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Seeds of resilience: the contribution of commons-based plant breeding and seed production to the social-ecological resilience of the agricultural sector

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ABSTRACT

Building resilience in food systems is a priority to meet societal challenges such as climate change and biodiversity loss. However, there has been little systematic research on the role of seed production in fostering agroecological resilience. The increasing commercialization and privatization in the conventional seed industry result in the development and use of only a small number of high-yielding varieties. To counter this trend, new organizational approaches and governance structures in plant breeding and seed production build upon common ownership and collective management. In this study, we analyse how commons-oriented seed production promotes agroecological resilience in comparison to conventional private-property-based seed production. We apply an indicator-based framework to analyse publications from breeding and seed-producing organizations in the German-speaking vegetable seed sector. We find that in comparison to conventional seed production, commons structures promote agroecological resilience in several respects. They foster diversity at the genetic, crop species, and landscape level, create redundancy in seed supply channels, and increase autonomy from external resource inputs and international markets. The governance structures of commons-based seed production contribute to agroecological resilience through a high degree of self-organization of farmers and breeders along the value chain, participatory breeding approaches, and greater access rights to seeds.

KEYWORDS

Agroecosystems; commons; resilience; seeds; governance

1. Introduction

Global agricultural production is currently facing new and accelerating challenges. Climate change combined with chronic stresses on agroecosystems, caused by the massive degradation of soils, water reservoirs, plant genetic resources and regulating ecosystem services, poses serious threats to food security from local to global level (Sinclair et al., 2014; Tendall et al., 2015; Urruty et al., 2016). Specifically, the loss of agrobiodiversity has been identified as a major threat to future agricultural production (Kahane et al., 2013; Lin, 2011; Mace et al., 2014; Mijatović et al., 2013; Petersen & Weigel, 2015). Systemic uncertainties, due to the increasing complexity and connectivity of

global food supply chains, constitute additional threats (Tendall et al., 2015). The predominant strategy to deal with these sometimes unpredictable external shocks and slow system changes has been to control environmental conditions in farming systems (Napel et al., 2006; Urruty et al., 2016). Control measures include the application of pesticides and mineral fertilizers, the use of irrigation, monoculture production systems, the breeding and use of genetically uniform high-yielding crop varieties, and smart and precision farming technologies (Loos et al., 2014; Pretty, 2008). However, this strategy of striving for optimal, controlled conditions makes agricultural systems more vulnerable to biotic stresses,

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such as pressure from herbicide-resistant weeds, pests, and pathogens (Altieri & Nicholls, 2004; Heine-mann et al., 2014), and less adaptable to climate change (Altieri et al., 2015; Rotz & Fraser, 2015).

To address these challenges, building resilience has been proposed in both science and international policy as a future priority for the governance of food and agricultural systems (FAO, 2018; Foresight, 2011; Ingram et al., 2019; Schipanski et al., 2016; Seekell et al., 2017). Food system studies taking a resilience perspective have primarily focused on crop cultivation and the production stage of the agricultural value chain (Hodobod & Eakin, 2015; Sinclair et al., 2014; Smith et al., 2016; Tendall et al., 2015; Urruty et al., 2016). Breeding is usually not considered, and there is little systematic research on the role of seed production for building agroecological resilience (Helicke, 2015; Lammerts van Bueren et al., 2018; McGuire & Sperling, 2013; Pautasso et al., 2013). However, plant breeding and seed production play a central role in fostering resilience capacities (Lammerts van Bueren et al., 2018). Seeds are the starting point of all agricultural activity, with any disturbance potentially affecting the entire agricultural value chain. Moreover, breeding shapes the agroeconomic characteristics of plant varieties, determining their suitability for specific climatic and biophysical conditions, while the genetic diversity within and between varieties and species links to the stability of food systems (Jackson et al., 2007; Lammerts van Bueren et al., 2018; Thrupp, 2000). Furthermore, breeding and seed production are closely tied to questions about ownership of and access to plant genetic resources, affecting farmers' ability to build up capacities to respond to disturbances. The governance of genetic resources, including intellectual property rights, global treaties, and national regulations on variety registration and testing, affects seed availability and farmers' access to seeds, in some cases curtailing their ability to save up seeds or access breeding material (Aguilar, 2001; Bonny, 2017; Clancy & Moschini, 2017).

Seed production in the Global North has experienced a high degree of commercialization and privatization in the last few decades, and is now a lucrative economic activity based on intellectual property rights on plant varieties (Clancy & Moschini, 2017). Market concentration in the global formal seed market is continuously increasing, with

currently only three companies – Bayer including Monsanto, ChemChina including Syngenta, and DuPont including Dow – sharing over 60% of the global seed market (Bonny, 2017; Howard, 2015, 2016; Moldenhauer & Hirtz, 2017). (New) organizational approaches in seed production, specifically in the context of organic vegetable breeding in Europe and in traditional agricultural systems in the Global South, present an alternative to the dominant approach of large-scale agribusiness (Baumann et al., 2020; Ceccarelli, 2006; Fenzi & Couix, 2021; Girard & Frison, 2018; Gmeiner et al., 2018; Kotschi, 2016; Sievers-Glotzbach et al., 2020; Vernoooy et al., 2015; Wirz et al., 2017; Wolter & Sievers-Glotzbach, 2019). They build upon common ownership and forms of collective management in plant breeding and seed production, including smallholder participation in variety development and management. Such a commons orientation in seed production appears to be a promising approach to improve agroecological resilience.

The aim of this paper is thus to analyse, conceptually and empirically, how a commons orientation in seed production promotes or impedes the resilience of agricultural production systems in comparison to conventional private-property-based seed production. We thereby address two knowledge gaps, leading to a better understanding of (i) the relationship between seed production, including breeding, and agroecological resilience in general, and (ii) the specific effects of a commons orientation in breeding and seed production on agroecological resilience.

First, we review literature on social-ecological resilience as a system property of agricultural systems and approaches to its measurement. Based on this review and work by Cabell and Oelofse (2012) and other resilience scholars, we develop an indicator-based assessment framework to delineate potential influences of seed production on core attributes of agroecological resilience. We then describe the methods of our document analysis of the German-speaking vegetable seed market. The results section comparatively assesses the impact of the two types of organizational structures (conventional vs. commons-based) on agroecological resilience. Finally, we discuss the findings in the context of larger scientific debates on food security and draw conclusions.

