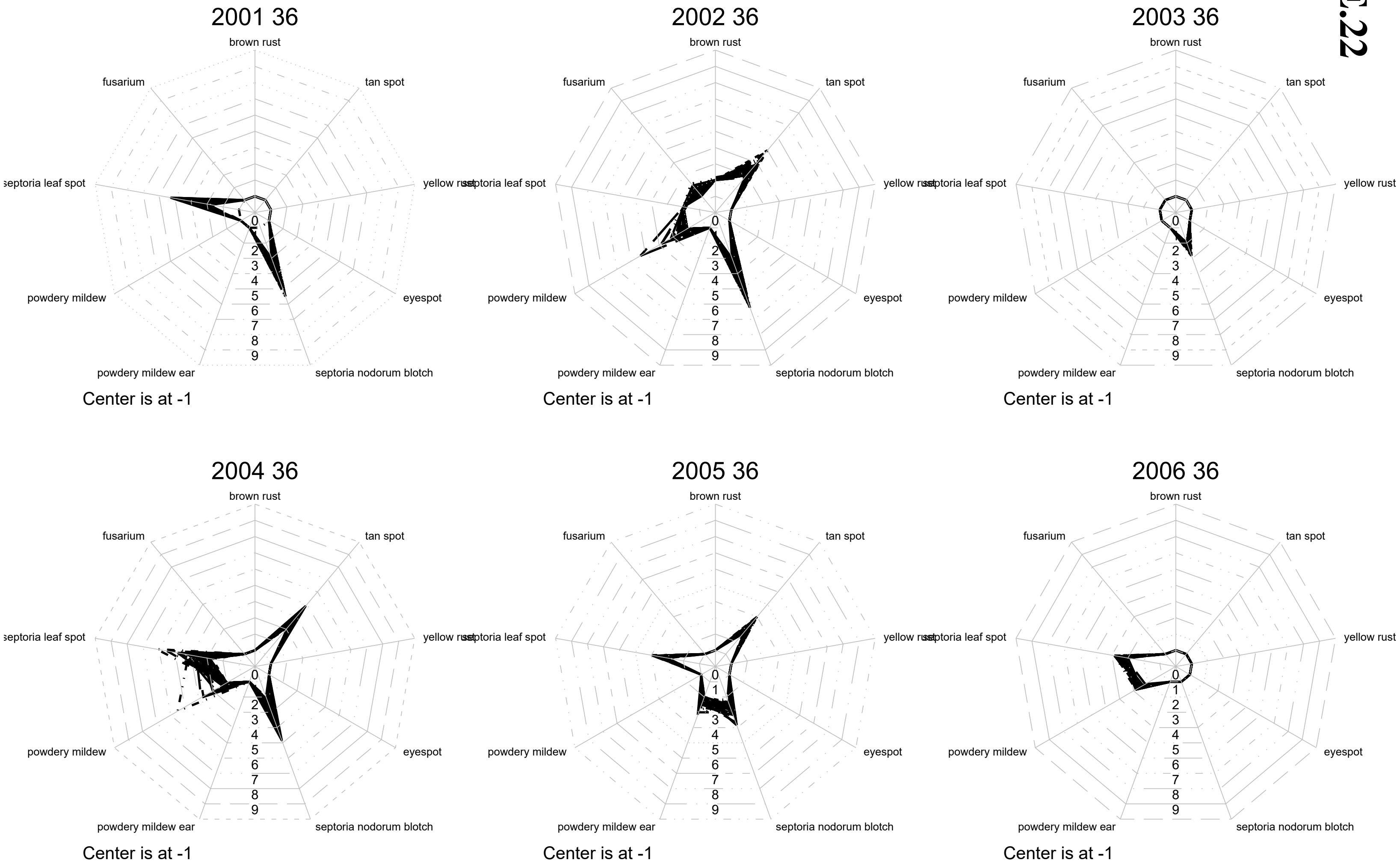
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fusarium
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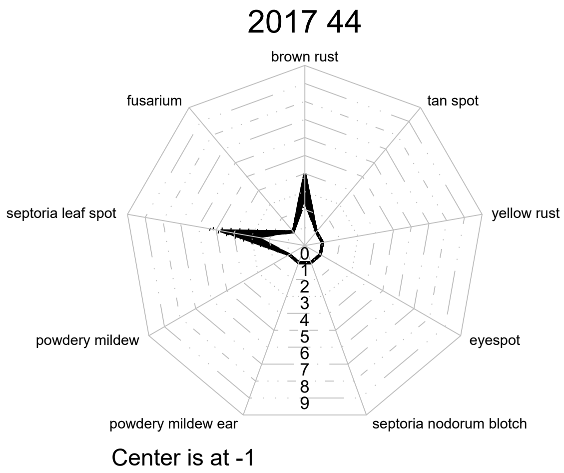
Center is at -1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powdery mildew ear
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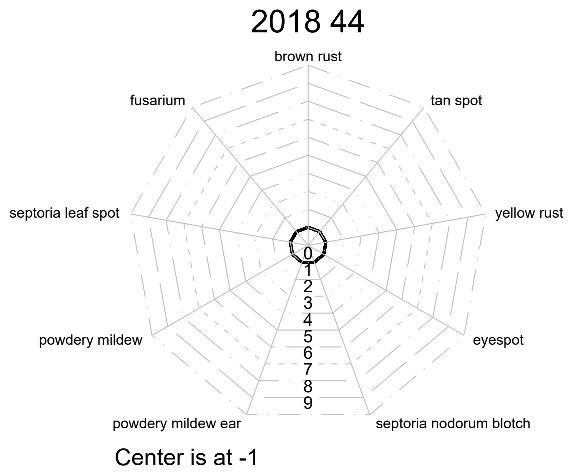
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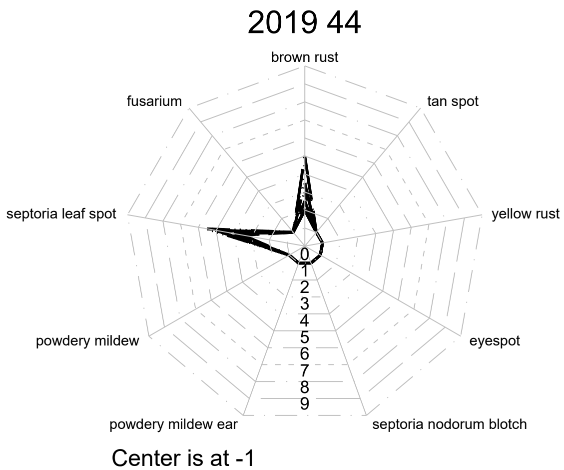
Center is at -1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fusarium
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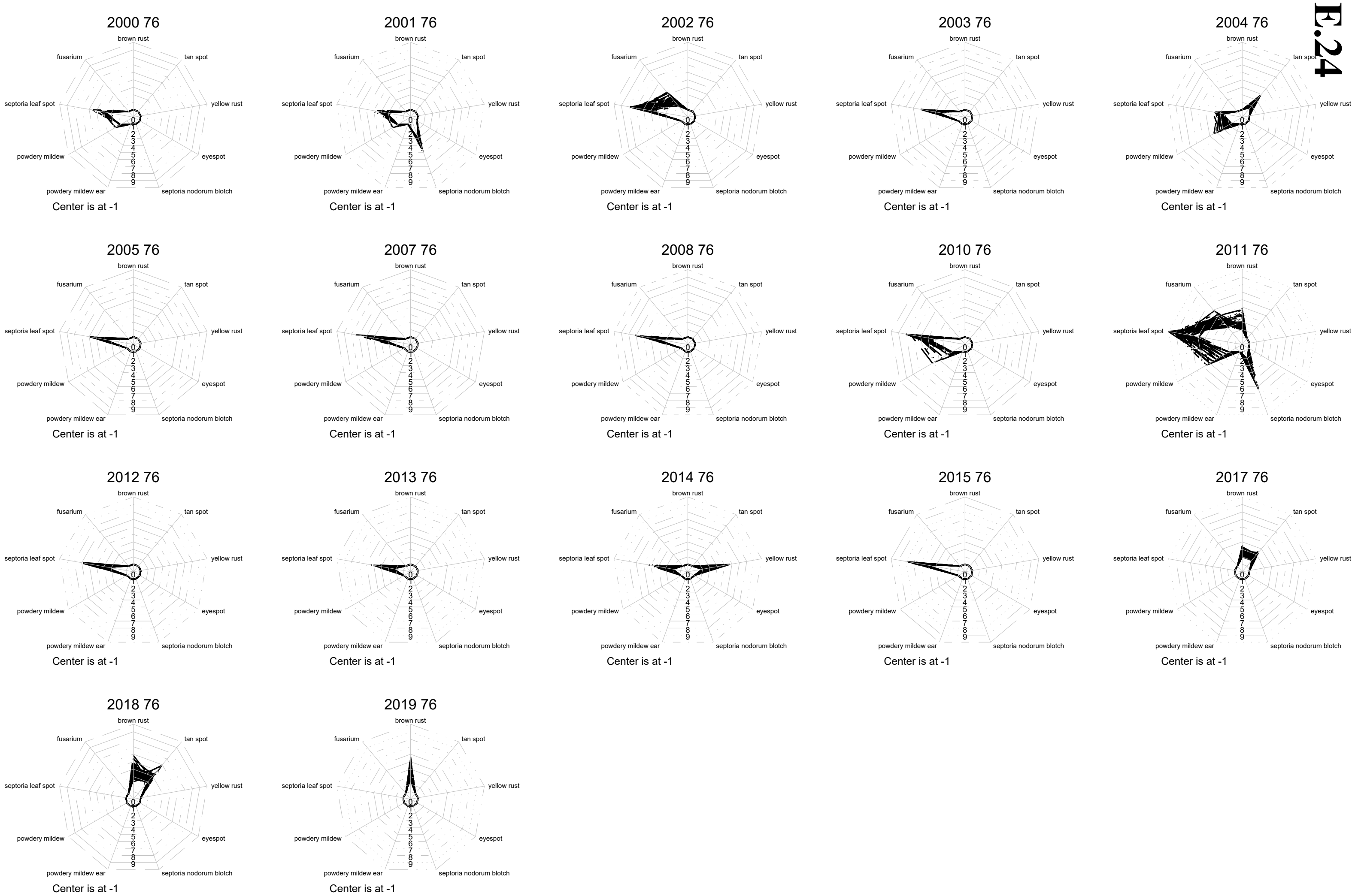
Center is at -1

E.24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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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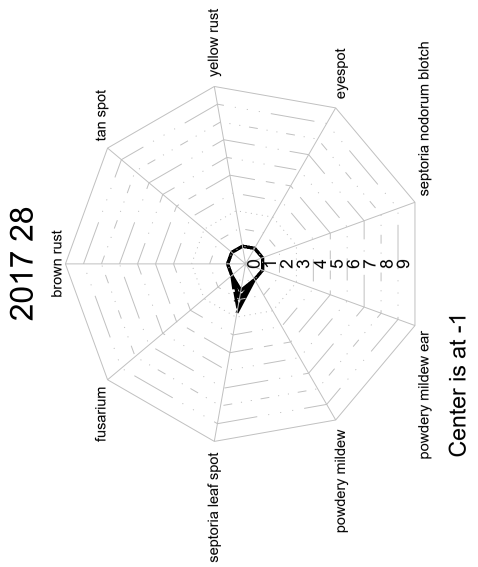
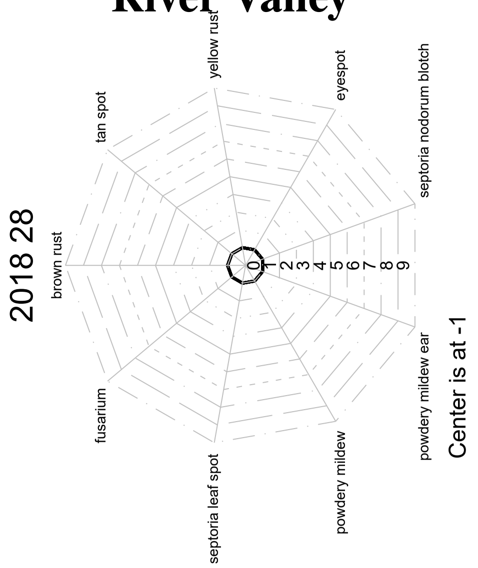
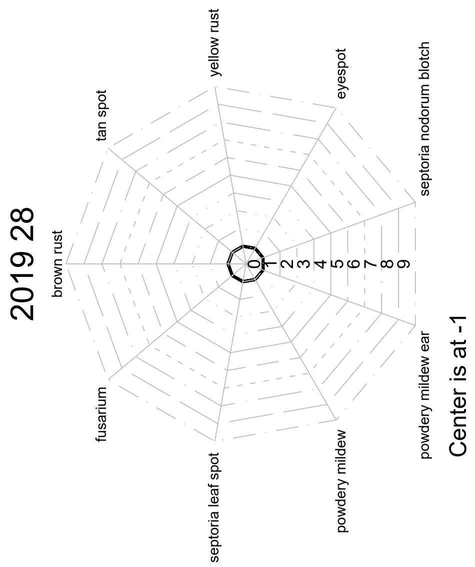
Center is at -1

