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Enhancing resilience through seed system plurality and diversity: challenges and barriers to seed sourcing during (and in spite of) a global pandemic

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Abstract
The effects of the COVID-19 pandemic have rippled across the United States' (US) agri-food system, illuminating considerable issues. US seed systems, which form the foundation of food production, were particularly marked by panic-buying and heightened safety precautions in seed fulfillment facilities which precipitated a commercial seed sector overwhelmed and unprepared to meet consumer demand for seed, especially for non-commercial growers. In response, prominent scholars have emphasized the need to support both formal (commercial) and informal (farmer- and gardener-managed) seed systems to holistically aid growers across various contexts. However, limited attention to non-commercial seed systems in the US, coupled with a lack of consensus surrounding what exactly a resilient seed system looks like, first warrants an exploration into the strengths and vulnerabilities of existing seed systems. This paper seeks to examine how growers navigated challenges in seed sourcing and how this may reflect the resilience of the seed systems to which they belong. Using a mixed-methods approach which includes data from online surveys (n = 158) and semi-structured interviews (n = 31) with farmers and gardeners in Vermont, findings suggest that growers were able to adapt – albeit through different mechanisms depending on their positionality (commercial or non-commercial) within the agri-food system. However, systemic challenges emerged including a lack of access to diverse, locally adapted, and organic seeds. Insights from this study illuminate the importance of creating linkages between formal and informal seed systems in the US to help growers respond to manifold challenges, as well as promote a robust and sustainable stock of planting material.

Keywords Seed systems · Resilience · Food systems · Adaptation · Informal seed systems · United States

Introduction

At the beginning of the COVID-19 pandemic in the early months of 2020, seed supply chains were disrupted globally due to lockdowns, country-wide curfews, travel bans, and social distancing measures that interrupted production and distribution across food systems (Shilomboleni 2020; Béné 2020; Poudel et al. 2020). In the United States (US), accounts in the popular media were profuse with stories of issues facing the commercial seed sector, often highlighting seed shortages due to heightened safety precautions and an increase in demand for seed (Nabhan and Kaufman 2020; Held 2021). The increased demand coupled with a need to bolster food security through multiple pathways resulted in some states, including Vermont, labeling seeds as "essential" despite restrictions on in-person purchases for most goods (Vermont Agency of Agriculture 2020). Alongside these efforts, conversations manifested globally centered around supporting non-commercial forms of seed production and exchange (Nabhan and Kaufman 2020; Organic Seed Alliance (OSA) 2020; The Crop Trust 2020; Soleri et al. 2022), despite the general lack of attention placed on non-commercial seed exchange by the public sector since long before the pandemic (Atalan-Helicke et al. 2021). Now three years since the pandemic began, these disruptions and initiatives continue to spotlight the COVID-19 pandemic not only as a moment in time that tested food systems, but

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also one in which lessons can be gleaned to improve the resiliency of food systems (Klassen and Murphy 2020), of which seeds are essential.

Accordingly, the following paper seeks to investigate how Vermont fared following the onset of the pandemic, how this event impacted the farmers and gardeners that rely on them, and how these impacts reflect the resilience of the seed systems with which they engage. Specifically, we use a combination of quantitative and qualitative data to explore how COVID-19 impacted seed systems within Vermont directly following the pandemic's onset (objective 1) and how different types of growers (i.e., farmers and gardeners) responded to these challenges (objective 2). These objectives begin to examine how key concepts of resilience (i.e., stability, adaptability, and transformability) relate to the social-ecological sustainability of seed systems, inspired by and drawing upon previous scholarly insight across disciplines regarding resilience and seed systems (Walker 2004; Folke et al. 2010; McGuire and Sperling 2013; McGuire and Sperling 2016; Tendall et al. 2015 Béné 2020; Kliem and Sievers-Glotzbach 2022). Given the centrality of seed systems to food production in both the short and long term, the findings of this paper provide evidence of how bolstering a plurality of seed systems has the potential to support resilience, reduce vulnerability, and support sustainability across food systems.