2. Conceptual framework: Integrating seed production into agroecological resilience assessment

2.1. Agroecological resilience

We conceptualize resilience as emergent properties that contribute to the stability and adaptability of social-ecological systems in case of perturbations. These properties include (i) the amount of disturbance a system can absorb while remaining within a domain of attraction, (ii) the capacity for learning and adaptation, and (iii) the degree to which the system is capable of self-organizing (Carpenter et al., 2001). Resilient systems are thus characterized by the capacity to withstand or reorganize following disturbance (Walker et al., 2004). Resilience approaches address the complexity and unpredictability of the future. Acknowledging that the trajectories of social-ecological systems cannot be fully predicted or controlled leads to a shift in focus from finding short-term optimal solutions to adopting long-term perspectives on the constant transformation of social-ecological systems (Darnhofer, 2014; Hodbod & Eakin, 2015). Hence, resilience approaches take into consideration not only the reactive capacity, i.e. the capacity to adjust to adverse conditions, but also the proactive capacity, i.e. the capacity to search for and create future options (Obriest et al., 2010). It thus builds upon narratives of uncertainty and vulnerability, to highlight the potential for adaptation and transformation in constantly changing social-ecological systems (Shaw & Maythorne, 2013).

Agroecosystems are 'ecosystem[s] managed with the intention of producing, distributing, and consuming food, fuel, and fibre. [Their] boundaries encompass the physical space dedicated to production, as well as the resources, infrastructure, markets, institutions and people' involved in these activities (Cabell & Oelofse, 2012, p. 2). Agroecological resilience is thus the ability of agricultural systems to withstand disturbance and ensure long-term food security for all (Hodbod & Eakin, 2015; McGuire & Sperling, 2013; Tendall et al., 2015). Agroecological resilience spreads across multiple scales and subsystems (Tendall et al., 2015). Here we focus on the subsystem of seed production and breeding, incorporating not only seeds as physical objects but also the institutions, relationships and knowledge that enable their production and use.

Resilience always relates to disturbances of the system in question. Here this pertains to any

disturbances that could diminish the ecological and/or social function of breeding and seed production, such as the impacts of climate change, globally declining genetic diversity, the development of pest and pathogen resistances, highly concentrated market structures, changing consumption patterns, or political instability. The normative dimension of resilience, which favours certain system states and outcomes over others, has gained increasing attention in recent years (Brown, 2014; Johnson et al., 2018). Besides addressing the question of 'resilience of what to what?' (Carpenter et al., 2001), it is thus crucial to ask, 'resilience for whom and with what purpose?' (Quinlan et al., 2016). This question needs to be addressed from an ethical perspective, pointing to the relevance of food security for the long-term survival of humanity and the internationally recognized human right to food (De Schutter, 2014).

2.2. Developing an indicator-based assessment framework

The dynamics of complex adaptive systems and the abstract, multidimensional nature of resilience make it difficult to operationalize social-ecological resilience (Darnhofer, 2014; Quinlan et al., 2016). Crossing catastrophic thresholds may not be obvious (e.g. the full extent of climate change impacts may only become fully visible decades later), and resilience performance may not be directly observable and must therefore be inferred indirectly (Carpenter et al., 2001; Cumming et al., 2005; Fletcher et al., 2006). In recent years, several indicator-based frameworks have been developed to attempt this difficult feat (e.g. Carpenter et al., 2012; Grace & Pope, 2015; Hughes & Bushell, 2013; IUCN, 2014; Nemeč et al., 2014; O'Connell et al., 2015; Speranza et al., 2014; UNU-IAS et al., 2014). Some of these have specifically focused on agroecosystems (e.g. Altieri et al., 2015; Cabell & Oelofse, 2012; Green et al., 2017; Porcuna-Ferrer et al., 2020; Worstell & Green, 2017).

Here, we take Cabell and Oelofse's (2012) framework as a starting point. We have chosen this framework since it is the most frequently cited, comprehensive framework known to us that focuses on agroecosystems and incorporates both social and ecological dimensions of resilience. Cabell and Oelofse identify 13 indicators of resilience, based on an extensive literature review. They do not explicitly consider plant breeding and seed production, but set the system boundary starting with the 'physical

space dedicated to production.’ We consequently adapt their framework to seed production and breeding. We do not aim to measure or quantify agroecological resilience at a specific location, but take a conceptual approach to deepen the understanding of system dynamics.

We assume that the role of seed production for agroecological resilience is twofold. First, the structures and characteristics of plant breeding and seed production influence the extent of agroecological resilience in plant cultivation. For instance, seed companies set breeding goals and specify breeding methods that determine the characteristics of available varieties, including factors such as genetic diversity, robustness, and natural reproducibility. Second, the governance structures of seed production can themselves be assessed in terms of their contribution to agroecological resilience. In our assessment framework (see Table 1), we thus include both indicators referring to the system to be governed (i.e. the properties and processes of the breeding and seed system that enhance agroecological resilience) and indicators referring to the governance system of breeding and seed production (i.e. the social system which is ‘made up of institutions and steering mechanisms such as organizations, legal rules and economic incentives’) (Jentoft et al., 2007, p. 612).

Further, we compare the indicators identified by Cabell and Oelofse (2012) with the seven principles for building resilience as described by Biggs et al. (2012, 2015), as well as with the eight qualities of resilient food systems as compiled by Worstell and Green (2017). Both frameworks serve as reference points to evaluate the comprehensiveness of Cabell and Oelofse’s framework. The seven resilience principles of Biggs et al. are the result of a meta-study across different types of social-ecological systems and extensive discussions among resilience scholars. We find that Cabell and Oelofse’s indicators do not explicitly address three of these resilience principles. These are: (1) foster complex adaptive systems thinking, (2) broaden participation, and (3) promote polycentric governance systems. Since we assume that these attributes capture core differences in the governance structures under investigation – that is, between conventional and commons-based seed production – we extend the indicator set accordingly. The eight qualities of resilient locally organized food systems from Worstell and Green (2017) are based on nine case studies and six prominent resilience frameworks,

including that of Cabell and Oelofse. We find that the qualities *accumulating reserves and physical infrastructure* and *conservative innovation* are not adequately captured in Cabell and Oelofse’s framework and hence add these indicators. Indicators from the Cabell and Oelofse framework that have limited relevance in the context of seed production, such as *spatial and temporal heterogeneity*, are deliberately excluded. Further, we merge and slightly modify some of the indicators to incorporate insights from recent social-ecological resilience research, specifically from Carpenter et al. (2012), Frankenberger et al. (2013), the Rockefeller Foundation (2014), and Walker and Salt (2006, 2012).¹

Building on analyses of the role of seeds and plant breeding in agricultural production systems (Christinck et al., 2017; Ficiyan et al., 2018; Lammerts van Bueren et al., 2018; McGuire & Sperling, 2013, 2016; Pautasso et al., 2013; Petersen & Weigel, 2015; Sperling, 2008; Tester & Langridge, 2010), we specify the relevance of each indicator in the context of breeding and seed production as displayed in Table 1.