E.25 116 Pedo-climatic zone - Gaeu, Danube and Inn River Valley







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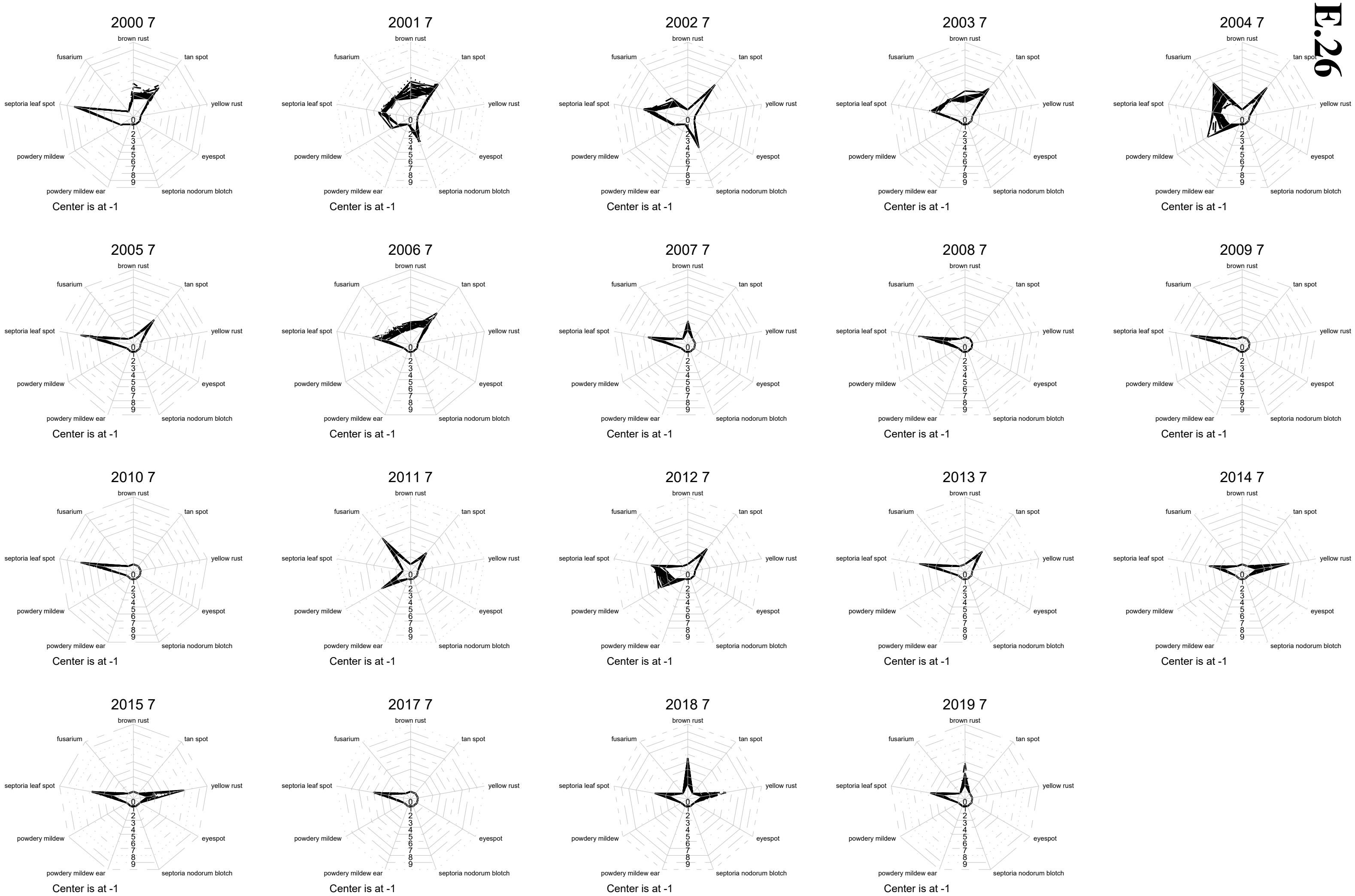
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2019 7
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
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fusarium
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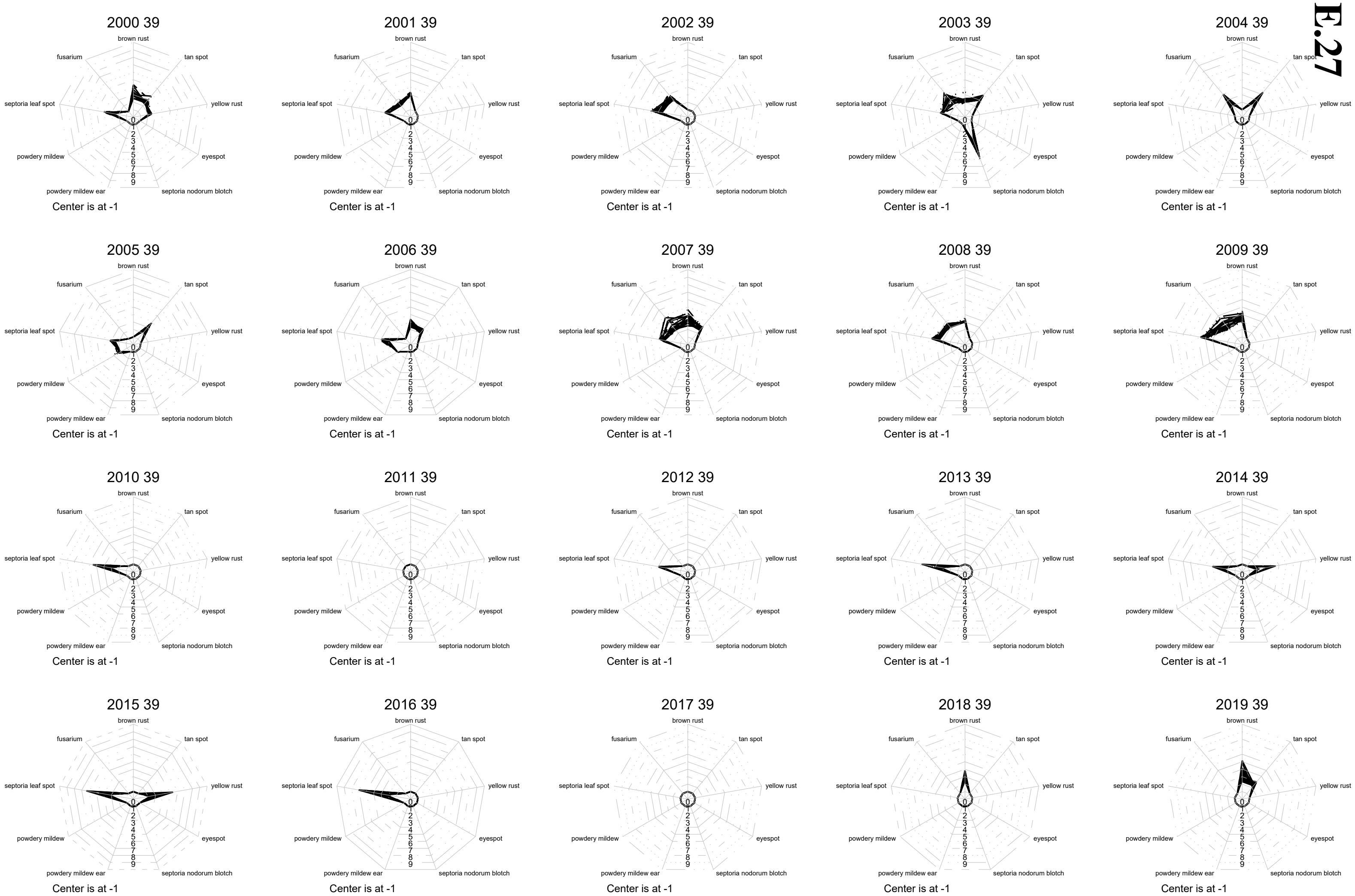
Center is at -1

E.27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2016 39
2017 39
2018 39
2019 39
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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Center is at -1

E.28 Construction of pest epidemic shocks

Pest shocks, also called pest epidemics in plant science, were constructed as relative measures representing underlying intuition that on average resistance of varieties in a place is breached such that spraying did not help their score performance anymore relative to the performance of the non-sprayed plants.

We developed this approach based on scoring practices by applied plant breeders, who design their nurseries such that they can evaluate pest shocks measures relative to the intensity of occurrence in a variety with a known threshold susceptibility (Becker, 2011; Braun, 2021; Gerullis, Heckelei, & Rasch, 2021; Timmermann, 2009). A variety measure is always the average over the variant plots of the same varieties, which received the same treatment or are part of the control group. We produced an average for each. This procedure will take care of random damage, e.g. due to deer, and lead to a more reliable estimate as it includes three to four different measures by the inspecting eye, and compensates for difference between people inspecting in the same place.

The original design of experiments includes a treatment and a control set of plots, with three to four repetitions for each. Where the treatment and control include the fertilization customary to the specific site location. The control receives no growth regulator and no fungicides, whereas the treatment will receive both if needed. If pesticides are applied they will be applied to the whole treatment group and not specific varieties. On average state testing includes roughly 30 admitted varieties, 10 varieties which have only regional relevance and 20 varieties which are tested for the federal variety admission process (Nickl & Schmidt, n.d.). We dropped the information from the federal variety admission process for our analyses.

When we say that we use the term **most susceptible variety**, as a relative measure, then it is important to recall, that we are using data from the state variety trials. Which means we are at a stage in the variety admission process, where we only encounter varieties, which exhibit a minimum resistance, as resistances are one of the thresholds criteria in the preceding admission process. We use the average of the most susceptible variety in the control to determine how intense pest infestations are.

This is due to the premise, that sprayed varieties will not exhibit as much of a pest incidence as non-sprayed ones.

We use the values of the most susceptible variety in a testing site to represent a kind of realized ecological niche (Hutchinson, 1957), where we use the most susceptible variety as a kind of indicator plant for how small or big the ecological niche is that varieties encounter in each place. Effectively, we transpose the most susceptible variety around the value 4.5. We chose the value of 4.5, as the score nomenclature is centered around this value, hence, a strong infestation will leave only little space visually - under the lines on the spokes of the radar graphs.

Visually we represented these types of ecological niches in the figures E.29 to **??**. The visual intuition, which we want to produce, is that we can see where the scoring of the varieties in a place breached the ecological niche, compared to where the varieties were resistant enough. Resistant enough means that they have a low score and hence visually "fit into" the bounds of the ecological niche set by the pest.[1] This notion of two organisms competing over an ecological space and was coined by Hutchinson (1957). In agriculture a field where a crop-pathogen interaction plays out, as we effectively see in the variety trial outcomes is subject to the same mechanisms, yet, outcomes are influenced by more uniformity in the crops compared to wild ecological environment (Brown, Tellier, et al., 2011).

For the interpretation of the graphs refer to figure E.1 for the following:

Figure E.1 shows that there is no pest occurrence in e.g. powdery mildew on the ears as encircled with the color green in panel B. Encircled with orange in panel B we see varieties responding to the disease outbreak, but it is not breaching our ecological niche line. Hence we can interpret this as not being such a severe outbreak of the disease and the varieties actually "fit" into the niche, marked in orange. In panel B on the spoke for septoria leaf spot, we see how an outbreak decomposes the varieties in those, which fit into the niche - marked in yellow - compared to those which are breaching the niche - encircled in blue.

[1]One can use the image of a shape sorting game that toddlers usually use where they need to sort different shapes into a whole shaped the same way.

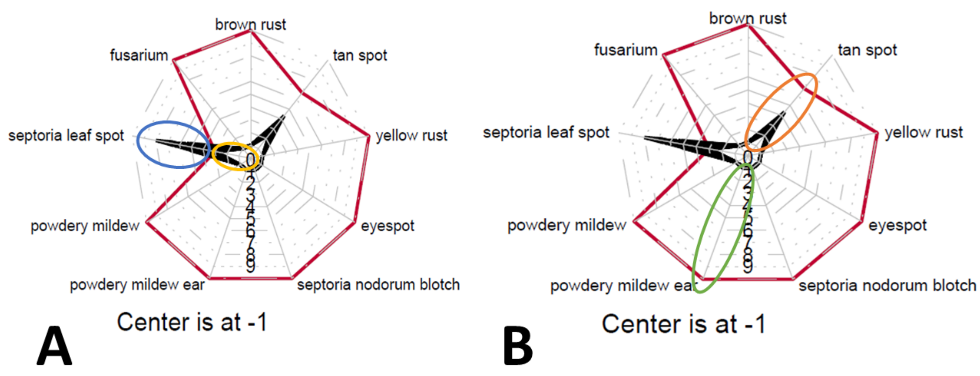


FIGURE E.1: Interpretation of pest occurrences relative to ecological niche

An epidemic shock occurs in our sample when all of the varieties in a place breach the ecological niche or meet their niche boundary. Our interpretation of this is that farmers even if they were to spray their varieties in case of such a severe pest occurrence, would not be able to do anything against it anymore.

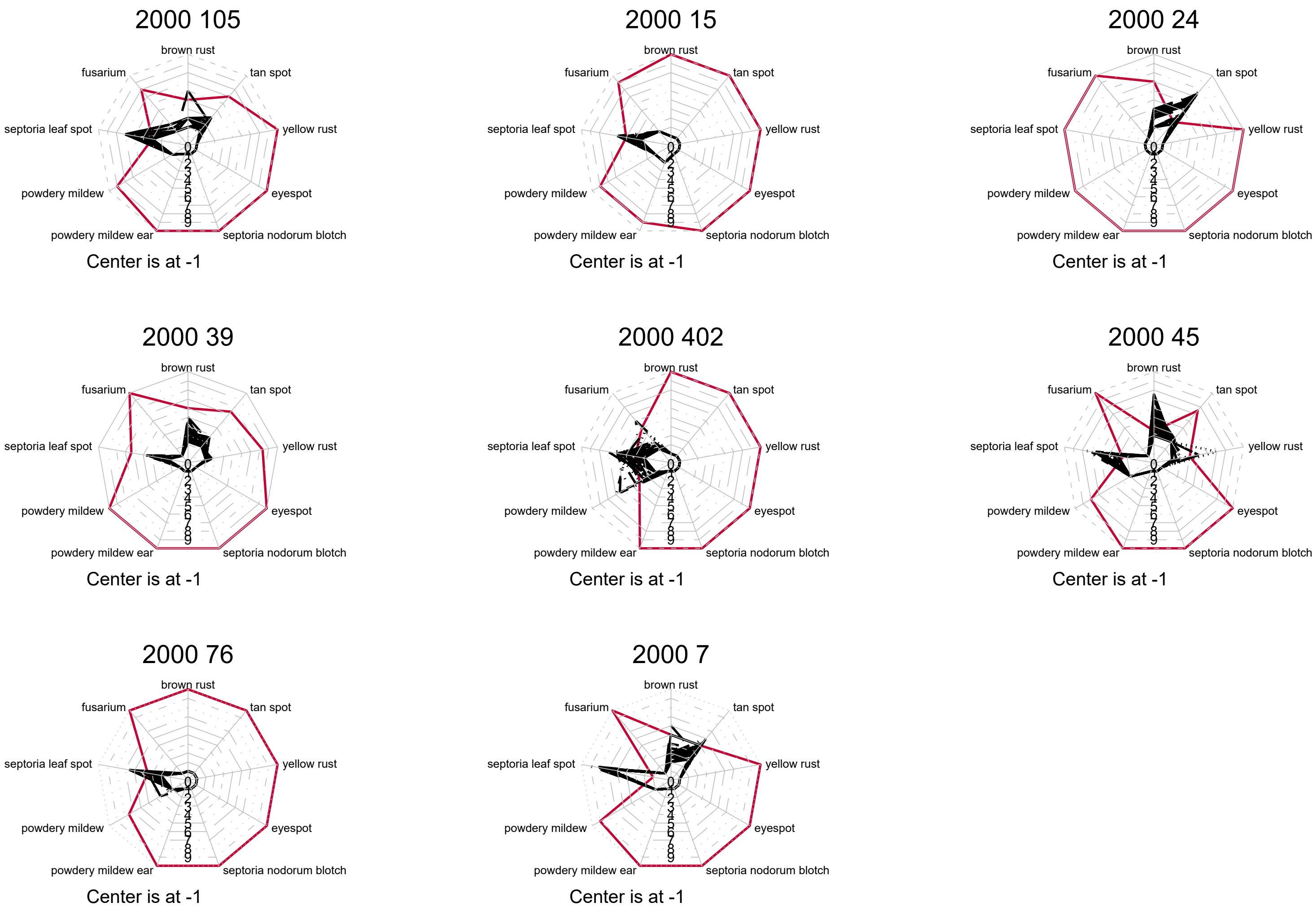
Nomenclature: On each of the following appendix pages we show for each year the concurrent occurrence of different diseases with one radar plot each per testing site. The first number above the radar plot denotes the year and the digits after each represent the testing site. Each spoke represents a different disease and the individual lines in black represent the variety performance of a variety under treatment with fungicides. The red line in each graph represents the realized ecological niche described above under appendix section E.28.

The scores for disease infection according to (Moll et al., 2009; Nickl & Schmidt, n.d.), which reflects national variety classification standards. (Bundessortenamt, 2000)

- 1 very little to no infestation
- 2 very little to low infestation

- 3 low infestation
- 4 low to medium infestation
- 5 medium infestation
- 6 medium to strong infestation
- 7 strong infestation
- 8 strong to very strong infestation
- 9 very strong infestation

E.29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2000 24
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2000 402
2000 45
2000 76
2000 7
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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
0
1
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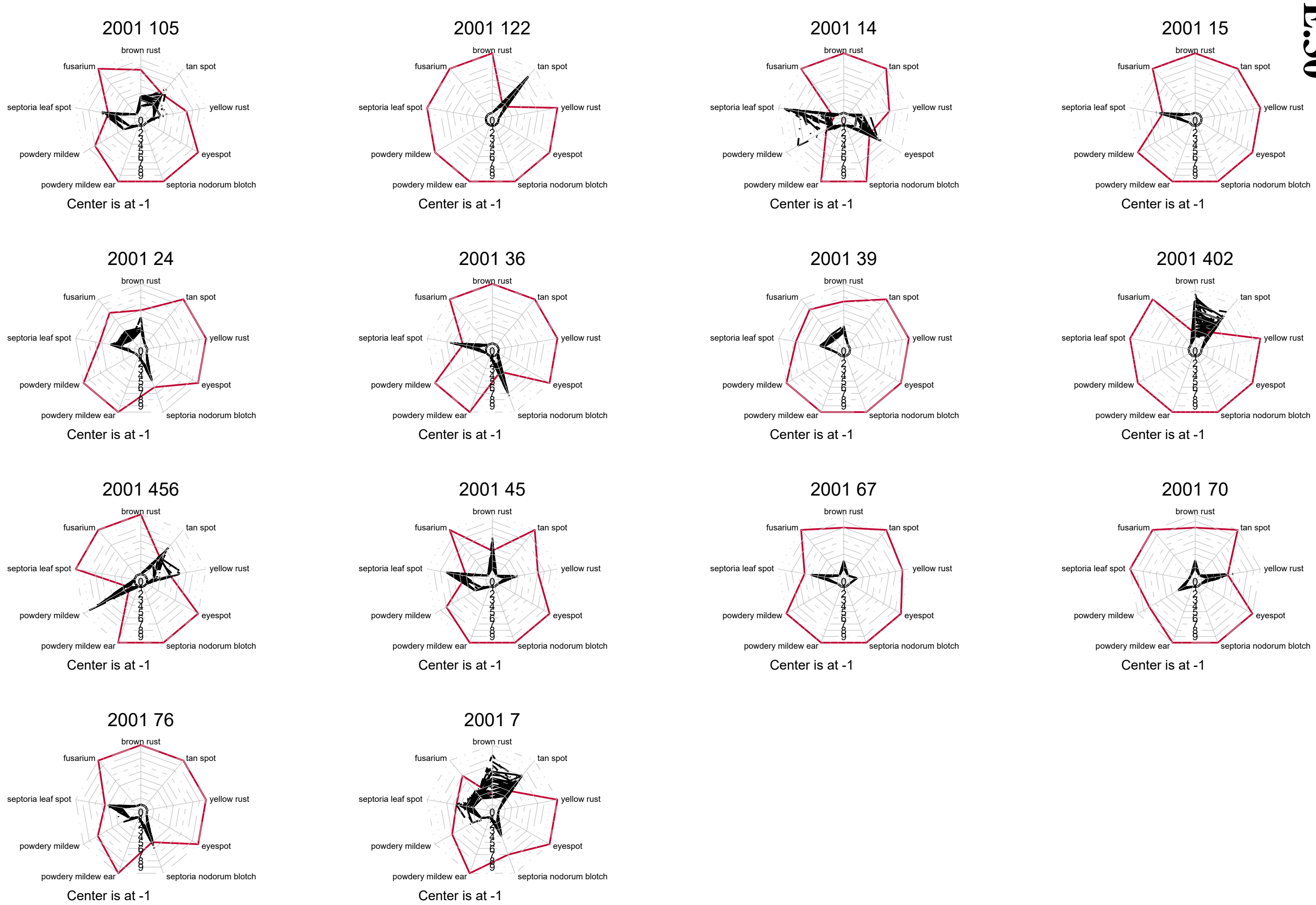
7
8
9
Center is at -1