As outlined poignantly in both Zimmerer and de Haan (2020) and Sperling et al. (2020), supporting agricultural producers globally following the pandemic necessitates, first and foremost, an acknowledgment of the diversity of systems which they use for seed, including *informal seed systems*, also known as "farmer seed systems" due to their being primarily defined by farmer-to-farmer exchanges of seed. However, the importance of informal seed systems globally continues to be routinely overlooked, despite between 80 and 90% of farmers in some countries (specifically in the Global South) depending on informal sources of seed (Wattnem 2016; Etten et al. 2017; Otieno et al. 2017). The recognition of the existence of informal systems in the Global North is particularly abysmal – again despite evidence of their persistence and importance to small-scale commercial producers and non-commercial gardeners alike (Campbell 2012; Veteto 2014; Isbell et al. 2021; Batur et al. 2021; Lyon et al. 2021). Instead, largely in part due to the high degree of corporate concentration within the seed industry with only four agrochemical/seed firms controlling approximately 62% of global propriety seed sales (Howard 2022), the *formal seed system*, which is principally composed of "improved" and certified seed from the commercial sector, continues to dominate policy and programs focused on seed systems. This emphasis on formal seed systems neglects other major forms of seed exchange which can enhance the amount, appropriateness, and in some cases, quality of seed stock available to growers (Batur et al. 2021). This paper's approach thus considers the impact of the COVID-19 pandemic on seed systems holistically – intentionally looking at a range of growers who operate within both informal and formal systems to understand the potential complementarities and conflicts within US seed systems that can better inform resilience strategies now and into the future.

Background

Seed system structures and trends

Seed systems are often distinguished by the degree to which they interact with "formal" institutions: hence common categorizations of seed systems as either formal or informal. Formal systems can be considered as both public (i.e., land-grant universities, national breeding programs, etc.) and private (i.e., seed companies) institutions that disseminate certified or verified seed, primarily through market channels. In comparison, informal or "farmer seed systems" typically consist of unregulated exchanges of seed between farmers and gardeners as well as a higher prevalence of seed saving (Kuhlmann and Dey 2021). Within both seed systems, there is a high degree of heterogeneity in terms of the types of seed that they maintain, making distinctions between formal and informal seed systems fairly fluid. For instance, while the formal seed system is a principal disseminator of improved, hybrid, and genetically modified planting material, some seed companies may instead be dedicated to organic, open-pollinated, or heirloom varieties (Helicke 2015). Similarly, while informal seed systems may oftentimes be composed of diverse, locally adapted, and environmentally resilient varieties, they also may circulate new or improved, non-local, or traditional seed of varying quality (McGuire and Sperling 2016). Despite the heterogeneity extant in both formal and informal seed systems, informal seed systems in particular have been undervalued due to a widely held assumption by development actors that formal seed systems are inherently "better" or more modern than informal seed systems, thus resulting in greater emphasis on formal seed systems within policy (Frison 2018).

As Coomes et al. (2015) outline and refute, common misconceptions of informal seed systems include that they always circulate poor quality seed, are a relic of pre-capitalist agricultural systems, and have minimal interaction with seed system actors outside of very small, local, and closed loops. In reality, informal seed systems not only continue to predominate in many areas of the world (Etten et al. 2017), but also are instrumental in maintaining agrobiodiversity

essential to the health of multi-species ecosystems (Letourneau et al. 2011; Pautasso et al. 2013), and often provide an alternative source of seed with traits desirable to farmers (Almekinders and Louwaars 1994; Croft et al. 2018). Additionally, informal seed systems should not be conflated with closed seed systems (i.e., hyper-localized systems with no exchange of planting material with externals sources): as exemplified by Heraty and Ellstrand (2016) in their study of conservation approaches taken by immigrant farmers in California, informal seed systems are often highly dynamic and contain a mix of germplasm taken from a variety of sources beyond a geographical place. Even the term "informal seed system" is increasingly contested due to negative connotations, with some opting instead for "farmer seed systems" (Batur et al. 2021). However, informality is an important characteristic in distinguishing these systems from other types of seed systems – and highlights the ways informal seed systems operate without a strict decoupling of functions (production, distribution, consumption, etc.) between disparate actors within a linear supply chain.