2.3. Conventional and commons-based seed production

To distinguish between conventional and commons-based seed production, we outline the main characteristics of private-property-based and commons-based seed organizations. Seed organizations of both types carry out plant breeding, seed multiplication and/or marketing. Conventional private-property-based seed companies are often large-scale agrochemical businesses. They build their business model on intellectual property rights (patents, legal plant variety protection), allowing them to control the use of newly developed plant varieties, single traits, or applied technologies. Their focus lies on high-yielding varieties for industrial farming and global seed markets. In contrast, commons-based seed companies and initiatives are guided by the principle that varieties are cultural heritage and common goods, which should not be privatized but governed collectively (Kliem & Tschersich, 2017; Sievers-Glotzbach et al., 2020). Consequently, they reject private property rights, such as patents and legal variety protection, to seeds and varieties. Their focus lies on diverse and regionally adapted varieties for local, often organic markets.

Table 1. Agroecological resilience assessment framework for breeding and seed production.

Indicator for agroecological resilience (partially adapted from Cabell & Oelofse, 2012, p. 4)	Definition for agroecosystems as social-ecological systems in general (partially adapted from Cabell & Oelofse, 2012, p. 4)	Specification for breeding and seed production systems ^a
Socially self-organized (Atwell et al. 2010; Frankenberger et al. 2013 ^a ; Holling, 2001; Levin, 1999; McKey et al., 2010; Milestad & Darnhofer, 2003; Speranza et al., 2014 ^a ; Walker & Salt, 2006 ^a , 2012 ^a ; Worstell & Green, 2017 ^a)	The social components of the agroecosystem can form their own configuration based on their needs and desires.	The social components of the agroecosystem can form their own breeding and seed production structures that fit specific needs (e.g. of organic or small-scale agriculture).
Ecologically self-regulated (Ewell, 1999; Glover et al., 2010; Jacke & Toensmeier, 2005; Jackson, 2002; McKey et al., 2010; Rockefeller Foundation, 2014 ^a ; Sundkvist et al., 2005; Swift et al., 2004; Walker & Salt, 2006 ^a ; Worstell & Green, 2017 ^a)	Ecological components self-regulate via stabilizing feedback mechanisms that send information back to the controlling elements.	Availability of varieties that are naturally reproducible and can adapt to changing local conditions, including ecological pest management.
Functional and response diversity (Altieri, 1999; Berkes et al., 2003; Biggs et al., 2012 ^a , 2015 ^a ; Carpenter et al., 2012 ^a ; Chapin et al., 2009; Darnhofer et al., 2010b; Di Falco & Chavas, 2008; Ewell, 1999; Frankenberger et al., 2013 ^a ; Folke, 2006; Folke et al., 2010 ^a ; Jackson et al., 2007; Luck et al., 2003; McIntyre et al., 2009; Moonen & Bärberi, 2008; Speranza et al., 2014 ^a ; Swift et al., 2004; Walker & Salt, 2006 ^a , 2012 ^a ; Worstell & Green, 2017 ^a)	Functional diversity is the variety of ecosystem services that components provide to the system. Response diversity is the range of responses of these components to environmental change.	Breeding and seed multiplication approaches that foster agrobiodiversity at the level of genetic diversity, crop species, and landscapes to increase functional and response diversity in plant cultivation.
Optimally redundant (Biggs et al., 2012 ^a , 2015 ^a ; Carpenter et al., 2012 ^a ; Darnhofer et al., 2010b; Low et al., 2002; Rockefeller Foundation, 2014 ^a ; Sundkvist et al., 2005; Walker et al., 2010; Worstell & Green, 2017 ^a)	Critical components and relationships within the system are duplicated in case of failure.	Redundancy of different supply channels for seeds and diversity of breeding organizations and structures.
Exposed to disturbance (Berkes et al., 2003; Folke, 2006 ^a ; Frankenberger et al., 2013; Gunderson & Holling, 2002; Rockefeller Foundation, 2014 ^a ; Worstell & Green, 2017 ^a)	The system is exposed to discrete, low-level events that cause disruptions without pushing the system beyond a critical threshold.	Variety development takes place under careful exposure to disturbance through in-situ breeding processes.
Coupled with local natural capital (Darnhofer et al., 2010a, 2010b; Ewell, 1999; Milestad & Darnhofer, 2003; Naylor, 2009; Robertson & Swinton, 2005; van Apeldoorn et al., 2011)	The system functions as much as possible within the means of the bioregionally available natural resource base and ecosystem services.	Availability of varieties that are adapted to regional environmental conditions and resources. Focus on varieties that are based on the bioregionally available natural resources.
Accumulation of reserves and physical infrastructure^a (Frankenberger et al., 2013 ^a ; Rockefeller Foundation, 2014 ^a ; Walker & Salt, 2012; Worstell & Green, 2017 ^a)	The buildup of reserves and physical infrastructure i.e. through delayed consumption and profit-taking.	Physical facilities for breeding, seed processing and storage are build up and maintained on-farm. Seed banks preserve genetic resources in the long term.
Appropriately connected: globally autonomous and locally interdependent in modular subsystems (Axelrod & Cohen, 1999; Biggs et al., 2012 ^a , 2015 ^a ; Carpenter et al., 2012 ^a ; Frankenberger et al., 2013 ^a ; Gunderson & Holling, 2002; Holling, 2001; Milestad & Darnhofer, 2003; Picasso et al., 2011; Rockefeller Foundation, 2014 ^a ; van Apeldoorn et al., 2011; Walker & Salt, 2006 ^a , 2012 ^a ; Walker et al., 2010; Worstell & Green, 2017 ^a)	Connectedness describes the quantity and quality of relationships between system elements. A system is globally autonomous if it has relative autonomy from exogenous (global) control, influences, and inputs. It is locally interdependent in modular subsystems if it exhibits a high level of cooperation between individuals and institutions in a network at the more local level with only weak connections to other networks.	Reduced reliance of (new) varieties on external inputs such as pesticides, fertilizers, international patents etc. A high degree of modular connectedness at the local level of breeders, farmers, gardeners, and other actors along the value chain.
Builds human capital and encourages reflective and shared learning (Berkes et al., 2003; Biggs et al., 2012 ^a , 2015 ^a ; Buchmann, 2009; Darnhofer et al., 2010b; Frankenberger et al., 2013 ^a ; McManus	The system takes advantage of and builds resources that can be mobilized through social relationships and membership in social networks. Individuals and institutions learn from past	Skills, knowledge and expertise on breeding and seed production are build up and social networks are formed. Knowledge and skills on breeding and seed multiplication as well as on variety traits and cultivation are

(Continued)

Table 1. Continued.