E.30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2001 24
2001 36
2001 39
2001 402
2001 456
2001 45
2001 67
2001 70
2001 76
2001 7
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yellow rust
eyespot
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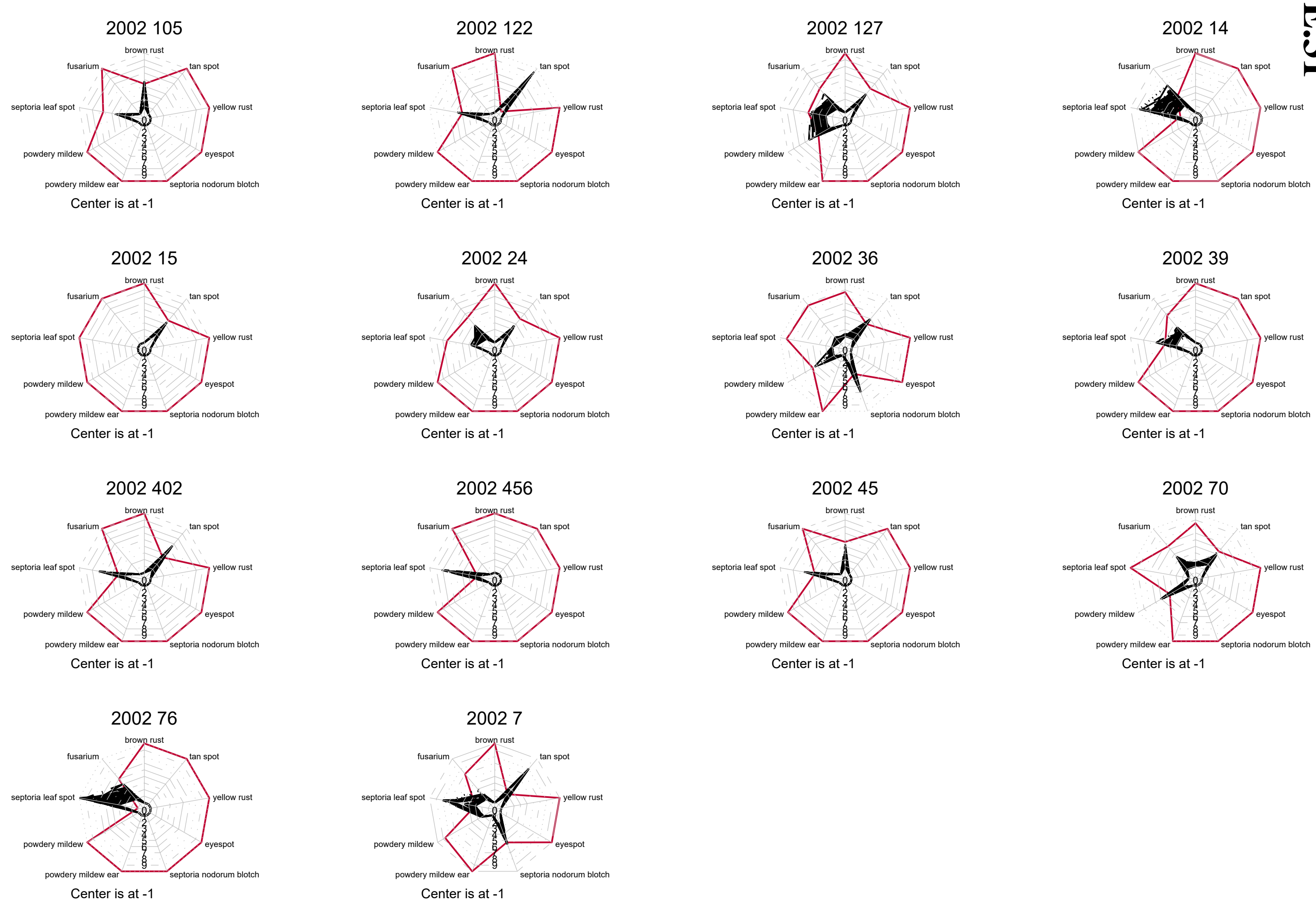
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1

E.31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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
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fusarium
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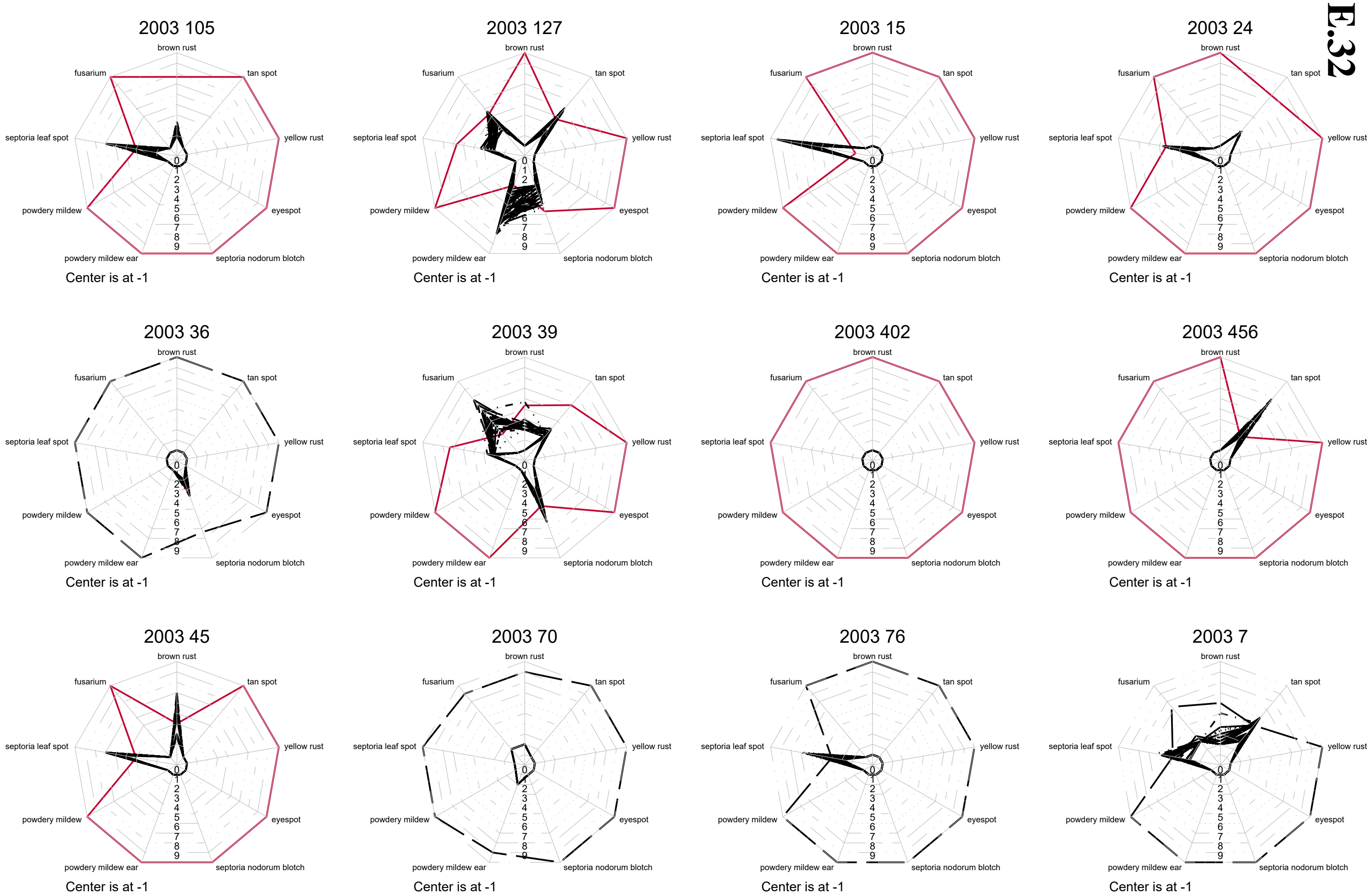
Center is at -1

E.32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powdery mildew
septoria leaf spot
fusarium
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Center is at -1
2003 127
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2003 15
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2003 24
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
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brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2003 39
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2003 402
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
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brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2003 45
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2003 70
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tan spot
yellow rust
eyespot
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powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2003 76
brown rust
tan spot
yellow rust
eyespot
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powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2003 7
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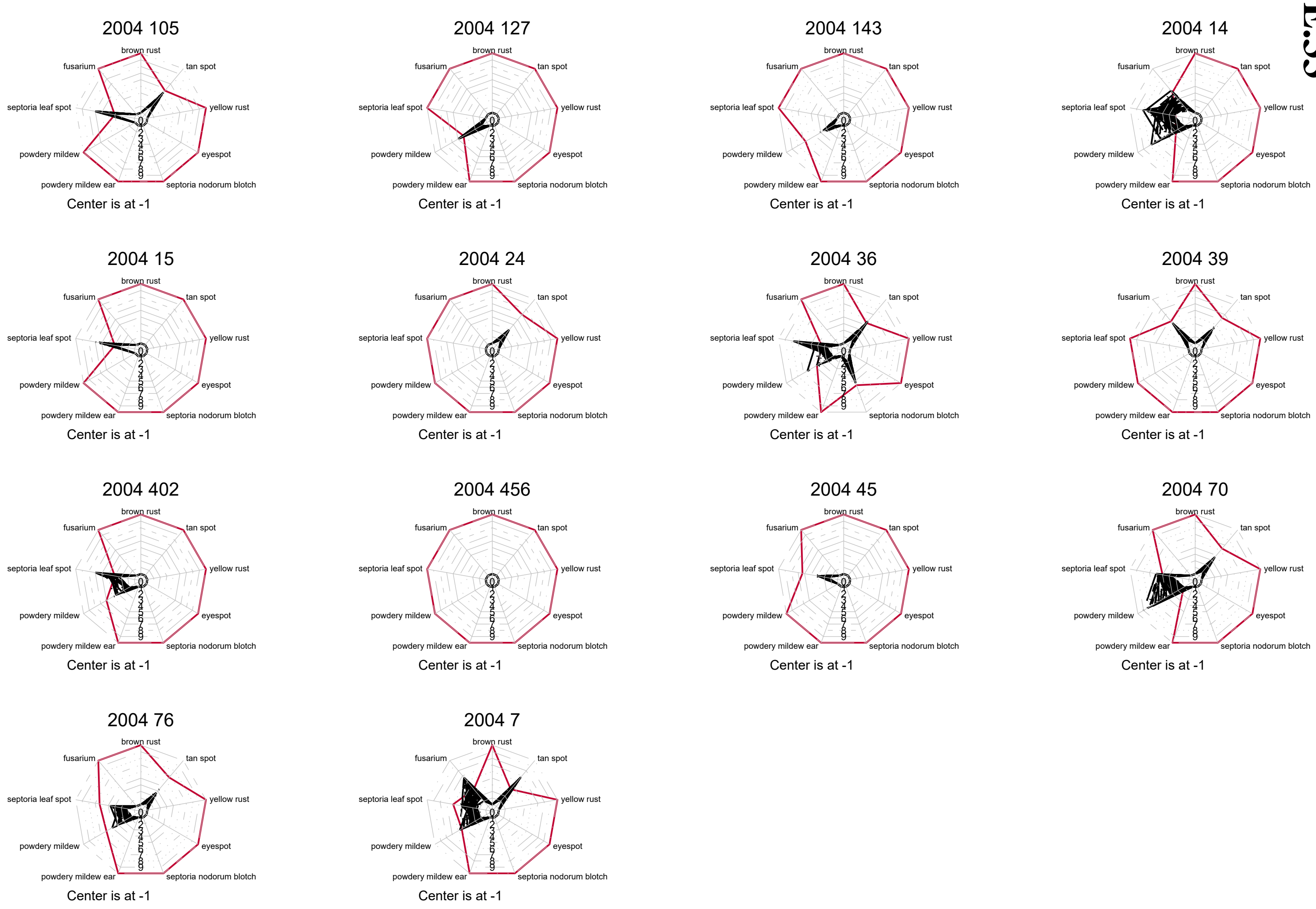
powdery mildew
septoria leaf spot
fusarium
Center is at -1

E.33



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2004 70
2004 76
2004 7
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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
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fusarium
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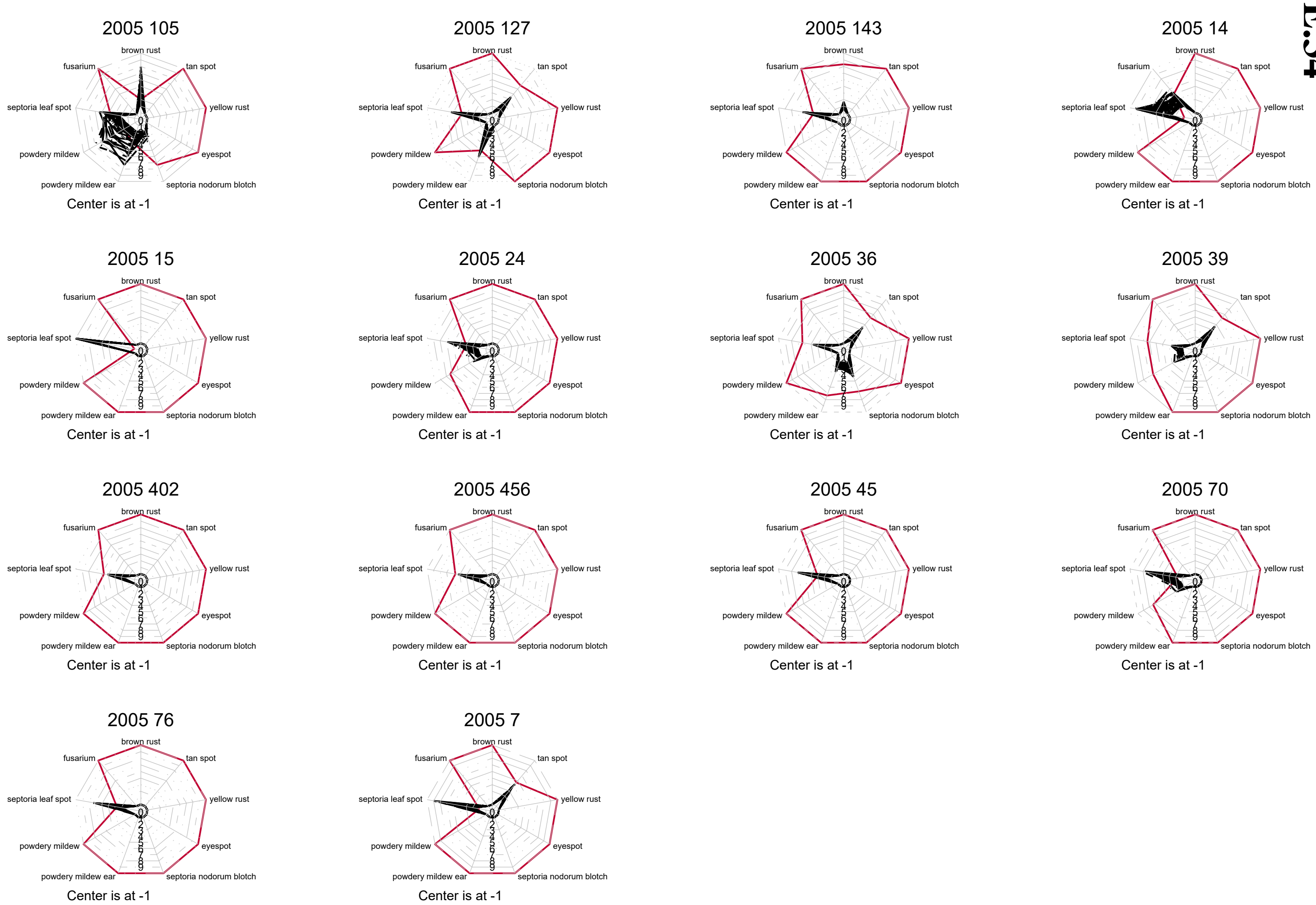
Center is at -1