As Lyon et al. (2021) highlight in their historical analysis of US and Canadian seed regimes (taking inspiration from Friedman and McMichael's (1989) theory of "food regimes"), the last century has dramatically shifted how seeds have been produced and exchanged. Following both the hybridization of seeds and the development of intellectual property rights (IPR), seed systems in the US are now dominated by the formal seed sector. Beyond the growing corporate consolidation of the seed industry, this shift has also meant the mass externalization of seed production; although once managed as an on-farm task, farmers were able to skip producing seed for the next year altogether as the formal seed system grew. This has led seed system scholars such as Kloppenburg (2004) to argue that US seed policy from the 1930s onward (starting with the Plant Patent Act of 1930 that allowed some patent-like protections of asexually reproducing plants (Howard 2015)) led to the enclosure of the "seed commons." In likening seed corporatization to the enclosure of common land that facilitated the spread of capital into rural areas in 16th century England (and has continued in other regions since), Kloppenburg is principally discussing the act of dispossessing farmers from their means of production (Kloppenburg 2010) which has resulted in farmers having to increase their dependence on outside sources for their livelihoods.

As Fig. 1 displays, within informal systems, individuals and households conduct all if not most of what is necessary to maintain a seed system, from production to consumption. Since seeds in this system may be saved (i.e., a small portion of harvest set aside to plant next year's crops), informal systems are also more cyclical than formal ones which typically require that farmers purchase a new stock of seeds each year. Again, this is not to say that informal systems are closed. On the contrary, there may be exchanging of seeds between individuals and households, as well as the sharing of certain functions to reduce the labor required to maintain a robust seed stock. However, in comparison, formal seed systems are much more linear, with each function being undertaken by a specialized actor. Additionally, everything before consumption is usually completed by entities external to a household (e.g., actors within a seed company's supply chain) – leaving consumers (in this case, farmers and gardeners) separated from all the processes that must be done to supply them with seed. The prevalence of formal

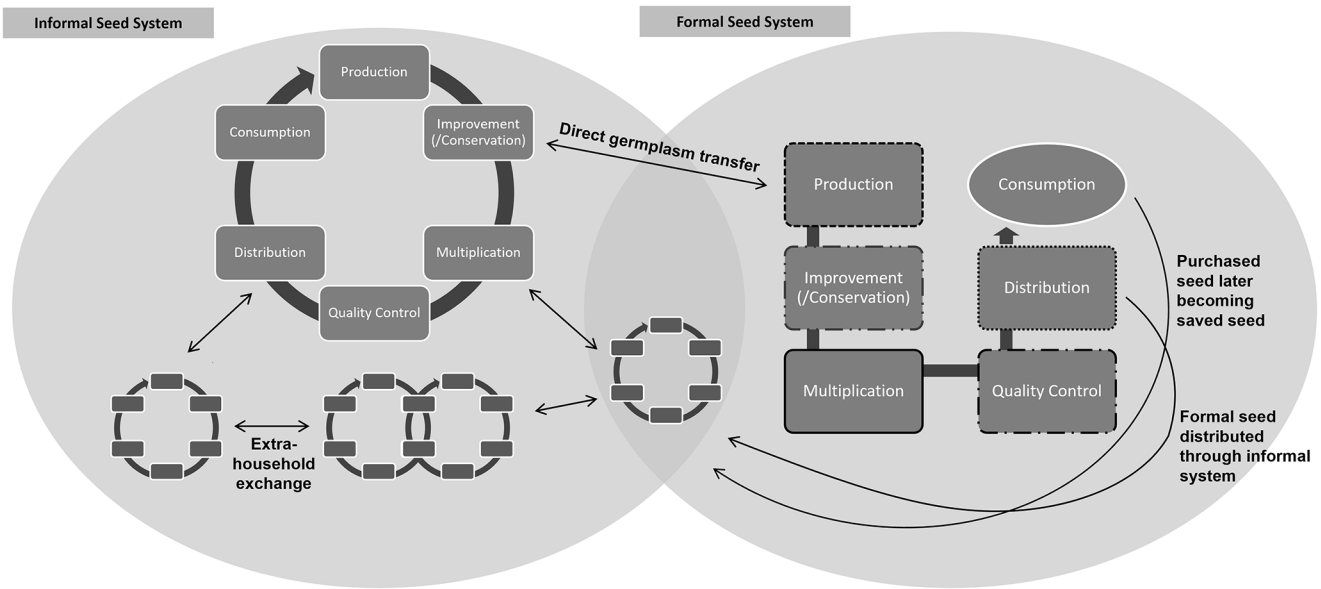

Fig. 1 Seed System Functions and Structure. (Adapted from Soleri (2018))