Indicator for agroecological resilience (partially adapted from Cabell & Oelofse, 2012, p. 4)	Definition for agroecosystems as social-ecological systems in general (partially adapted from Cabell & Oelofse, 2012, p. 4)	Specification for breeding and seed production systems ^a
et al., 2012; Milestad et al., 2010; Nahapiet & Ghoshal, 1998; Rockefeller Foundation, 2014 ^a ; Shava et al., 2010; Walsh-Dilley et al., 2016)	experiences and present experimentation to anticipate change and create desirable futures.	documented, disclosed, and passed on. Practical on-farm experience is integrated into breeding activities.
Conservative innovation that honours legacy (Biggs et al., 2012 ^a , 2015 ^a ; Carpenter et al., 2012 ^a ; Cumming et al., 2005; Gunderson & Holling, 2002; Frankenberger et al., 2013 ^a ; Rockefeller Foundation, 2014 ^a ; Shava et al., 2010; van Apeldoorn et al., 2011; Walker & Salt, 2006 ^a , 2012 ^a ; Worstell & Green, 2017 ^a)	Conservative innovation describes a form of system innovation that honours legacy. The current configuration and future trajectories of systems are influenced and informed by past conditions and experiences.	Use of traditional breeding methods (besides some modern breeding techniques) for the continuous development of new varieties. Ensuring the availability and use of underutilized and heirloom varieties.
Reasonably profitable (Frankenberger et al., 2013 ^a ; Speranza et al., 2014 ^a)	The segments of society involved in agriculture can make a livelihood from the work they do without relying too heavily on subsidies or secondary employment.	Long-term financial viability of breeding and seed multiplication is ensured.
Bases on polycentric, decentralized governance structures^a (Biggs et al., 2012 ^a , 2015 ^a ; Carpenter et al., 2012 ^a ; Ostrom, 2005 ^a ; Walker & Salt, 2006 ^a ; Walsh-Dilley et al., 2016 ^a)	The governance structures of the agroecosystem are characterized by multiple, nested governing bodies at different scales, with autonomy to make and enforce rules within an agricultural system.	Breeding and seed production is organized through decentralized governance structures at various levels.
Ensures resource access and broadens participation^a (Biggs et al., 2012 ^a , 2015 ^a ; Frankenberger et al., 2013 ^a ; McGuire & Sperling, 2016 ^a ; Rockefeller Foundation, 2014 ^a ; Tendall et al., 2015 ^a ; Walsh-Dilley et al., 2016 ^a)	An appropriate institutional framework of the agroecosystem with equitable (access) rights, entitlements and decision-making processes is established.	Access to seeds and genetic material, including for small-scale farmers, gardeners, and breeders, is ensured. Broad participation in breeding and conservation efforts is given. Decision-making processes within organizations are inclusive.
Encourages complex adaptive systems thinking^a (Biggs et al., 2012 ^a , 2015 ^a)	Core actors acknowledge that the agroecosystem is based on a complex and unpredictable web of connections and interdependencies and adapt their practices accordingly.	Holistic approaches to breeding and seed production that acknowledge the interdependencies of social and ecological factors and their partial unpredictability.

^aIndicates references, indicators and descriptions that have been added to the original framework as developed by Cabell and Oelofse (2012).

3. Research approach

This paper is based on a document analysis that includes publications from conventional and commons-based (vegetable) seed companies. Document analyses as a qualitative research method enable us to develop an understanding of actors' rationales and uncover meaning. As such, the analysis allows us to capture the practices of the different seed companies and their officially stated views and values. This poses an advantage over interviews and other qualitative methods that can only capture individual opinions. It does not, however, allow us to gain insight into the day-to-day operations of the organizations or to treat these records as firm evidence of empirical realities (Bowen, 2009).

In a first step, we identified companies and initiatives of both types, which coincided completely with the classification outlined in section 2.3. The selection

of organizations is geographically limited to Germany, Austria, and Switzerland, but many of the conventional companies are international firms that operate globally. The empirical focus on German-speaking countries was chosen since there are several organizations here that have integrated commons principles into their work and are well established in their respective local markets. Since these organizations predominately focus on vegetable seeds, the analysis was limited to seed companies with a vegetable seed assortment.

Based on their market share of the European vegetable seed market (c.f. Mammana, 2014), we selected the following conventional companies: (1) Bayer AG (including Monsanto Agrar Deutschland GmbH), (2) Syngenta Seeds GmbH, (3) Limagrain GmbH, and (4) KWS Saat SE, all operating in Germany. The commons-based companies and initiatives included in the analysis are: (1) Bingenheimer Saatgut AG, (2)

Kultursaat e.V., (3) Dreschpflögel GbR, and (4) Saat:gut e.V. in Germany, as well as (5) ReinSaat KG in Austria and (6) Sativa Rheinau AG in Switzerland. A larger number of commons-based than conventional companies was included, to be able to capture the diversity of commons-based organizational structures and practices. In the geographical area of study, commons structures have so far only emerged in the organic seed sector.

The initial identification of relevant publications from these companies and initiatives occurred through a two-step search. First, we systematically searched the web pages of the companies for publications. In a second step, we carried out a Google-based web search with the name of the respective company and one of the following terms: 'sustainability' / 'Nachhaltigkeit,' 'resilience' / 'Resilienz,' and 'breeding' / 'Züchtung.' The search was carried out in German and English. In total, we identified 87 publications for conventional private-property-based companies and 68 for commons-based companies and initiatives. The great majority of publications (134 out of 155 publications) were self-portrayals such as sustainability reports or annual reports, or advertising brochures and magazines. If several similar publications were available, such as sustainability reports from various years, we chose the most recent publication. We did not consider publications from before 2015.

We subsequently scanned all documents to select those that provided the most comprehensive information on aspects relating to agroecological resilience. Publications such as seed catalogues, which provide limited information beyond the current seed assortment of the company, were disregarded. 46 publications from private-property-based and 49 publications from commons-based companies and initiatives were included in the analysis. The documents from the conventional companies are on average much longer than those from commons-based organizations (conventional: mean = 106 pages; median = 96.5 pages; commons-based: mean = 44 pages; median = 23 pages). This is not surprising since the average company size, turnover, and range of activities of conventional companies is much larger.

For the analysis, we first manually scanned publications for relevant passages. Text passages were considered relevant if they directly or indirectly provided information on the organization's practices, views or values related to any of the indicators. If available, passages referring to the organization's

understanding of agroecological resilience were also identified. We subsequently assigned each passage to one or in some instances several indicators. This procedure resulted in two matrices – one for conventional and one for commons-based organizations – with text passages of varying lengths. 446 text passages were included in the analysis, with 216 passages from publications by conventional companies and 230 passages from publications by commons-based organizations. The assignment of text passages to indicators was cross-checked by the second author. We subsequently synthesized the data for each indicator individually, by identifying reoccurring aspects. We did not consider practices and views that were specific to a particular organization. The focus of the analysis was on aspects differing between the two forms of organization.