E.34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2005 76
2005 7
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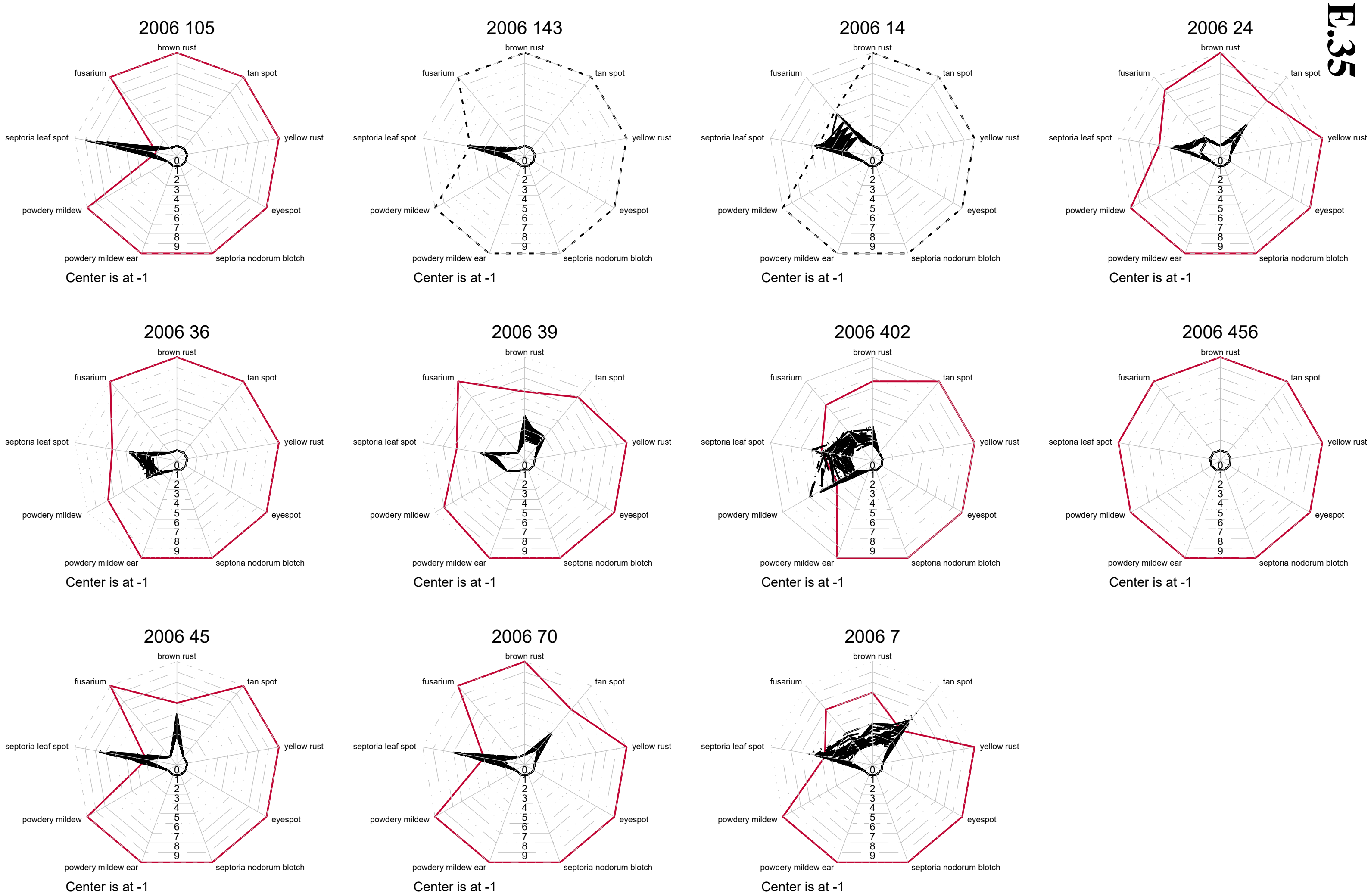
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1

E.35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powdery mildew ear
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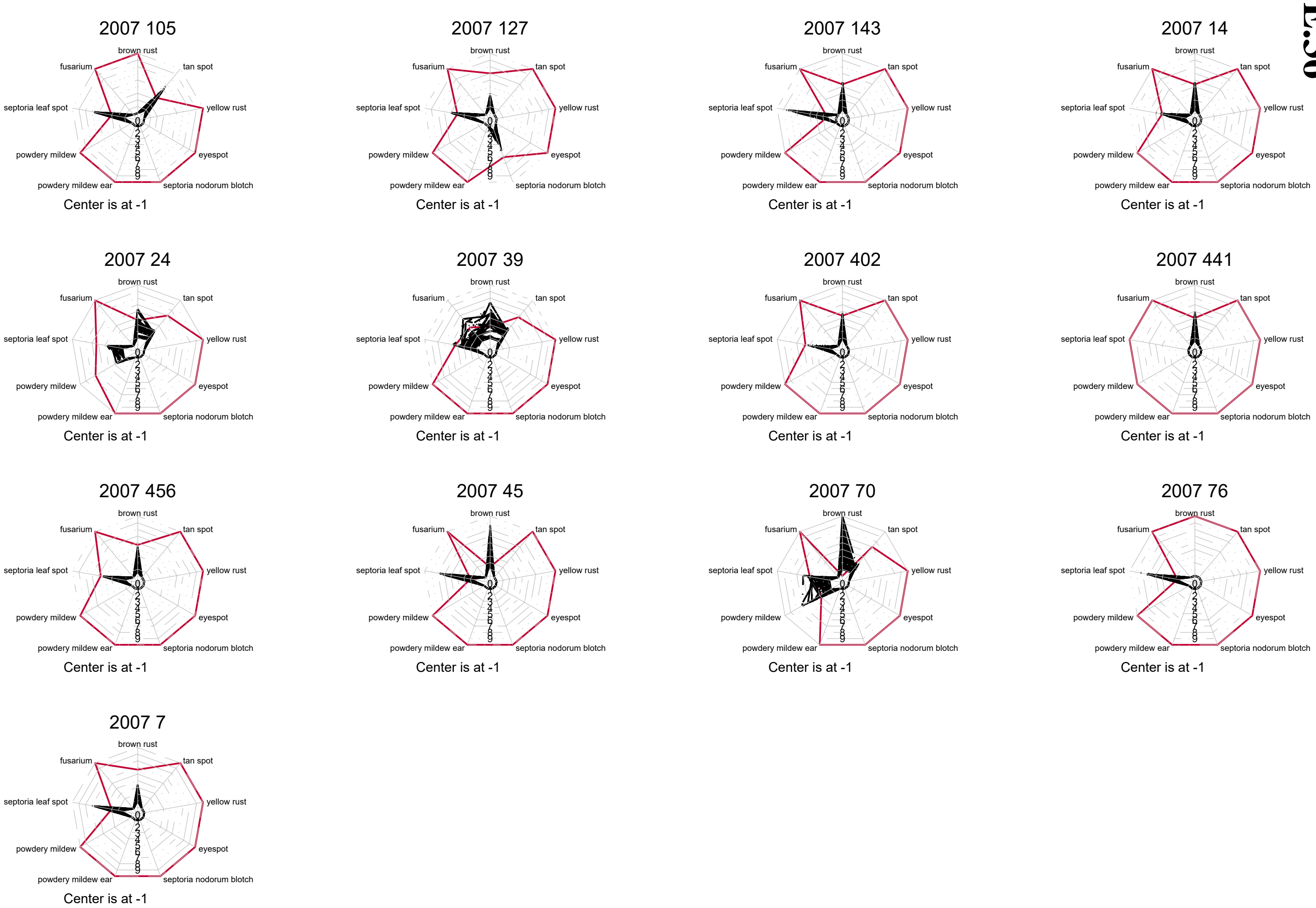
Center is at -1

E.36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powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1
2007 127
Center is at -1
2007 143
Center is at -1
2007 14
Center is at -1
2007 24
Center is at -1
2007 39
Center is at -1
2007 402
Center is at -1
2007 441
Center is at -1
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2007 70
Center is at -1
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Center is at -1

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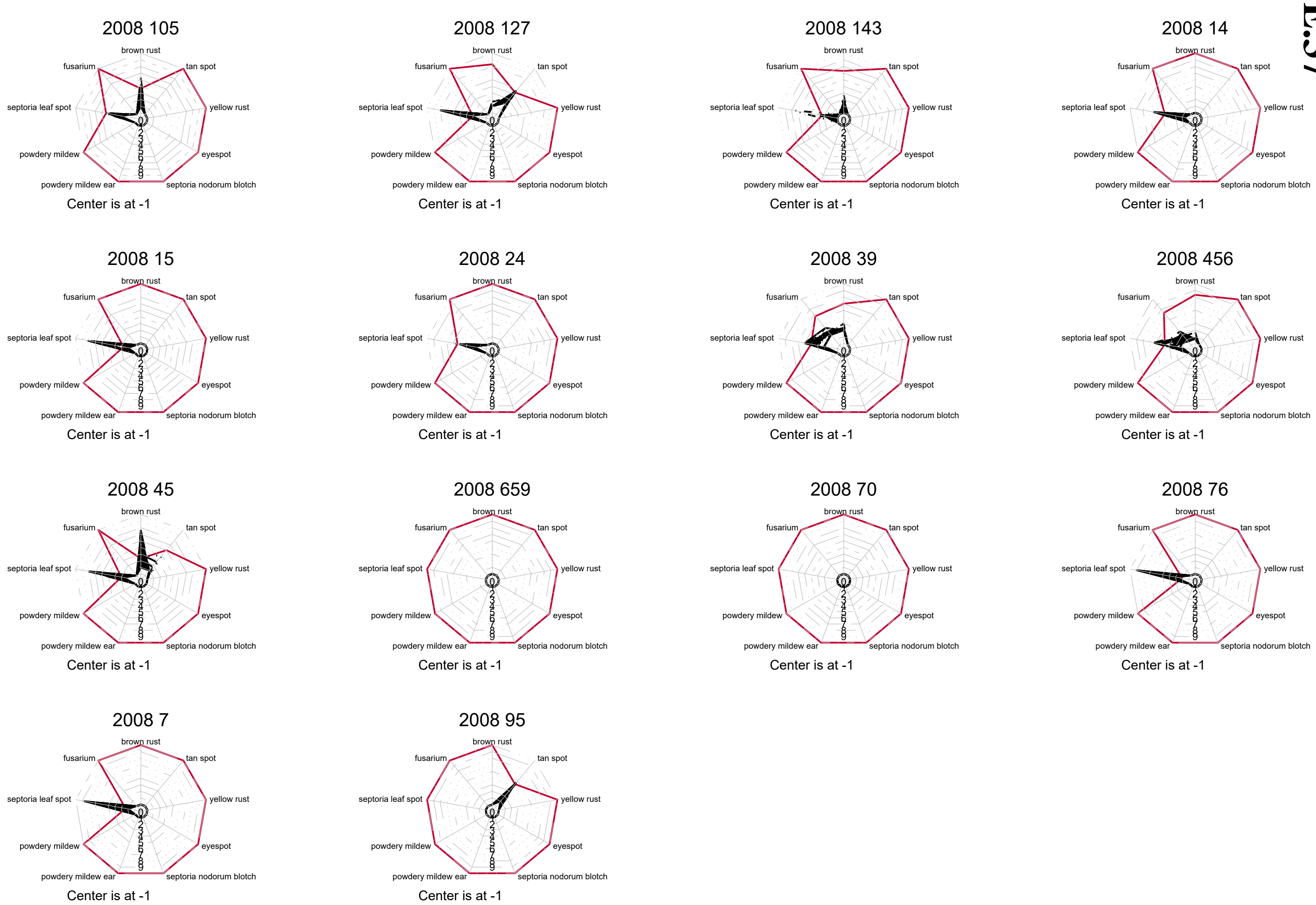
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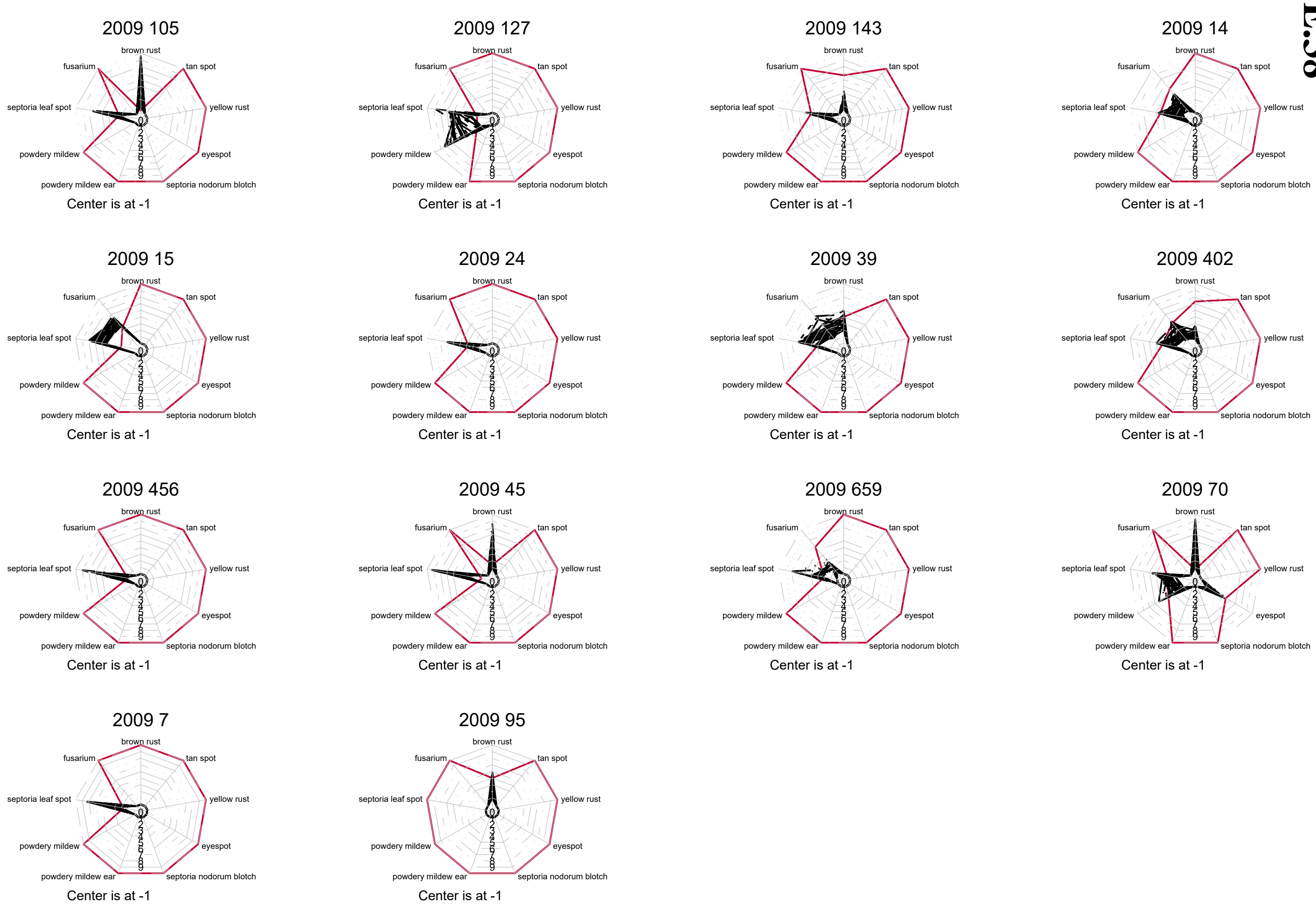
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1

E.38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tan spot
yellow rust
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powdery mildew
septoria leaf spot
fusarium
Center is at -1