seed systems has thus raised serious concerns in several areas of importance which include the ability of contemporary seed systems to contribute to community and individual seed sovereignty (La Via Campesina 2021; Soleri et al. 2022), maintain the agrobiodiversity necessary to adapt to challenges such as climate change (Etten et al. 2017), and support polycentric governance within the global food system (Tschersich 2021). When considering the function and structure of seed systems, many of these issues can be traced to the linear functioning of formal seed systems, where seed knowledge and selection are undertaken by a select number of individuals rather than by a collection of households or other groups of actors (Soleri 2018).

Indeed, the formalization of seed systems, and with it, the concentration of power and minimization of functional diversity (both in terms of a household conducting multiple functions to produce seeds for food, and the diversity of germplasm available from those seeds), has drawn wide and varied criticism. For instance, farmer organizations such as La Via Campesina actively denounce programs that attempt to promote formal seed systems in areas where they are absent or underdeveloped, asserting that they erode peasants' ability to self-determine their own seed, and ultimately, food system (La Via Campesina 2021). This sentiment is also reflected in the Global North, with many community organizations taking it upon themselves to create seed systems that are decentralized and more democratic (Soleri et al. 2022). Others warn that the hegemony of the formal private system will erode crop diversity and agricultural heritage, and cause long-term damage to the resiliency of agri-food systems (Wise 2020). Contesting these trends, several alternative structures have been proposed in opposition which include a bolstered and reimagined informal sector led by peasant farmers (La Via Campesina 2021), commons-based approaches which attempt to de-commodify seed through community-based exchanges (Soleri et al. 2022), open-source seed initiatives to reverse seed enclosures (Montenegro de Wit 2019), and "integrated" (or *pluralistic*, as we typify in this paper) systems which seek to leverage the benefits of formal and informal seed systems alike (Sperling et al. 2013). These movements share the commonality of acknowledging equitability, diversity, and plurality over singularity within seed systems – albeit through sometimes different mechanisms.

Despite the traditional conceptualization of formal and informal seed systems as binary and separate, in practice, most farmers globally rely on formal *and* informal seed sources to supply at least a portion of their seed (Lopez Noriega et al. 2021), which Fig. 1 attempts to capture by showcasing overlap between systems and households who may operate out of both. Fig. 1 also provides a few examples of how seed can flow through both systems (e.g., direct germplasm transfer from informal to formal systems, distribution of formal seeds through informal channels, and purchased seed being taken and subsequently saved), thus problematizing the conceptualization of formal and informal systems as strictly separate. On the contrary, they can be quite complementary. For instance, in places such as sub-Saharan Africa, the COVID-19 pandemic has demonstrated how informal systems can work complementarily with local seed markets to enhance seed security (de Boef et al. 2021). Moreover, Vernooy et al. (2022) highlight the potential for community seed banks to not only enhance access to important crops but also promote community empowerment and provide a source of local income – benefits that are made possible by leveraging capacities of both formal and informal seed systems.

Beyond growers using both types of seed systems, there is also a high degree of overlap and exchange between the two systems. For instance, the formal system is highly dependent on germplasm originating from the informal sector, just as the informal system is often a major disseminator of improved varieties from the formal sector (Wattnem 2016). Moreover, ample examples of integrated or pluralistic seed systems exist, even in the Global North. In the US, open-source, organic, and heirloom seed companies have proliferated across the country (Helicke 2015), many of which actively challenge the rigid structure of formal seed systems by creating civil society-business models which help promote common goals held across seed system actors. One of the most successfulformal system initiatives includes the *Safe Seed Pledge* created by High Mowing Organic Seeds in 1999 which is meant to prevent the distribution of genetically modified seed, and now has more than 300 signatories across private and civil sectors (High Mowing Organic Seeds, n.d.). Furthermore, efforts to bring together informal seed system actors (e.g., farmers and gardeners, community organizations) and formal seed system actors (e.g., plant breeders, seed companies) exist and are challenging traditional power and influence discrepancies (Lyon et al. 2021). What these examples point to is the need to question the segregation between informal and formal seed systems, as well as acknowledge the ways that they may be complementary rather than exclusive, and in doing so benefit a wider range of growers (Sperling et al. 2020). Seed system categorizations should thus be considered as generally permeable (Batur et al. 2021), especially considering that seed systems rarely exist in their "ideal" states. However, while imperfect, understanding the formal/informal seed system characterization is oftentimes helpful, especially when considering concepts such as resilience which are centered around understanding functionality and system structures.