4. Findings

In commons-based seed companies and initiatives, farmers and growers form their own structures for breeding, seed multiplication, and marketing, based on a high degree of coordination and cooperation along the value chain (*socially self-organized*). For example, the breeding organizations Kultursaat e.V. and Saat:gut e.V., together with the seed vendor Bingenheimer Saatgut AG, have formed a platform to coordinate their breeding and seed production efforts. They collectively decide upon future breeding projects and programmes to ensure coordination along the value chain. Personal relations and close collaboration are integral to their organizational structure:

The exchange within the network is the breeding ground for the success of our work. As economic partners, we take time for each other to make joint progress in organic seed production. The intensive cooperation comes alive at biannual meetings, where we continue to educate ourselves together, offer a platform for exchange [...] and take time for personal discussions – this gives us a stable basis for a cooperation based on mutual trust. This form of cooperation is rare in the seed industry, where customers usually dictate the terms and conditions. (Bingenheimer Saatgut AG 2017, p. 120)

In conventional seed production, such a high degree of social self-organization cannot be observed. Increasing market concentration in the sector through company mergers has increased not only horizontal but also vertical integration, and breeding,

seed multiplication and the production of agrochemicals are now different corporate divisions of the same company. The needs of other actors along the agricultural value chain are integrated primarily through supplier and stakeholder management practices such as community advisory panels or stakeholder events and surveys. The focus is on creating efficient organizational structures to maximize productivity, increase shareholder value and minimize disturbances that could negatively impact these. Stakeholder integration is part of risk monitoring and is seen as an opportunity to gain a better understanding of the market, rather than as a foundation for equitable economic relations.

A further difference lies in the breeding goals and methods applied. Breeding programmes in commons-based organizations aim at open-pollinated varieties, plant robustness without chemical inputs (*ecologically self-regulated*), and varieties that are adapted to specific regions and agroecological conditions (*coupled with local natural capital*). A key concern of all commons-based organizations included in the analysis is a focus on breeding methods resulting in naturally reproducible varieties that can be maintained on-farm, i.e. breeding through crossing and selection. Hybrid breeding, marker-assisted selection, genetic engineering and other forms of molecular breeding are rejected:

[We] exclusively develop open-pollinated varieties without genetic engineering or hybrid breeding. During breeding and propagation, the vitality and resistance of the plants are at the center of our work. [...] Careful breeding, selection and continuous reproduction provide robust seeds that, unlike hybrid seeds, can adapt to heterogeneous environmental and site-specific conditions and thus offer long-term yield security. (ReinSaat 2018)

Furthermore, the commons-based organizations focus on in-situ breeding under exposure to site-specific disturbances (*exposed to disturbance*). On-farm breeding is considered crucial to ensure plants' interaction with local ecosystems and allow for the continuous adaptation of varieties to regional environmental conditions: 'Our breeding and propagation predominantly take place on the field. [...] Variety selection and development take place decentrally in various places, to allow for regional adaptation' (Dreschflegel Website 2018). The commons-based initiatives thus take an approach to breeding that focuses on natural evolution and adaptation, and highlights the capacity of plants to develop

robustness through exposure. Such low-technology seed production methods encourage the buildup of on-farm infrastructure, including (mechanical) seed cleaning and processing technology, as well as appropriate storage facilities (*accumulation of physical infrastructure*).

In contrast, conventional seed companies concentrate on the breeding of hybrid varieties and employ integrated solutions encompassing seeds and complementary pesticides for effective chemical pest management. Adaptation to regional conditions and to changing climatic conditions is achieved through biotechnological enhancements based on genetic modification and genomics, where legally allowed. Breeding processes mostly take place under controlled environmental conditions in the lab and through field experiments:

We use advanced breeding technologies to produce hybrids and varieties with superior performance in farmers' fields, and we use biotechnology to introduce traits that enhance specific characteristics of our crops. [...] Our current research and development strategy and commercial priorities are focused on bringing our farmer customers integrated yield solutions through our innovative platforms in plant breeding, biotechnology, chemistry, biologicals and data science. (Monsanto 2017, p. 10)

Conventional seed companies seek to increase yields while reducing the use of resources (e.g. land, fertilizers or pesticides), using technical solutions that aim to optimize genetic composition and homogeneity and create controlled cultivation conditions:

We rely on modern breeding methods to attain [our] objectives sooner and more precisely and offer increasingly productive varieties. [...] We aim to deliver annual yield progress of one to two percent. The development of sugar beet is a good example [...]. Figures over the past years show that yield has not only risen per hectare but this has been accompanied by a reduction in the use of fertilizer and pesticides. This is a very practical demonstration of how sustainable agriculture can work'. (KWS Saat 2017, p. 6)

This conventional approach to seed production leads to a buildup of high-technology breeding and seed processing infrastructure, including centralized seed storage facilities.

A further difference between conventional and commons-based seed production lies in the organizations' approaches to diversification. Commons-based initiatives aim to foster agrobiodiversity through the creation and maintenance of high

levels of genetic and crop species diversity – i.e. through population breeding and the inclusion of landraces and traditional crop species (*functional and response diversity*). Conserving and/or creating a diversified gene pool lies at the heart of the work of many of the organizations included in the analysis. Furthermore, commons-based seed organizations deliberately create redundancy in seed supply channels, e.g. by encouraging gardeners to multiply their own seeds, promoting seed exchanges, and fostering the establishment of an independent organic seed sector (*optimally redundant*). They encourage farmers to build up reserves through seed saving practices and establish small-scale community seed banks to ensure the long-term availability of genetic resources (*accumulation of reserves*).

In contrast, conventional seed organizations primarily focus on enhancing biodiversity in farm environments, e.g. by implementing measures to protect wildlife and pollinators threatened by large-scale industrial agriculture practices: ‘We advocate and pioneer the protection and promotion of biodiversity, primarily through the creation of rich, cohesive wildlife habitats on less productive plots of land and water’ (Syngenta 2017, p. 16). Conventional seed production follows a path of increasing reliance on a small number of highly profitable crop species and generalist varieties that are suited for larger regions, to maximize profit margins. Genetic resources are primarily regarded as company assets, which are to be managed, developed, and stored in central seed banks to secure future competitiveness. A diversification of seed supply channels is not prioritized.