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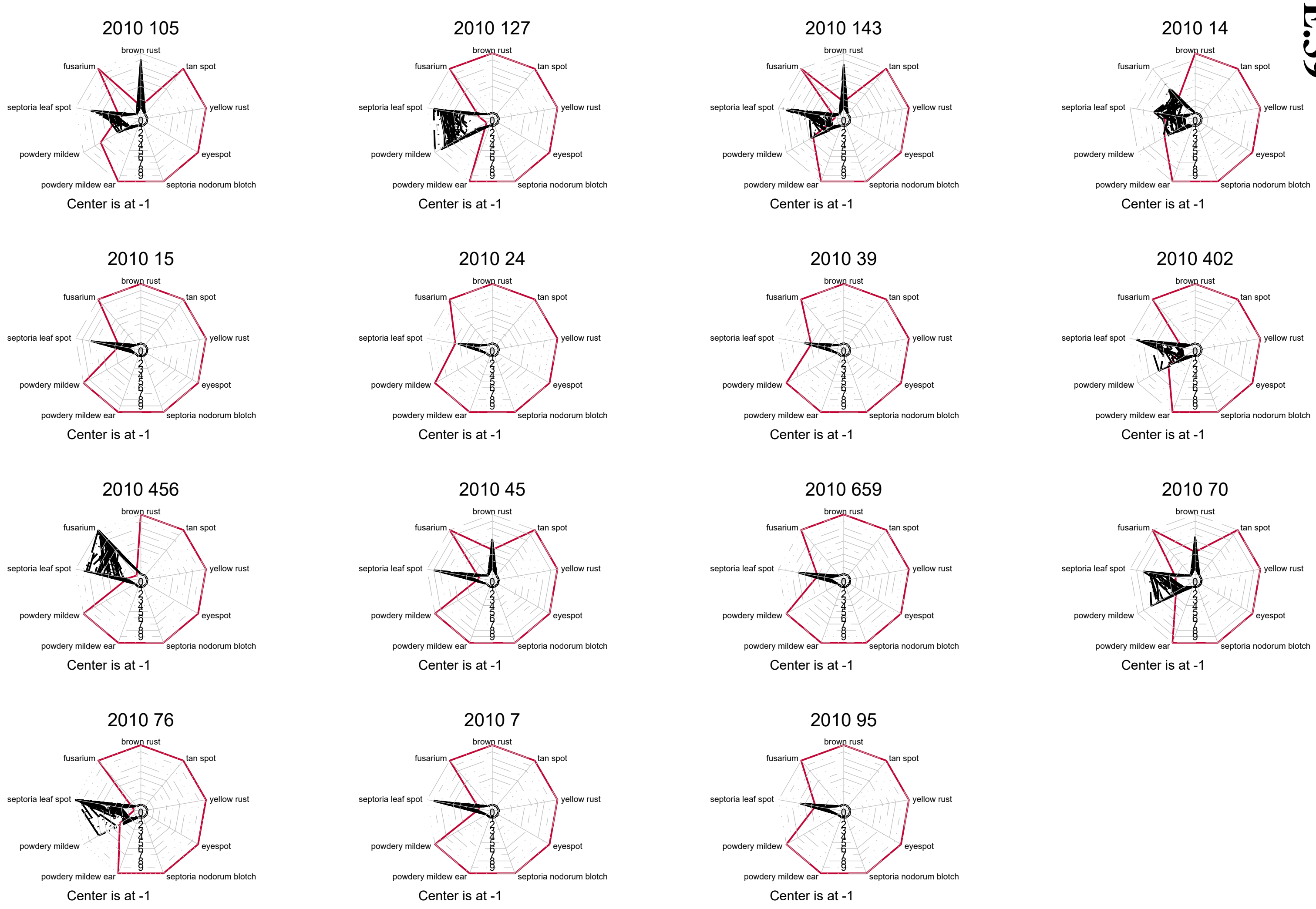
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brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
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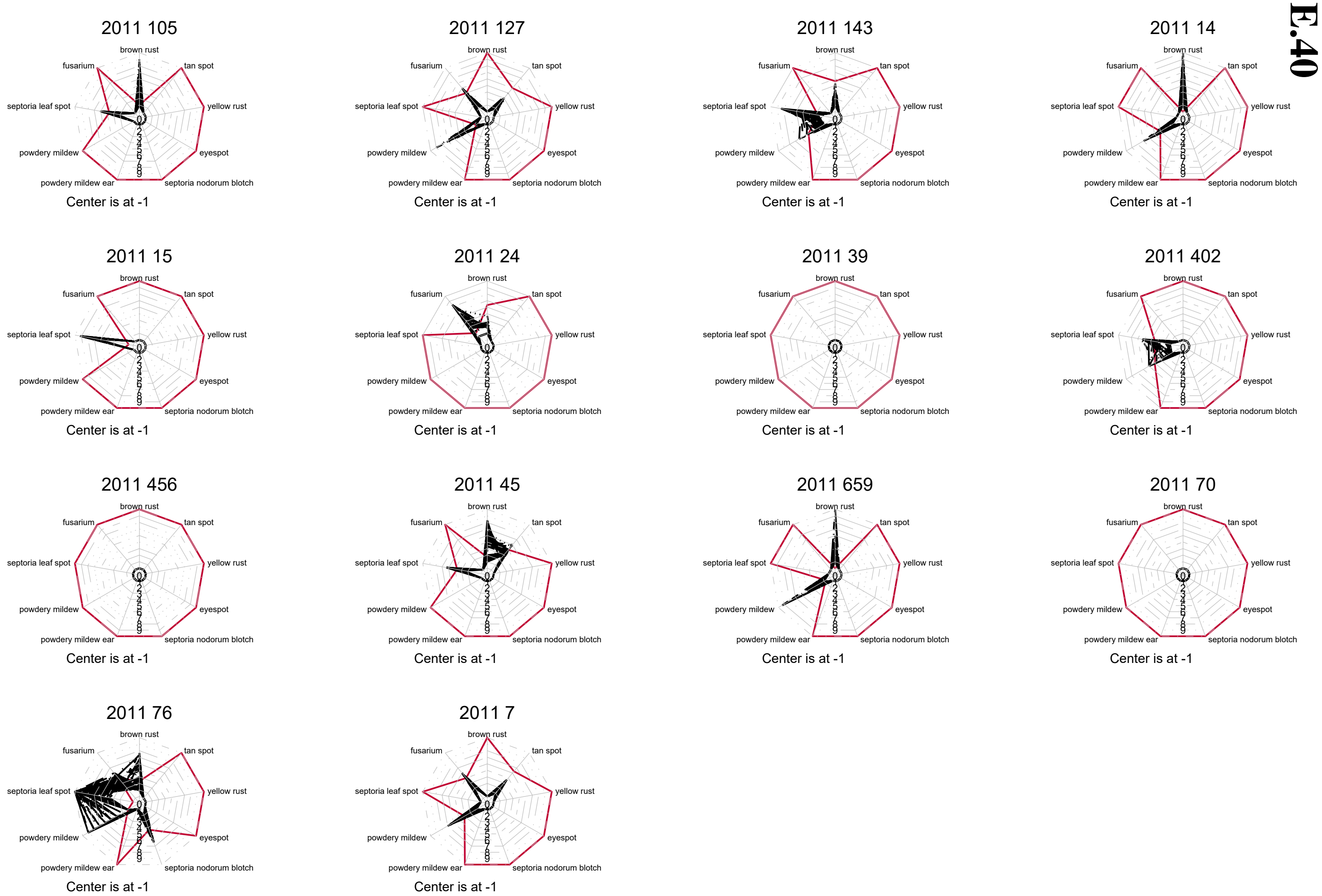
E.40



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2011 76
2011 7
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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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Center is at -1

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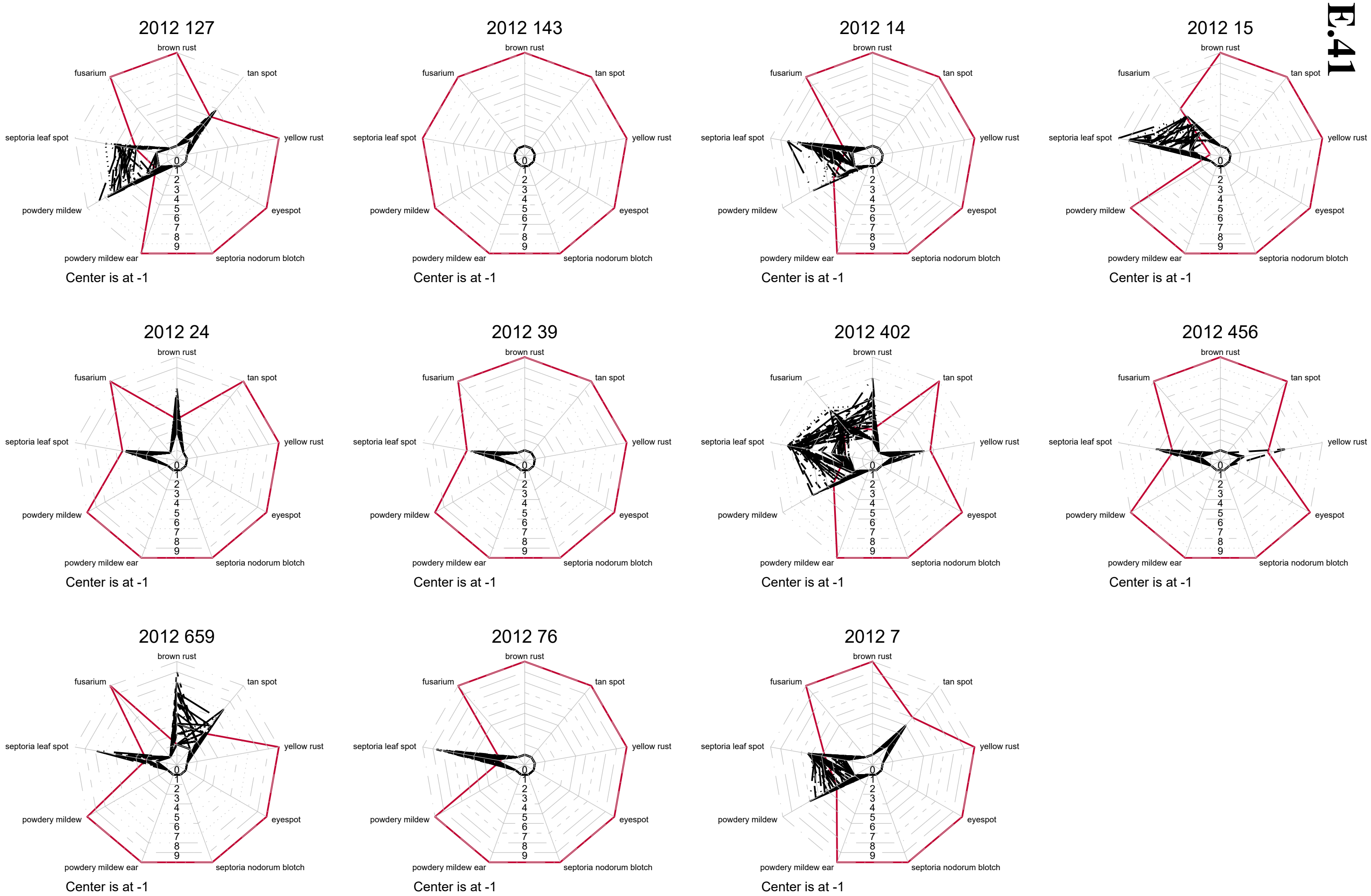
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tan spot
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eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
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fusarium
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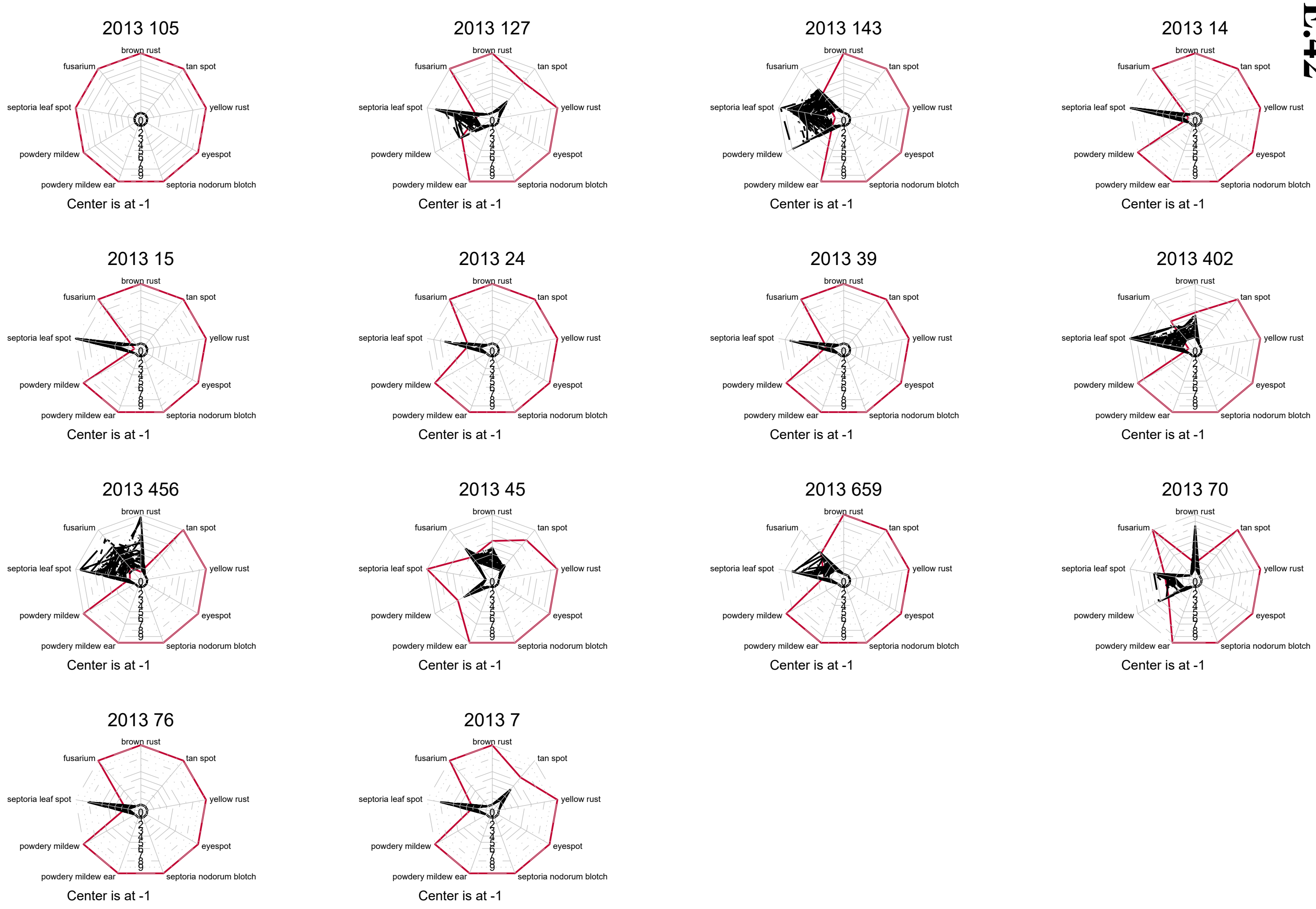
Center is at -1

E.42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2013 70
2013 76
2013 7
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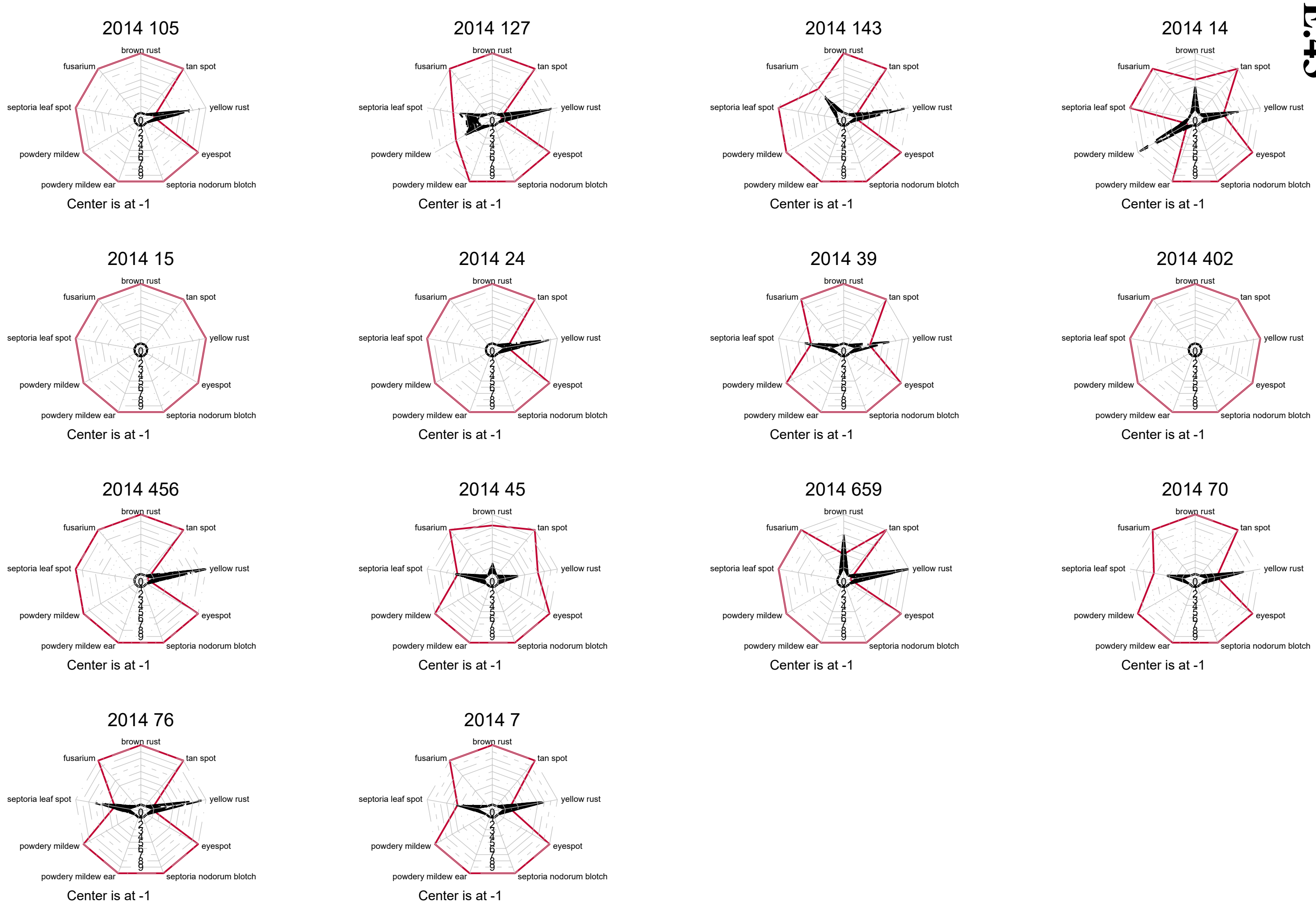
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1