Seed system resilience

Despite substantial research into seed systems globally, there is no universally accepted definition for what constitutes a resilient seed system. However, much can be gleaned from the study of resilience in the natural and social sciences; in most cases, resilience can be 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 et al. 2004). Social-ecological resilience, which acknowledges the interconnectivity of human and environmental systems, goes further by including in its definition the ability to re-organize, learn, and transform to changing conditions as determined by the actors within the system (Holling 2001; Adger 2000), constituting what Folke et al. (2010) refer to as *adaptive capacity*. As they explain, although resilience is often misunderstood as necessitating total stability under a constant equilibrium (see Holling 1996 for further discussion on the differences between what he calls engineering resilience and social-ecological resilience), the ability of actors within a system to both adapt and transform the system which they are a part of should be considered as a prerequisite of resilient social-ecological systems (SES), which seed systems can be categorized as. This attention towards actors is essential to seed system resilience as well, with the Alliance of Bioversity International and the International Center for Tropical Agriculture (Bioversity-CIAT Alliance) providing a preliminary description of a resilient seed system as one which "relies on the ability of seed system actors to absorb disturbances, regroup or reorganize, and adapt to stresses and changes caused by a perturbation in the environment" (Vernooy et al. 2019, p. 7). Beyond the ability of actors to make changes in a system, Vernooy et al. (2019) also underscore the importance of fulfilling actor preferences as a component of resilience, essentially meaning that a resilient system should be responsive to both the needs and desires of actors.

Social-ecological resilience also depends on flexibility during system disruptions and perturbations, which is predicated on the capacities (i.e., skills and resources) of that system (Béné 2020). Understanding the variability inherent within SES, Béné (2014) further categorizes resilience capacities into *absorptive* (persistence with minimal system change), *adaptive* (pro-active incremental adjustments), and *transformative* (working towards systemic change) capacities – all of which serve to reduce the vulnerability, defined as sensitivity and exposure to external stresses (Adger 2000), of actors as parts of the system and the system overall. These capacities recognize the fluid nature of SES and the importance of having multiple options in that social-ecological resilience can sometimes necessitate transformation or transition over relative stability if that system is considered socially undesirable or unsustainable (Smith and Stirling 2010). For instance, although the term "resilience" is often associated with positive outcomes, this is not always true as "evil dictatorships, salinized landscapes, and psychotic states in people can be very resilient" (Walker 2020, p. 1) but obviously not desirable to most people.

Considering various actors with frequently divergent goals, constraints, and preferences engage in seed systems, understanding what social-ecological resilience within these systems looks like can be difficult. Resilience is often already a normative concept, with discourse around which systems are resilient or not tending to reflect the goals and values of dominant groups, thus further marginalizing other knowledge systems (Thorén and Olsson 2018), particularly of women and people of color (Vernooy et al. 2019; Beale Spencer et al. 2015). Efforts to enhance resilience thus may inadvertently neglect groups that are considered less important economically or politically such as non-profit organizations, community-based groups, and, in the case of seeds and agriculture, non-commercial growers (i.e., gardeners and homesteaders). For instance, as it stands, the US seed system is by-and-large not geared towards fulfilling the needs of non-commercial producers and producers who prefer alternative characteristics of seed that may be hard to find through conventional formal seed systems (e.g., organic seed). Additionally, plant breeding programs have historically been more oriented towards breeding for large-scale commercial agriculture, with lucrative characteristics such as seed size and yield often taking precedence over taste, nutrition, and uniqueness (Kloppenburg 2004).