In addition, the two types of seed systems differ in the connectedness of their system elements. Commons-based seed production is characterized by its independence from external resource inputs and thus shows only very few links to global markets, but strong local connections between breeding initiatives, farmers and growers. This implies a modular architecture of connectivity, with several compartmentalized communities catering to local and regional seed markets (*appropriately connected: globally autonomous and locally interdependent in modular subsystems*). The reliance of commons-based initiatives on local resources arises from an understanding that agriculture must be able to produce its own inputs. In contrast, conventional seed production is highly dependent on external inputs from international markets, such as

technological equipment, complementary pesticides, and genetic material. Their seed retail relies on complex international supply chains and international intellectual property rights, creating system-relevant dependencies on external inputs.

The governance structures of conventional and commons-based seed production differ considerably. The organizational structure of commons-based breeding organizations can be characterized as polycentric, whereas the increasing market concentration in the conventional seed industry opposes polycentric structures. In commons-based seed production, decentralized networks of breeders and seed producers with their own decision-making competencies allow diverse breeding projects and can flexibly respond to environmental changes and social requirements (*polycentric, decentralized governance structures*). In contrast, conventional seed production in the countries of investigation is dominated by multinational seed companies with centralized facilities and research centres, usually governed in a hierarchical structure by a single governance body.

The two types of seed production also vary greatly in their approach to resource access. Commons-based seed production contributes to ensuring access to seeds by farmers and breeders by waiving private property rights for varieties, employing participatory breeding approaches, and encouraging seed saving for future cultivation and breeding. Since commons-based breeding organizations understand varieties as common property, they register their varieties to nonprofit organizations and/or declare them to be free for use and further development:

We see varieties as common property that should not be privatized. Therefore, we explicitly renounce intellectual property rights of any kind (plant variety protection and patents) [...] [We] register the varieties (e.g., through the German Federal Office of Plant Varieties), so that they can be marketed [but] new varieties are not considered property of the association (legal person) or the breeder (natural person). Access to [our] varieties is therefore free and not subject to any regulation; any interested party may reproduce the varieties or distribute the seed. (Kultursaat e.V. 2017, p. 11)

Some initiatives have also explored the use of open-source pledges and licenses. Furthermore, they publicly share information on the breeding history and parental lines of newly developed varieties. These variety genealogies allow other breeders to trace their breeding background and develop them further. Some of the commons-based organizations

also aim to broaden access and participation by offering practical training on breeding and seed multiplication for commercial and hobby gardeners (*builds human capital and encourages reflective and shared learning*). The focus is on encouraging farmers and gardeners to actively engage in breeding and seed saving practices and raise public awareness of the importance of agrobiodiversity. In contrast, conventional seed companies have built their business model around intellectual property rights and reject practices of seed saving by farmers and gardeners. The breeding history and breeding methods of new varieties are usually not disclosed. Their understanding of genetic resources as private property that ought to be protected for commercial reasons leads them to strictly inhibit any use of their varieties or genetic material by others:

We hold a broad business portfolio of patents, trademarks and licenses that provide intellectual property protection for our seeds and genomics-related products and processes [...]. [They] are crucial to our business [...]. We endeavor to obtain and protect our intellectual property rights. [...] Competitors, farmers, or others in the chain of commerce may raise legal challenges to our rights or illegally infringe on our rights [...]. For example, the practice by some farmers of saving seeds from non-hybrid crops containing our biotechnology traits has prevented and may continue to prevent us from realizing the full value of our intellectual property. (Monsanto 2017, p. 9)

Commons-based and conventional approaches to seed production also take different views of traditional knowledge. Commons-based seed organizations use both traditional breeding techniques and traditional crop species and varieties in breeding (*conservative innovation that honours legacy*). They consider varieties as cultural assets that link the work of farmers over generations and ought to be preserved and further developed:

Seeds are far more than just a means of production. They are the starting point for food production and carry the flow of crop development from the past into the future. Our goal is to preserve this cultural asset for future generations. (Bingenheimer Saatgut AG 2017, p. 8)

In contrast, conventional seed companies spread a narrative of technological progress, which they argue is necessary to feed an increasing world population. Biotechnological advancements designed to control natural processes and improve genetic 'purity' (including – in some companies –

transgenesis) are favoured over traditional breeding methods that lead to the development of natural plant disease and pest resistances. This focus on biotechnological solutions reflects a worldview of domination of nature, whereas commons-based seed organizations practice breeding on-farm in natural environments based on a worldview of working with nature (*complex adaptive systems thinking*).

When it comes to the long-term financial viability of the breeding sector, the conventional seed companies are highly profitable, reporting growth rates and profit margins that widely exceed those of commons-based seed companies (*reasonably profitable*). At the same time, conventional companies must make substantial (re-)investments in biotechnological advancements to remain competitive, and are highly dependent on their shareholders. In contrast, many of the commons-based seed organizations face insecurity regarding the long-term financing of their breeding activities. Income sources such as licenses and replication fees do not apply and are not compatible with commons principles. In addition, the polycentric structure of breeding and seed production and the development of varieties that are adapted to specific regions mean small sales markets for newly developed varieties. The seeds are primarily purchased in small quantities by hobby gardeners and small-scale farmers, with low profit margins making it more difficult to finance breeding activities. To ensure the continuous development of varieties, some seed companies have developed models of voluntary breeding contributions that are negotiated between breeders and multipliers:

Above all, it must be ensured that the multiplication of the seed is economically viable for the producing farms in the long term. At the same time, we want to offer seed at attractive prices. For this reason, the [breeders and multipliers] are discussing pricing and payment modalities in a continuous dialogue based on partnership and are developing them further together [...]. We pay a variety development contribution for varieties registered in [our] name. [This] contributes to maintenance breeding and the development of new varieties. (Bingenheimer Saatgut AG 2017, pp. 8)

Nevertheless, many commons-based initiatives have yet to develop profitable financing models enabling them to gain financial sustainability and independence from sponsors. Table 2 summarizes the results of the agroecological resilience indicators.

Table 2. Assessing the impact of conventional and commons-based seed production on agroecological resilience.