E.43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2014 402
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2014 70
2014 76
2014 7
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tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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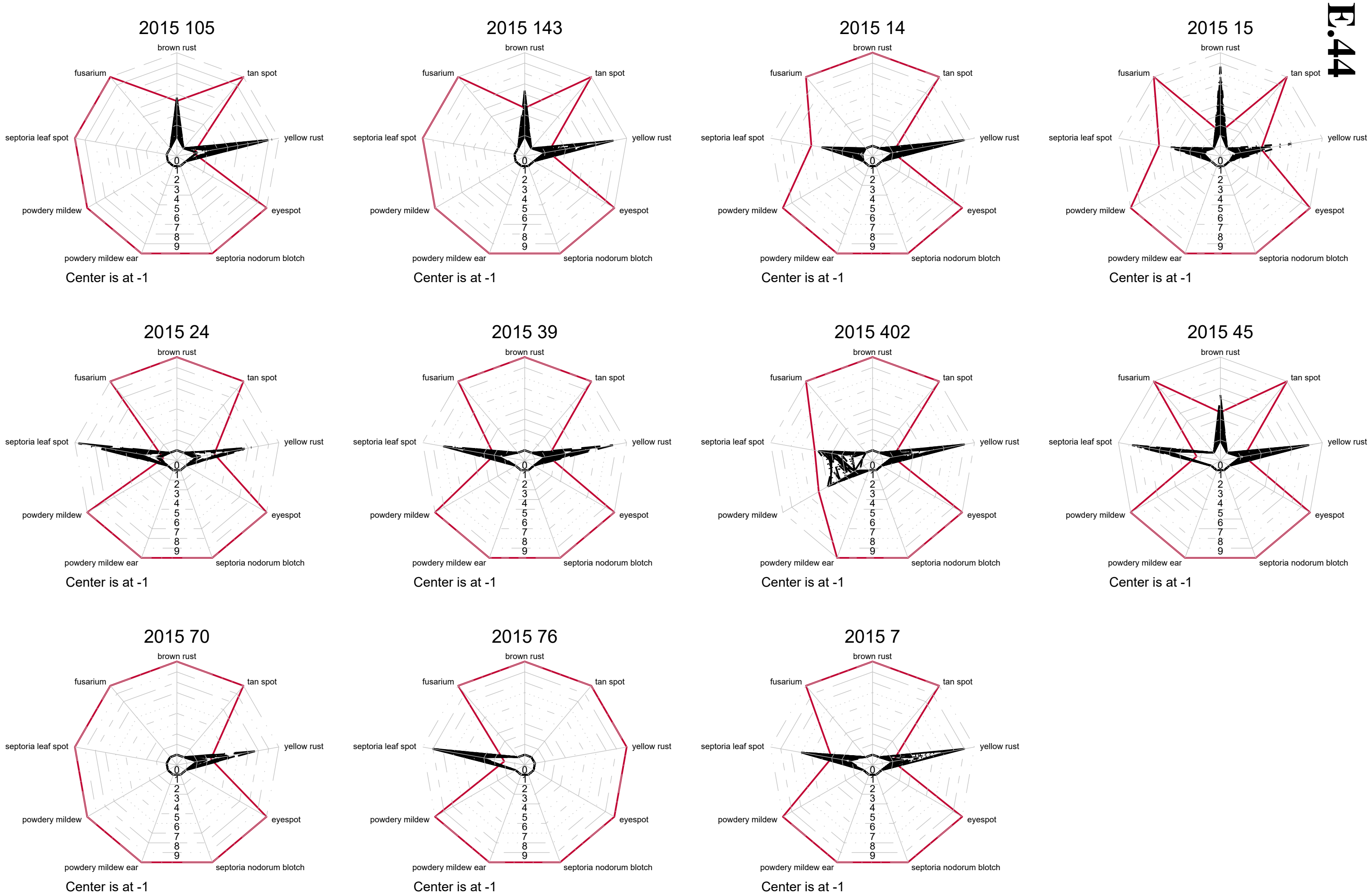
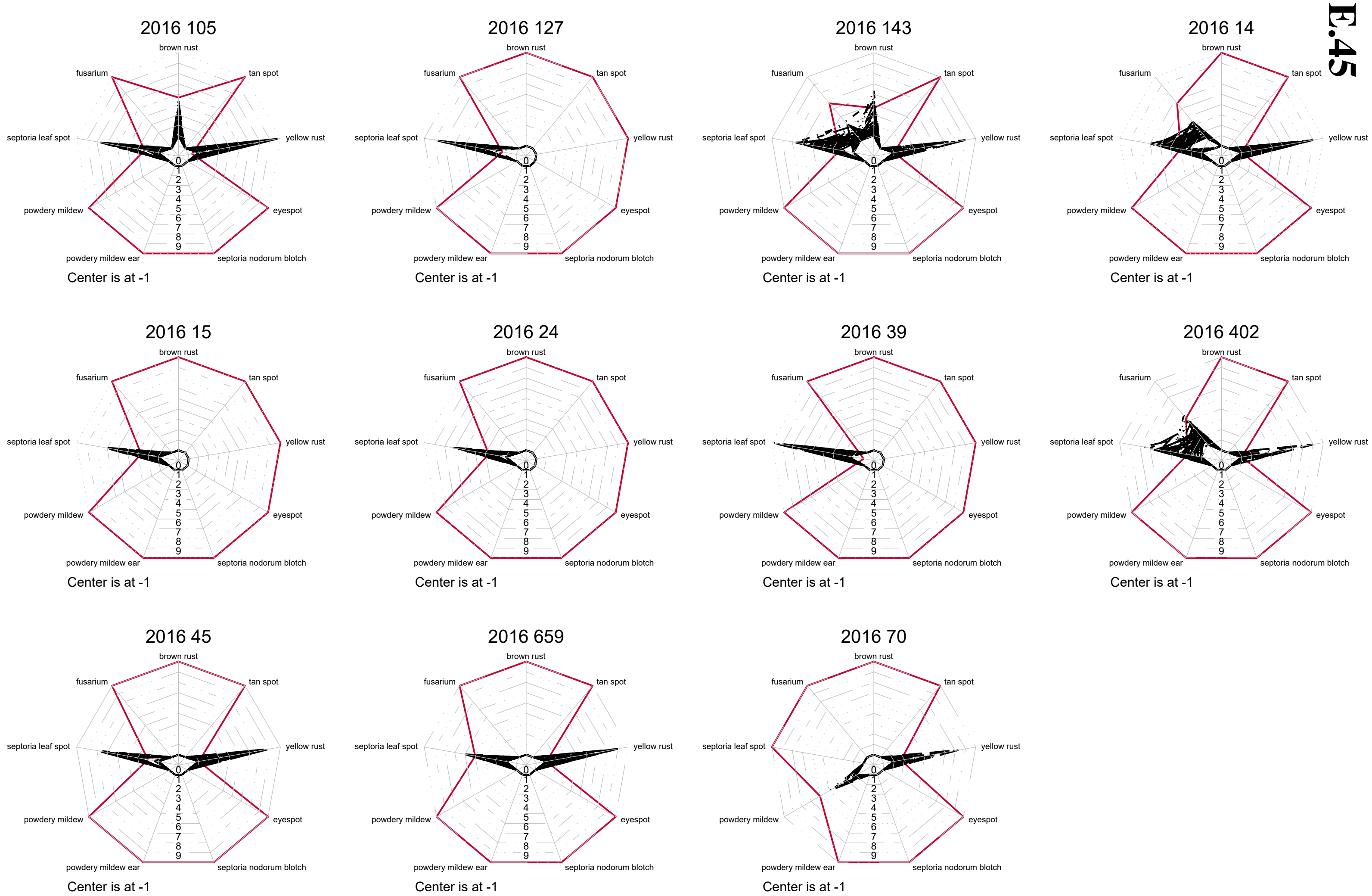
8
9
Center is at -1

E.44


2015 105
2015 143
2015 14
2015 15
2015 24
2015 39
2015 402
2015 45
2015 70
2015 76
2015 7
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
0
1
2
3
4
5
6
7
8
9
Center is at -1

E.45


2016 105
2016 127
2016 143
2016 14
2016 15
2016 24
2016 39
2016 402
2016 45
2016 659
2016 70
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
0
1
2
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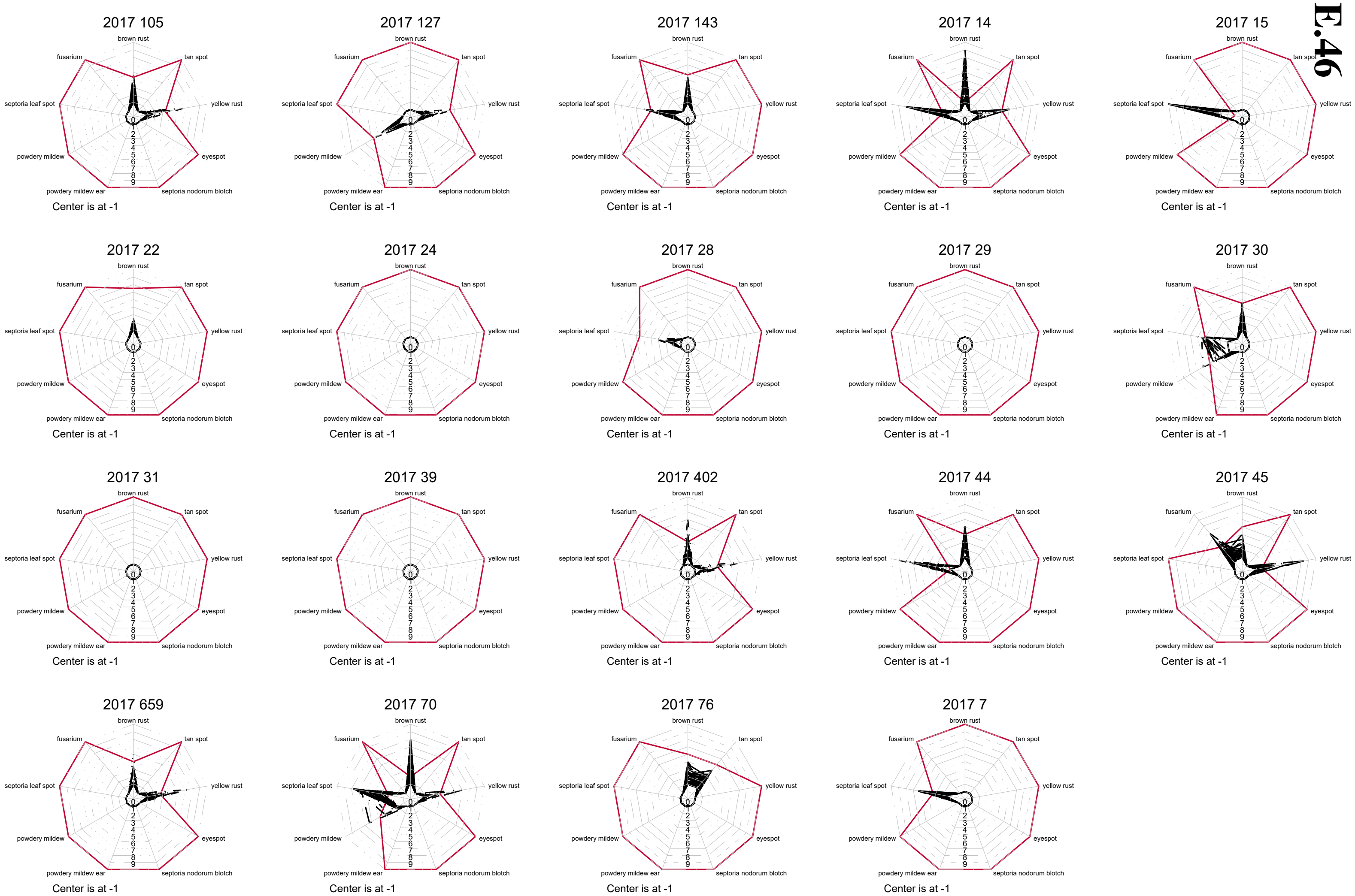
4
5
6
7
8
9
Center is at -1

E.46


2017 105
Center is at -1
2017 127
Center is at -1
2017 143
Center is at -1
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2017 15
Center is at -1
2017 22
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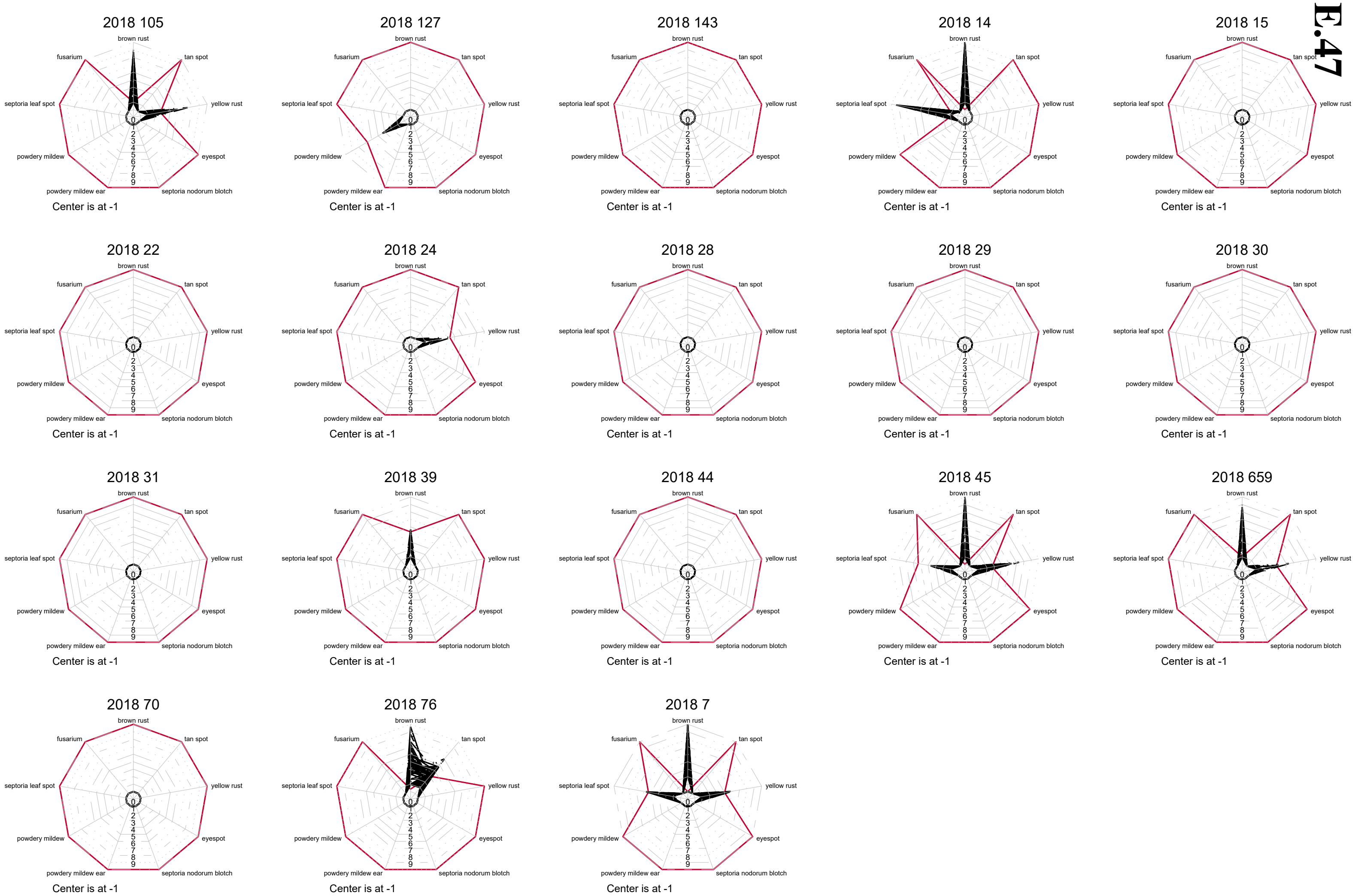
2017 24
Center is at -1
2017 28
Center is at -1
2017 29
Center is at -1
2017 30
Center is at -1
2017 31
Center is at -1
2017 39
Center is at -1
2017 402
Center is at -1
2017 44
Center is at -1
2017 45
Center is at -1
2017 659
Center is at -1
2017 70
Center is at -1
2017 76
Center is at -1
2017 7
Center is at -1
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium

E.47


2018 105
2018 127
2018 143
2018 14
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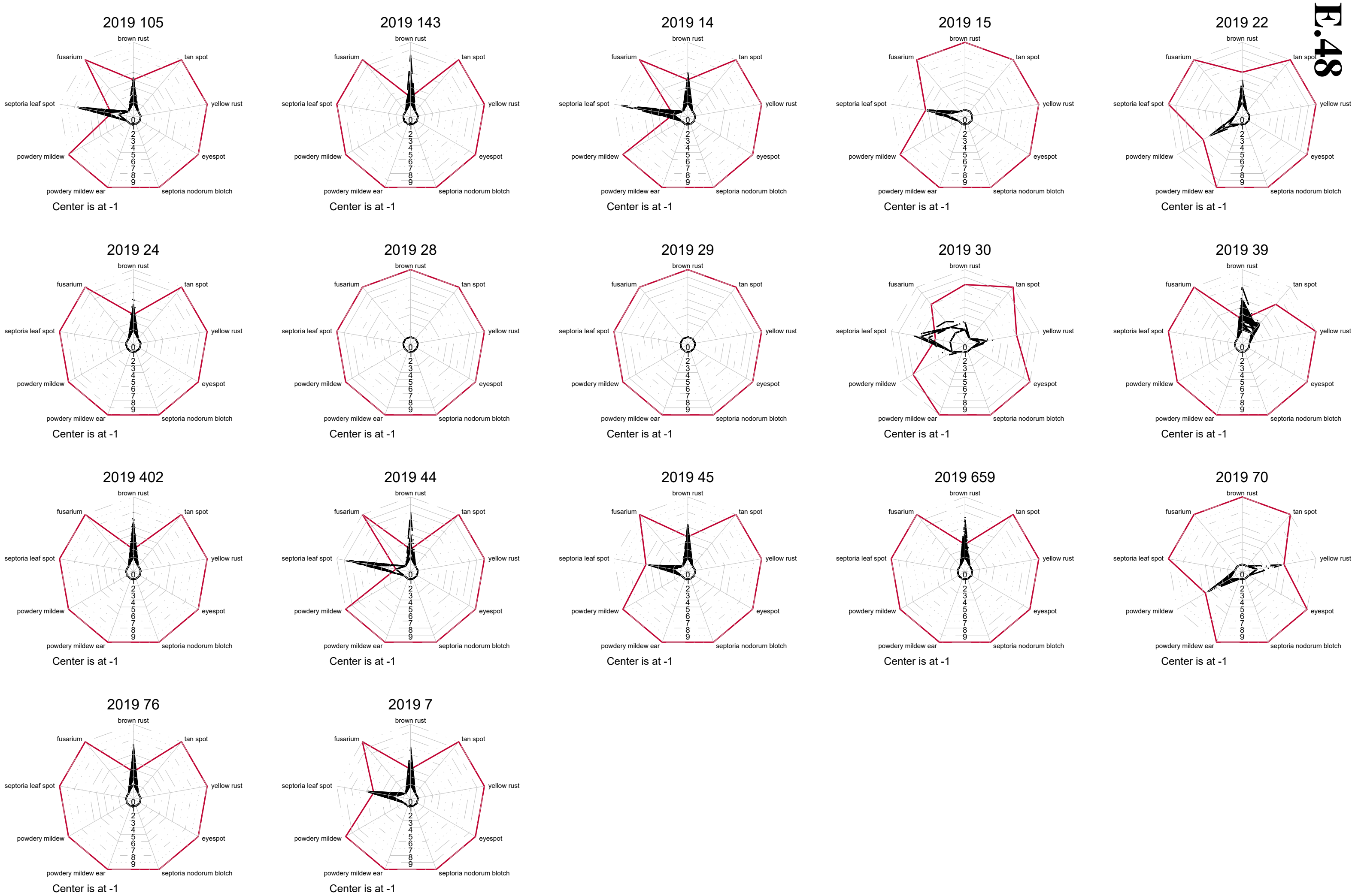
2018 30
2018 31
2018 39
2018 44
2018 45
2018 659
2018 70
2018 76
2018 7
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
Center is at -1

E.48



2019 105
2019 143
2019 14
2019 15
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2019 30
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2019 402
2019 44
2019 45
2019 659
2019 70
2019 76
2019 7
brown rust
tan spot
yellow rust
eyespot
septoria nodorum blotch
powdery mildew ear
powdery mildew
septoria leaf spot
fusarium
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Center is at -1

E.49 Parallel Trends Testing

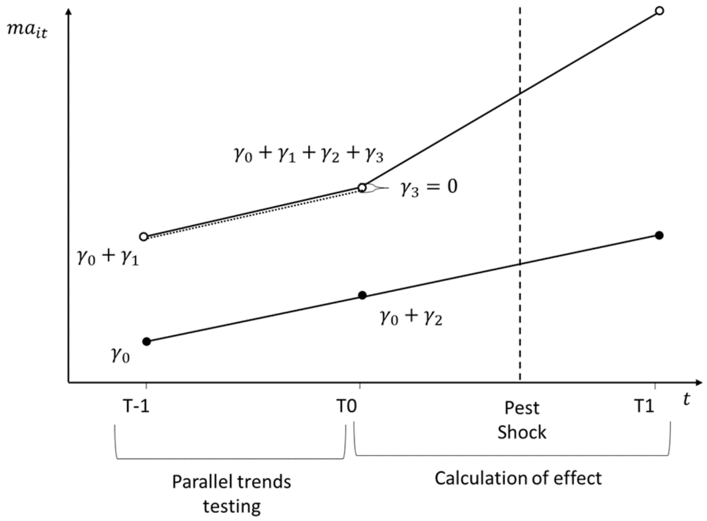
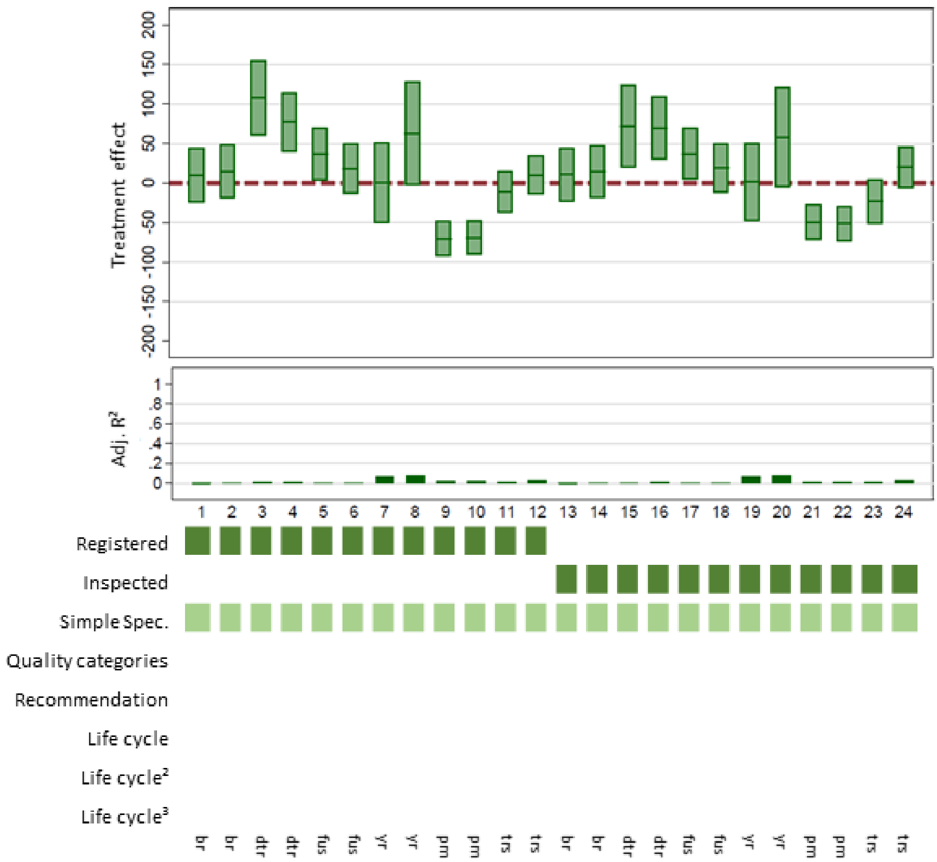


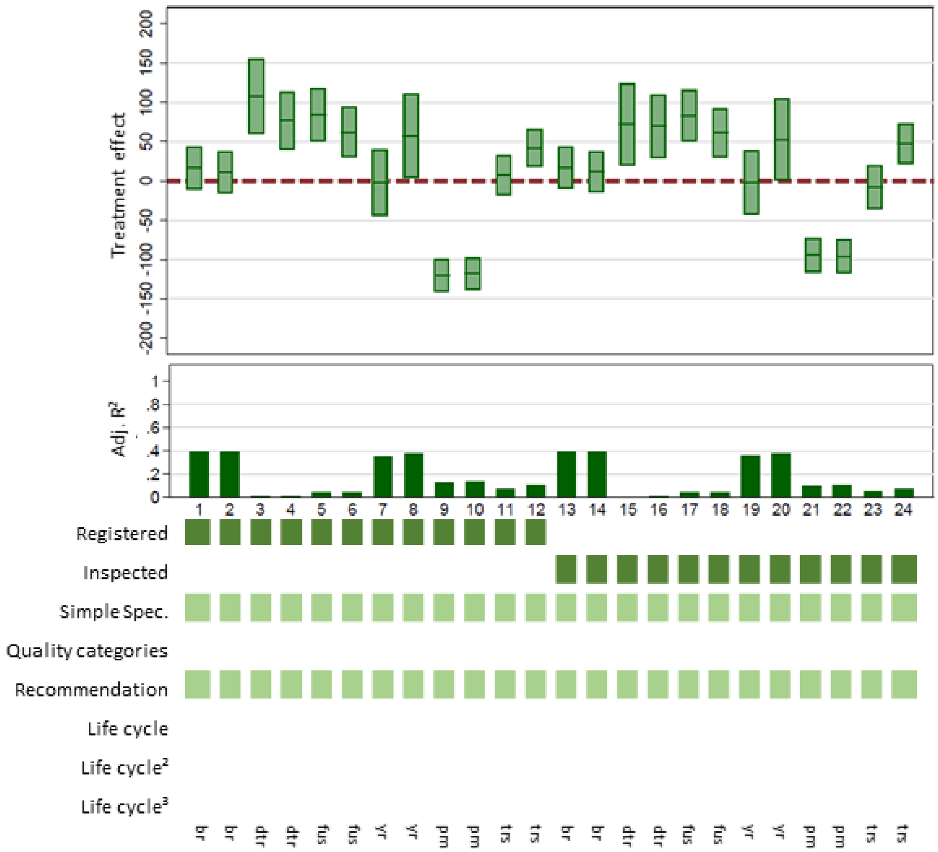
FIGURE E.2: Illustration of parallel trends testing for empirical approach

Figure E.2 shows for each site, that experiences a pest shock varieties that are resistant in the treated group and non-resistant varieties are in the untreated group. This notion is then extended to the years previous to the shock (lead years), where we conduct our parallel trends testing with the two previous periods. For parallel trends testing we want γ_3 to be zero, to then validate that resistant and non-resistant varieties behaved in a comparable manner before the shock. This is an underlying assumption to the difference-in-differences methodology (Angrist & Pischke, 2009).



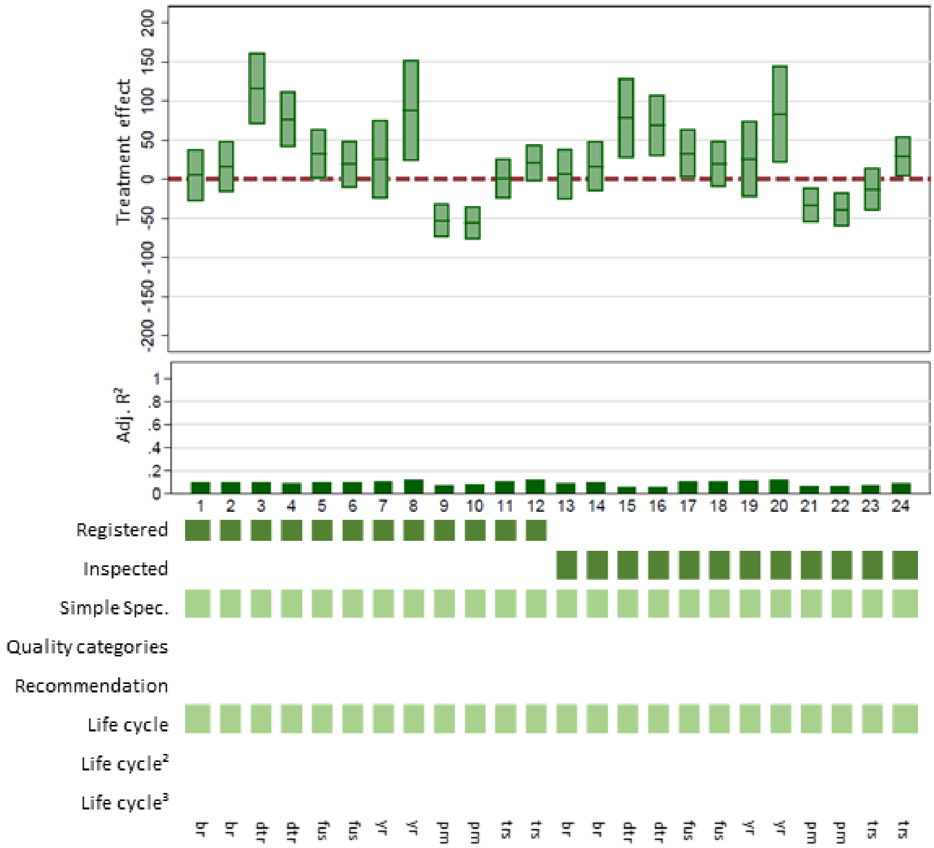
Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.2 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE E.3: Results from parallel trends testing for simple specification



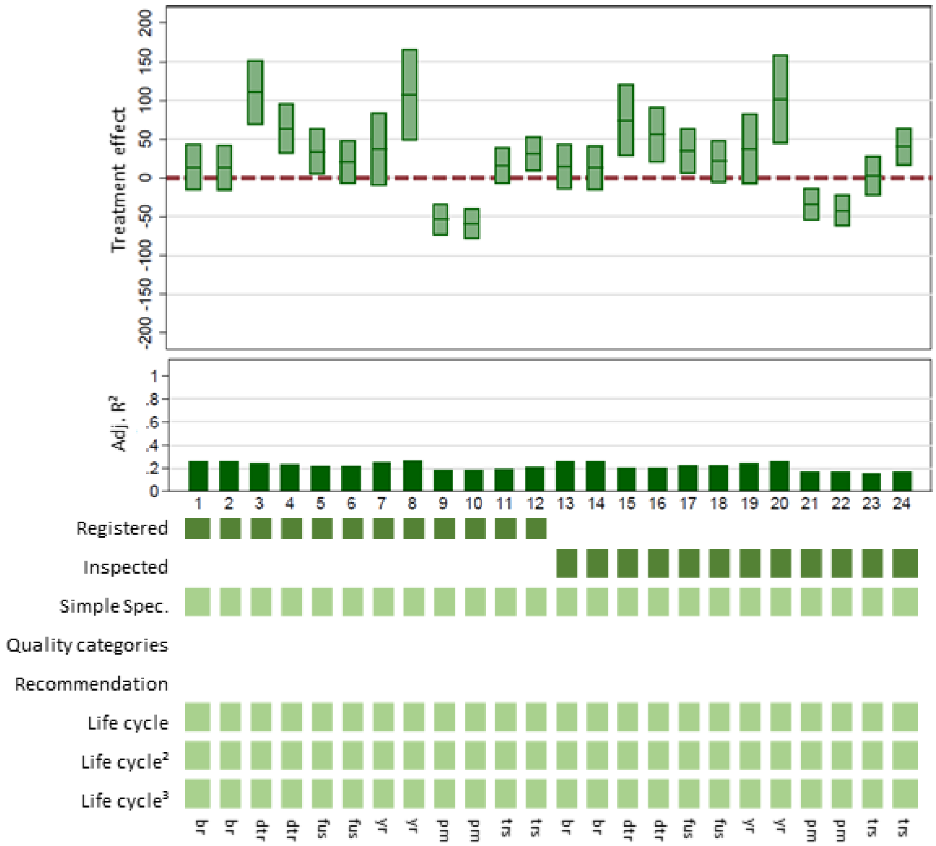
Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.2 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE E.4: Results from parallel trends testing for simple specification with recommendation variable