Seed system resilience must also consider the importance of diversity across a multitude of planes – socially (e.g., seed source and network diversity and network diversity), environmentally (e.g., inter- and intra-crop species diversity), and politically (e.g., cultural and knowledge-system diversity) (Kliem and Sievers-Glotzbach 2022). Indeed, diversity (or "optimally redundant systems" (Kliem and Sievers-Glotzbach 2022)) is essential to resilience within SES, ensuring that if a certain capacity is absent, another can be substituted to enable adaptability (Walker 2020). For example, as McGuire & Sperling (2010) highlight in their analysis of Seed Security Assessments (SSA) in Sub-Saharan Africa, effective seed security responses mobilize not one but many responses such as direct seed aid, vouchers for seed purchases, and engagement with informal "knowledge-brokers" to provide variability and seed access across various channels. This array of responses highlights the importance of redundancy in functionality to system resilience, although redundancy is often disregarded for the sake of efficiency within the conventional global agri-food system and seed systems within it (Garnett et al. 2020; Walker

2020). Supporting a diverse array of seed system structures (i.e., both formal and informal, which together can form pluralistic seed systems) can promote greater supply-chain resilience, ensure that the needs of a wide array of growers are catered to, as well to promote greater accessibility to all growers at whatever scale – all essential components of social-ecological resilience (Smith and Stirling 2010).

Lastly, there are also temporal considerations that foreground the fact that seed system resilience should not only manifest in immediate responses to acute shocks but also relates to the long-term functioning and well-being of a system, although this is often overlooked empirically in studies attempting to measure resilience. By and large, this may be because of the fact that resilience is very difficult to measure in the long term, resulting in most studies that claim to examine resilience being limited to investigating components or indicators of resilience (Béné 2020). However, as Kliem and Sievers-Glotzbach (2022) demonstrate in their conceptualization of agroecological resilience, this temporal aspect is especially crucial when considering agricultural systems and, more specifically, seed systems considering not only the immediate and instrumental necessity of seed for growers' livelihoods but also for the long-term security and adaptability of food systems globally to natural and anthropometric challenges. With this temporal aspect in mind, alongside the importance of diversity and flexibility as discussed above, the following sections seek to examine the current capacities and shortcomings of informal and formal seed systems following the COVID-19 pandemic, with the goal of understanding if and how each contributes to seed system resilience.

Conceptual framework

Following the resilience literature on SES described in the previous section, Fig. 2 outlines the resilience framework used for this paper, providing the lens through which seed system resilience is assessed in this study. As displayed within the figure, we assume that a seed system's *response* indicates resilience (or lack thereof) in the short-term, *recovery* relates to the medium-term, and *impact* (either system transformation or adjustment and stabilization) relates to the long-term impacts of a shock, which can be considered as a culmination of various system deviations (Folke et al. 2010), as determined by the strength of a systems capacities.