Indicator for agroecological resilience	Conventional seed production	Commons-based seed production
Socially self-organized	<ul style="list-style-type: none"> • Social self-organization of farmers and breeders is not given • The needs of farmers and other actors along the agricultural value chain are integrated through stakeholder and sustainability management 	<ul style="list-style-type: none"> • Farmers and breeders form their own structures for breeding, seed multiplication and marketing • A high degree of coordination and cooperation along the agricultural value chain
Ecologically self-regulated	<ul style="list-style-type: none"> • Focus on achieving adaptability to changing environmental conditions through biotechnological enhancements based on genetic modification and genomics: breeding of primarily hybrid and genetically modified varieties • A core breeding goal is increased resource efficiency in terms of pesticide, nitrogen, water, energy, and land use • Chemical pest management through 'integrated solutions' of (genetically modified) seeds and complementary pesticides 	<ul style="list-style-type: none"> • Focus on achieving adaptability to changing environmental conditions through natural enhancements of varieties: breeding of open-pollinated, naturally reproducible varieties via crossing and selection methods • A core breeding goal is plant robustness without chemical inputs. Varieties are specifically adapted for organic cultivation conditions • Ecological pest management through breeding and seed multiplication under organic conditions
Functional and response diversity	<ul style="list-style-type: none"> • Breeding predominately for monogenetic resistances and genetic uniformity • Concentration on few crop species and crowding out of regionally adapted varieties through a focus on generalist high-yielding varieties • Agrobiodiversity at the landscape level is reduced through the impacts of pesticides and synthetic chemical fertilizers used in seed multiplication 	<ul style="list-style-type: none"> • Breeding of open-pollinated varieties favours higher genetic diversity in varieties • Preserving and enhancing agrobiodiversity at crop species level using traditional crop species and varieties in breeding and in-situ maintenance of conservation varieties • Fostering of functional diversity of cultural landscapes in seed multiplication
Optimally redundant	<ul style="list-style-type: none"> • Reduced redundancy of supply channels for seeds through an increasing market concentration due to company mergers and acquisition 	<ul style="list-style-type: none"> • Increased redundancy of different seed supply channels through encouraging commercial and hobby gardeners to carry out their own seed-multiplication and promoting seed exchanges • Contributing to an independent organic seed sector, thereby creating redundancy of breeding structures
Exposed to disturbance	<ul style="list-style-type: none"> • Breeding takes mostly place under controlled environmental conditions, in the lab and in field experiments 	<ul style="list-style-type: none"> • Breeding takes place on-farm – in situ breeding allows for exposure to site-specific disturbances and changing environmental conditions
Coupled with local natural capital	<ul style="list-style-type: none"> • Breeding of varieties that are adapted to specific climates and (large) regions • Agricultural inputs rely on complex global value chains 	<ul style="list-style-type: none"> • Breeding of varieties that are adapted to specific regions and agroecological conditions • Agricultural inputs are limited to available local natural resources

(Continued)

Table 2. Continued.

Indicator for agroecological resilience	Conventional seed production	Commons-based seed production
Accumulation of reserves and physical infrastructure	<ul style="list-style-type: none"> • Focus on increasing centralized high-technology breeding, seed processing and storage facilities • Buildup of centralized seed banks 	<ul style="list-style-type: none"> • Focus on increasing on-farm infrastructure through low-technology breeding, seed cleaning, and processing as well as appropriate storage facilities • Encouraging farmers to build up reserves through seed saving practices and establishing small-scale community seed banks
Appropriately connected: globally autonomous and locally interdependent in modular subsystems	<ul style="list-style-type: none"> • (New) varieties are highly dependent on external inputs e.g. on complementary pesticides or technological equipment • Focus on international markets for seed (and pesticide) retail, relying on highly complex international supply chains • Trend of increasing global market concentration and merger with pesticide producers 	<ul style="list-style-type: none"> • (New) varieties are largely independent of external inputs • Focus on regional and informal markets for seed retail • A high degree of modular connectivity at the local level of breeders and farmers e.g. through networks and participatory breeding approaches
Builds human capital and encourages reflective and shared learning	<ul style="list-style-type: none"> • Practical training of farmers on cultivation techniques, secure application of agrochemical products and access to markets and credits • No training/ information of farmers on breeding and seed production • Breeding history and – methods of new varieties are usually not disclosed 	<ul style="list-style-type: none"> • Practical training on breeding for commercial and hobby gardeners • The breeding history and -methods of new varieties are shared publicly
Conservative innovation that honours legacy	<ul style="list-style-type: none"> • Future and part of current practice is seen in biotechnical breeding methods, specifically gene editing rather than traditional breeding techniques • Use of modern rather than landraces and traditional varieties • Variety development is mainly based on scientific breeding knowledge, traditional practical knowledge of farmers is not appreciated 	<ul style="list-style-type: none"> • Application and further development of traditional breeding techniques • Use of landraces and traditional crop species and varieties in breeding • Traditional practical knowledge of farmers is appreciated and integrated alongside scientific breeding knowledge
Reasonably profitable	<ul style="list-style-type: none"> • Highly profitable, which is necessary to continuously re-invest in biotechnological advancements • High dependency on shareholders and investors (as external factors) 	<ul style="list-style-type: none"> • Insecurity regarding the long-term financing of breeding activities due to a lack of profitable financing models • Diverse sources of financing, mostly on voluntary or charitable grounds (e.g. through foundations and donations), partly external to the SES
Polycentric, decentralized governance structures	<ul style="list-style-type: none"> • Organization of multinational seed companies into centralized facilities and research centres worldwide which are governed by a single governance body • Increasing market concentration opposes polycentric structures • Hierarchical but partially democratic governance structures within seed organizations 	<ul style="list-style-type: none"> • Polycentric organization structure of breeding organizations, seed producers and – preservers including decentralized breeding projects with own decision-making competences • Non-hierarchical and democratic decision making structures within seed organizations

(Continued)

Table 2. Continued.

Indicator for agroecological resilience	Conventional seed production	Commons-based seed production
Ensuring resource access and broadening participation	<ul style="list-style-type: none"> • Application of intellectual property rights on newly developed varieties (e.g. variety protection, patents on genetic material and breeding technologies) limits access to seeds and genetic material for both farmers and breeders • Non-reproducing varieties and re-seeding fees create dependencies of farmers on seed companies • Focus on access to knowledge and credit through training and technology transfer 	<ul style="list-style-type: none"> • Access to varieties for farmers, gardeners and breeders is secured through the waiving of private property rights and/or adaptation of open-source systems • Reproducing varieties allow for farmers' independence • Focus on participatory breeding approaches
Complex adaptive systems thinking	<ul style="list-style-type: none"> • Worldview of domination of nature leads to a focus on (bio)technical solutions (e.g. breeding under optimally controlled conditions) 	<ul style="list-style-type: none"> • Worldview of working with nature leads to a holistic breeding approach (e.g. breeding on-farm in natural environments). Focus on social rather than technical innovations

5. Discussion

The extended indicator framework enabled us to characterize core differences between commons-based and private-property-based seed production systems, and their effects on agroecological resilience. The findings show that commons-based approaches to seed production, in comparison to conventional seed production, tend to foster agroecological resilience. Building commons structures can therefore be a highly relevant strategy in agricultural systems, particularly if the control of environmental conditions in the face of disturbances is not possible (e.g. on marginal agricultural land), not cost-efficient (e.g. in the case of peasant agriculture in the Global South), or where common 'control technologies', such as pesticide application or genetic engineering, are incompatible with ethical principles (mainly in organic agriculture).