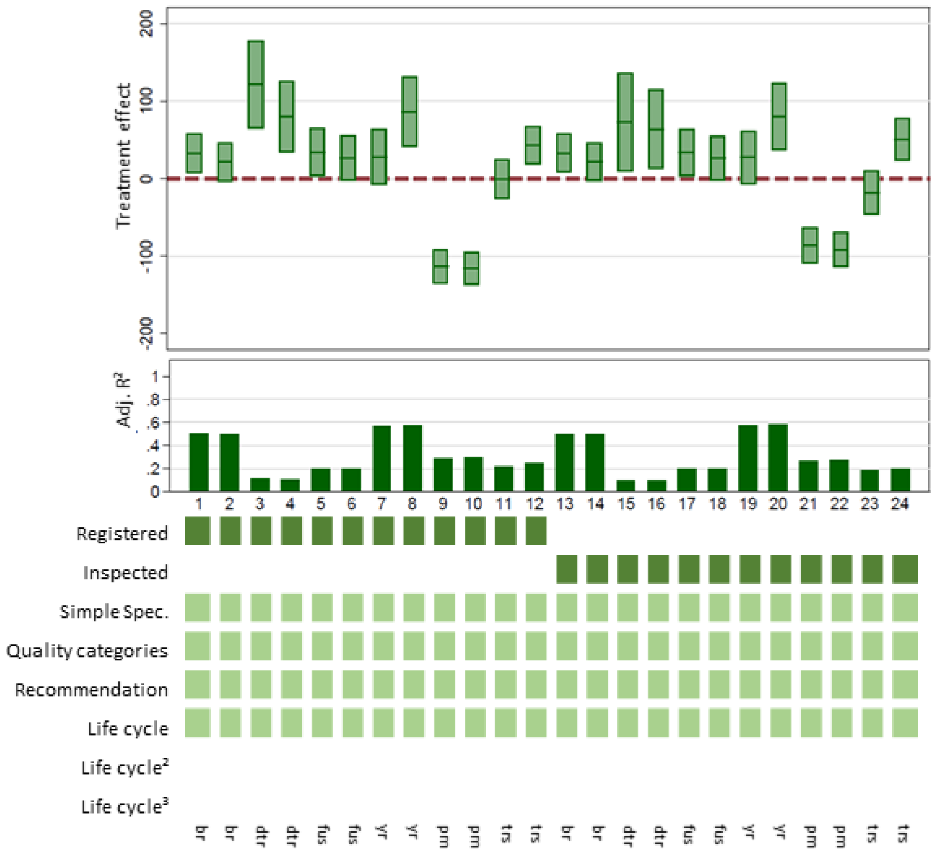
Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.2 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE E.5: Results from parallel trends testing for simple specification with life-cycle variable included



Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.2 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

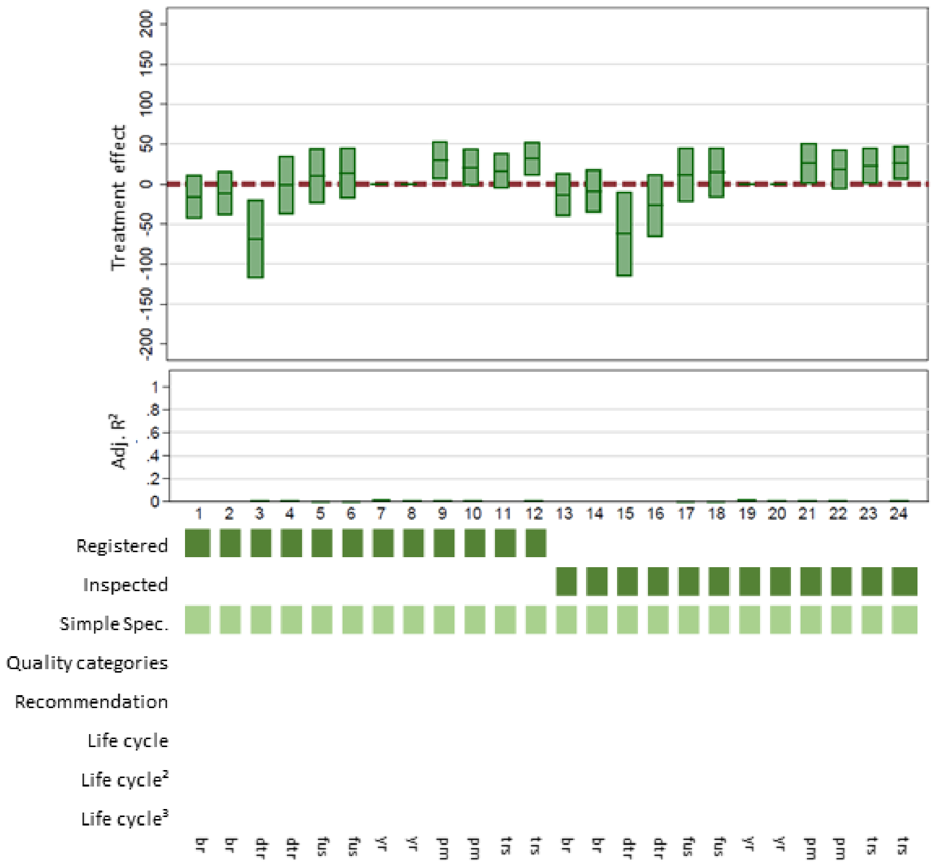
FIGURE E.6: Results from parallel trends testing for simple specification including all life-cycle variables



Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.2 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

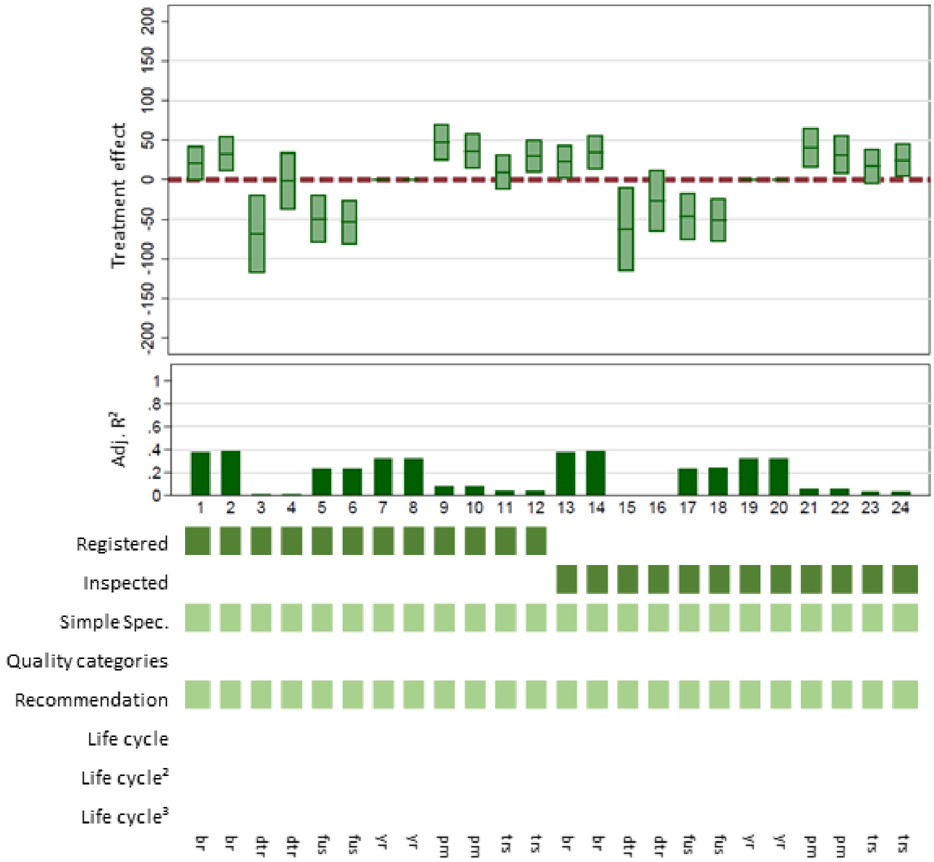
FIGURE E.7: Results from parallel trends testing for full specification with simple life-cycle variable

E.50 Robustness in Specifications



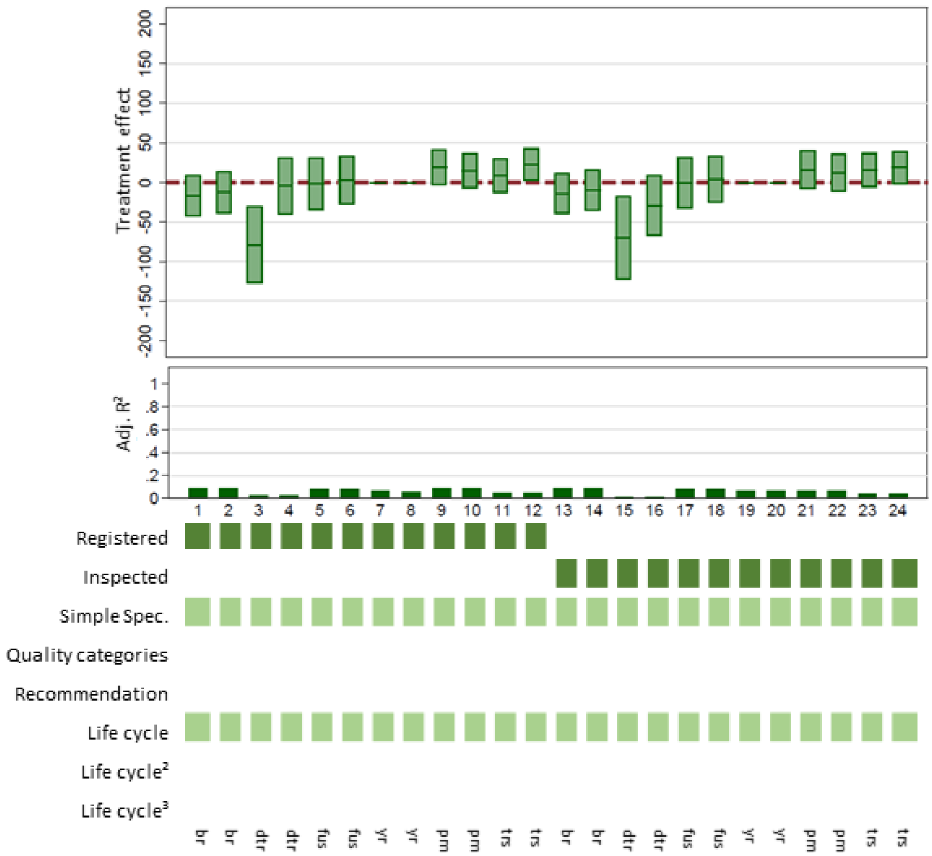
Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.1 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE E.8: Results from disease regressions for simple specification



Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.1 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE E.9: Results from disease regressions for simple specification with recommendation variable

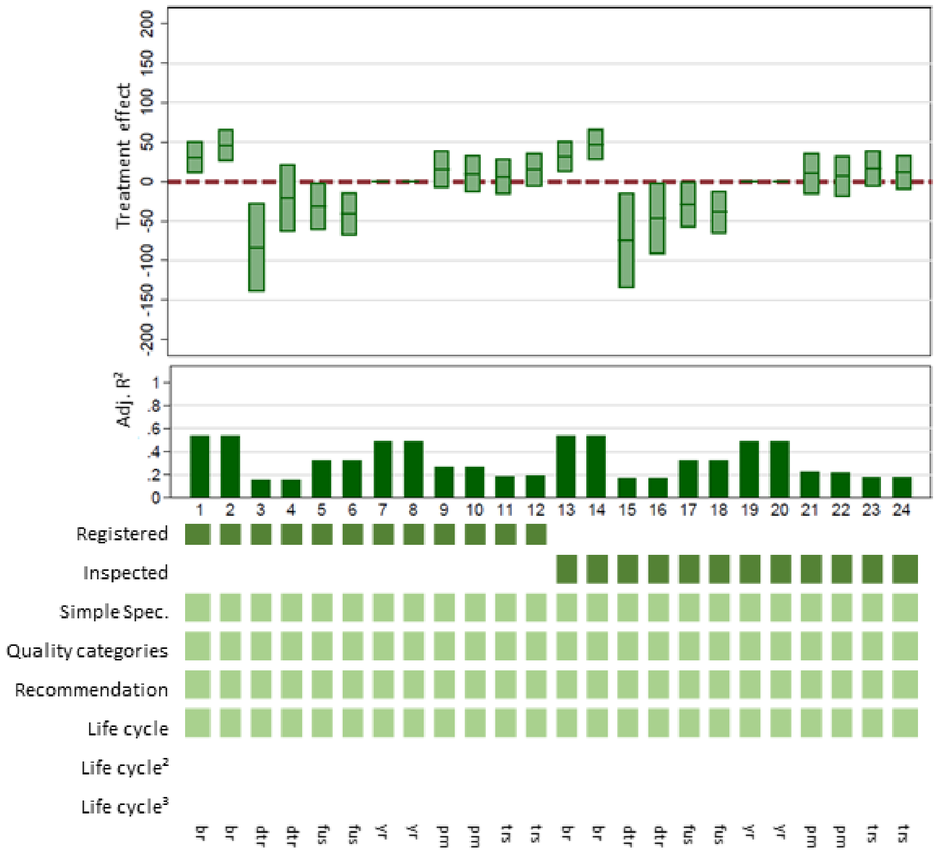


Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.1 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE E.10: Results from disease regressions for simple specification with life-cycle variable included

Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.1 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE E.11: Results from disease regressions for simple specification including all life-cycle variables



Diseases are abbreviated as: br = brown rust; dtr = tan spot; fus = fusarium; yr = yellow rust; pm = powdery mildew; trs = septoria leaf spot. Simple specification follows the underlying specification of equation 5.1 just without controls; odd numbers are specifications with score 3 for the resistance dummy, even numbers are with score 4 or lower to be counted as resistant.

FIGURE E.12: Results from disease regressions for full specification with simple life-cycle variable

E.51 Additional comments on heterogeneous effects in varieties

Yellow rust poses the difficulty of there being too much attrition in observations due to overlap with other pest shocks in following years for the simple specification. Technically seen 802 observations survived data attrition, passed parallel trends testing and yielded a very sharp effect with a very sharp estimator of zero in yellow rust. Yet, hand inspection of left over observations showed that the variation within these 802 observations does not reflect the overall picture of the disease spread and shock. Hence, we reported it but did not deem the results as valuable.

E.52 Bibliography

Angrist, J. D., & Pischke, J.-S. (2009). *Mostly harmless econometrics: An empiricist's companion*. Princeton university press.

Becker, H. (2011). *Pflanzenzüchtung*. UTB.

Braun, V. (2021). Holding on to and letting go of seed: quasi-commodities and the passage of property. *Journal of Cultural Economy*, *14*(3), 306–318. doi: 10.1080/17530350.2020.1824934

Brown, J. K., Tellier, A., et al. (2011). Plant-parasite coevolution: bridging the gap between genetics and ecology. *Annual review of phytopathology*, *49*(1), 345–367.

Bundessortenamt. (2000). *Richtlinien für die durchführung von landwirtschaftlichen wertprüfungen und sortenversuchen*. Hannover.

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

Hutchinson, G. (1957). Population studies: animal ecology and demography: concluding remarks. cold spring harbor symp. *Quant. Biol.*, *22*, 425–427.

Moll, E., Flath, K., & Sellmann, J. (2009). Schätzen der befallsstärke-(k) ein problem. *Journal für Kulturpflanzen*, *61*(12), 440–442.

Nickl, L. H. A. W. T. E., U., & Schmidt, M. (n.d.). Versuchsergebnisse aus bayern 2017 faktorieller sortenversuch winterweizen. *Landessortenversuch Winterweizen*.

Timmermann, M. (2009). *Der züchterblick: Erfahrung, wissen und entscheidung in der getreidezüchtung*. Shaker.