In the region under study, commons approaches have so far only been implemented in the context of organic breeding and organic seed production. Thus, positive agroecological resilience effects linked to commons characteristics need to be disentangled from effects stemming from the practices of organic agriculture. Whereas commons approaches place a stronger emphasis on the organization of resource governance and the corresponding social processes, which can foster agroecological resilience, the principles of organic agriculture place ecological aspects in the foreground. The two approaches can thus be seen as complementary and mutually reinforcing when it comes to fostering agroecological resilience.

However, commons-based seed systems also have some drawbacks that diminish their contribution to agroecological resilience. Most prominently, a lack of sufficient profit to maintain and grow enterprises without government support may significantly reduce the overall impact of commons-based organizations. Reasonable profitability is a precondition for the long-term survival of these organizations, as well as for their ability to invest in physical, human and social capital. A lack of funding may thus offset advantages on other indicators. This also raises the question of whether there is a need to weigh individual indicators to determine overall resilience capabilities. This goes beyond the scope of this paper but requires further investigation.

Furthermore, due to higher financial investments and the use of technologies that allow the development of new varieties faster than natural selection

does, conventional seed production has a higher innovation speed and output than commons-based seed production. Conventional seed production also shows advantages in terms of production efficiency under optimal cultivation conditions. Such a trade-off between efficiency and social-ecological resilience (specifically, diversity, redundancy, and reserves) has been observed across different social-ecological systems: resilient systems are often not as productive as other systems (Anderies et al., 2004). Since food security as an internationally recognized goal cannot be compromised on moral grounds (c.f. United Nations, 1948, 2015), the question of the contribution of agricultural productivity and agricultural resilience to local and global food security is crucial.

Competing narratives and problem framings around the governance of food security conceptualize the role of production efficiency and resilience and their interactions differently (Jiren et al., 2020; Loos et al., 2014; McMichael & Schneider, 2011). They share the perspective that food security is a complex, multidimensional concept, and that both production efficiency (often discussed as approaches to agricultural intensification) and resilience attributes influence the state of food security. They differ, however, in whether resilience attributes are understood as an additive or as an essential precondition for increasing food security (Loos et al., 2014). The impact of the recent COVID-19 pandemic on food security provides empirical evidence for the latter perspective: it has demonstrated how the efficiency of a non-redundant system and therefore food security can decrease dramatically, and how community-based systems with shorter, more direct supply chains can be much more reliable (Duguma et al., 2021; Worstell, 2020). Further, as represented by the indicator *ensuring resource access and broadening participation*, the concept of agroecological resilience also links to aspects of food and seed sovereignty (Kloppenborg, 2014), which are considered to be highly relevant for realizing food security (De Schutter, 2012; IPBES Food 2020). Commons-based seed production is especially strong in this regard.

Lammerts van Bueren et al. (2018) propose a framework of systems-based breeding that is directed towards achieving the international sustainability targets of food security, food sovereignty, social justice, agrobiodiversity, ecosystem services, and climate robustness. One core element of such a systems-based breeding orientation is free access to

genetic resources, to allow all actors in the seed sector to access a broad genetic base of seed material (Lammerts van Bueren et al., 2018). This would challenge a key component of the conventional breeding model, but may be a starting point in building more resilient seed and agricultural systems.

6. Conclusion

In this paper, we have developed a conceptual framework to systematically examine the contribution of seed production, including breeding, to agroecological resilience. Specifically, we extended the indicator framework compiled by Cabell and Oelofse (2012) and broadened its scope by focusing on seed production – thereby developing an indicator framework that allows us to assess how different organizational approaches to seed production contribute to agroecological resilience. We showed that plant breeding and seed production affect agroecological resilience in multiple dimensions, including the characteristics of available varieties (such as genetic diversity, adaptation to specific needs and biophysical conditions) and access rights to seeds for farmers, gardeners, and breeders.

Our empirical assessment, based on a document analysis of publications from breeding and seed-producing organizations in the German-speaking vegetable seed sector, revealed the positive effects of commons structures in seed production on agroecological resilience. These include a high degree of self-organization of farmers, gardeners and breeders along the value chain of plant cultivation; the development of open-pollinated, naturally reproducible varieties; redundancy of different seed supply channels, achieved by encouraging hobby and commercial gardeners to carry out their own seed multiplication, and by establishing seed exchanges and an independent organic seed sector; and autonomy from external resource inputs such as pesticides, synthetic chemical fertilizers, and genetic sequences and technologies protected by intellectual property rights. Further, commons approaches as organizing principles improve the resilience of the governance structures of seed production by facilitating knowledge exchange and social learning, a polycentric organization of breeding, non-hierarchical decision-making structures and participatory breeding approaches. However, commons-based seed production is often threatened by insecurities regarding the long-term

financing of its breeding activities, and may under optimal conditions be less productive and innovative than conventional seed production.

Positive effects of commons approaches in the seed sector on the resilience of the global agricultural and food system can be assumed, especially if an out-scaling (geographical diffusion within the niche) and up-scaling (widening of the scale of operation; Douthwaite et al., 2003) of commons-based seed and breeding initiatives is politically supported. Potential positive effects include an increase in available agrobiodiversity, the buildup of networks and close social ties among actors along agricultural value chains, knowledge diffusion and a focus on sustainable resource management. Further research could apply the framework developed in this paper to analyse seed production practices in the Global South, or to identify suitable entry points for integrating commons principles in conventional seed production.

Notes

1. We do not include the indicator *spatial and temporal heterogeneity*, defined as ‘patchiness across the landscape and changes through time (e.g., patchiness on the farm and across the landscape, mosaic pattern of managed and unmanaged land, diverse cultivation practices, crop rotations)’ (Cabell & Oelofse, 2012, p. 4), into our assessment, since there is no direct causal link between the configuration of seed production and heterogeneity in cultivation systems. Further, we combine the indicators *appropriately connected* (‘the quantity and quality of relationships between system elements,’ Cabell & Oelofse, 2012, p. 4) and *globally autonomous and locally interdependent* (the ‘relative autonomy from exogenous (global) control and influences [and a] high level of cooperation between individuals and institutions at the more local level,’ Cabell & Oelofse, 2012, p. 5), since the second indicator characterizes a specific type of connectedness. To address the need for modularity, to contain disturbances by compartmentalizing social-ecological systems (Carpenter et al., 2012; Worstell & Green, 2017), we construct the indicator *appropriately connected: globally autonomous and locally interdependent in modular subsystems*. In addition, we merge the indicators *builds human capital and reflective and shared learning* (see Table 1 for their definitions), since they describe related resource and process dimensions of the same characteristic of the governance system. Finally, we rename the indicator *honours legacy* as *conservative innovation that honours legacy*, following Worstell and Green (2017, p. 33), to stress the role of innovation for social-ecological resilience in its combination with honouring ideas from the past that work.

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