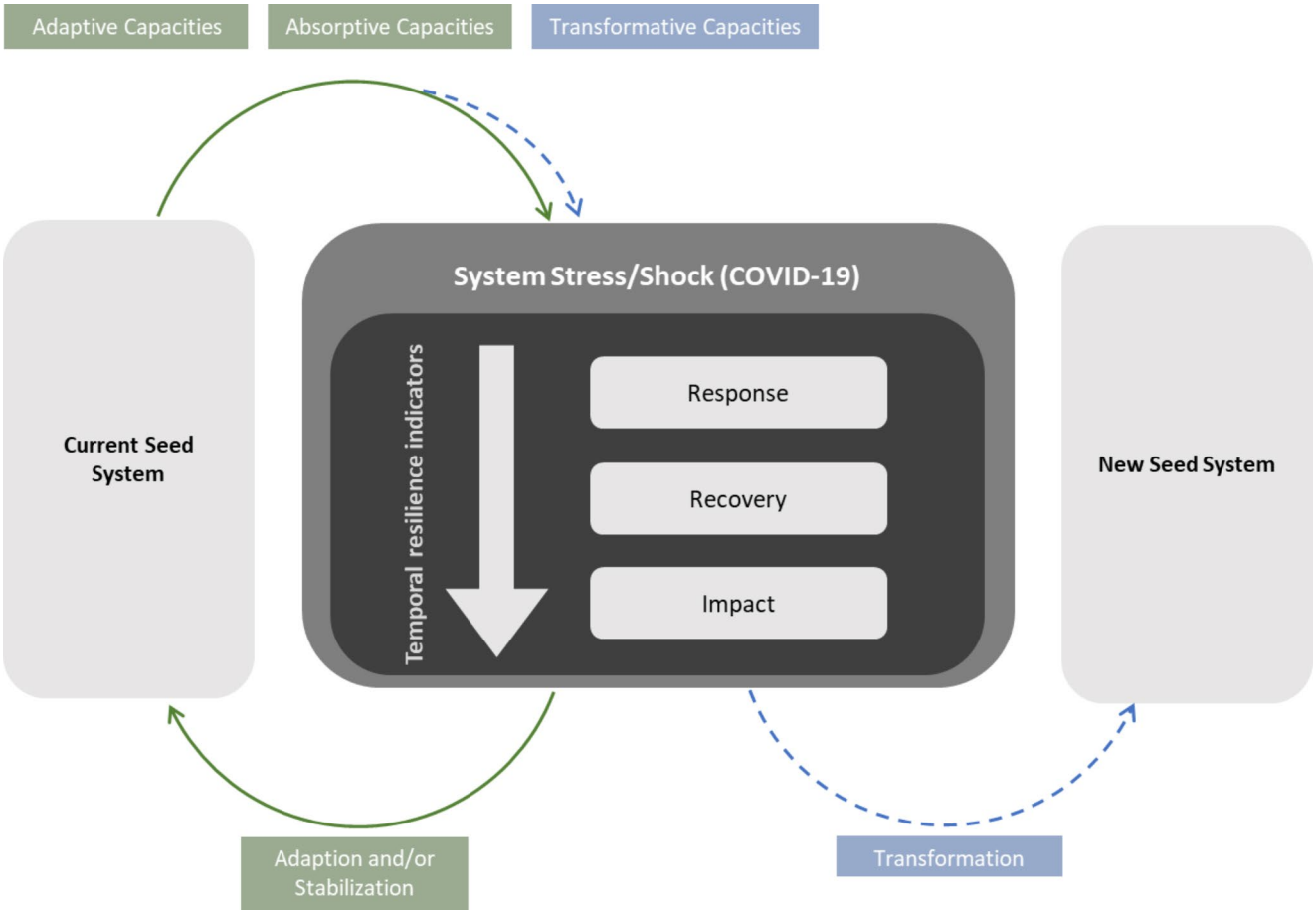

Fig. 2 Seed System Resilience Framework. (Source: Author)

The capacities (absorptive, adaptive, and transformative), as outlined by Béné (2014), indicate whether or not a seed system will eventually stabilize or go above a threshold and transform into a new system. Importantly, although not displayed in this figure for the sake of simplicity and clarity, a transformation is not necessarily bad – but perhaps indicates a desire for the actors within a system to make substantial changes. Given the current state of seed systems in the US, this may take the form of imaginings of new (or renewed) forms of seed exchanges and understandings and the incorporation of alternative knowledge systems.

Furthermore, as highlighted by Vernooy et al. (2019) it should also be stressed that a resilient seed system must satisfy the needs and preferences of its diverse stakeholders. We thus define a resilient seed system as one that can not only respond positively to system disruptions such as COVID-19 by ensuring that individuals still maintain access to seed, but also that their values and preferences are fulfilled. As will be presented in the following sections, we use individual actors as our principal unit of analysis following assumptions that they often reflect the adaptability of an SES (Folke et al. 2010), and as grounded by other research which has used actor-level responses to shocks to understand the resilience of a system to which they belong (González-Quintero and Avila-Foucat 2019). This is supported by ideas surrounding social resilience which specifically deals with the way that social entities (e.g., individuals and communities) cope with various threats to their lives and livelihoods (Keck and Sakdapolrak 2013). As such, while general system resilience does not always translate to individual resilience (social resilience instead usually centers on the utilitarian ideal of allowing for the most adaptability for the greatest number of people (Pauley et al. 2019)), the ability of actors to adapt is usually indicative of the adaptability of a system with which they interact. Individual and social-ecological resilience are thus importantly distinct (e.g., in the sense that a minority within a system may not benefit fully from it (Walker 2020)) but related so that, when considering systems that are strongly influenced by humans (such as domesticated agriculture), individual or community resilience often becomes a way to understand system resilience, considering that individual actions are highly constrained or supported by the system in which they operate.

Methods

Study design, population, and sample

All data were collected in the fall and winter of 2021 and 2022 and relied primarily on remote recruitment and data collection methods due to public health safety concerns. Before this project began, IRB approval was obtained from The University of Vermont (UVM) on October 17th, 2020, after ensuring the validity and reliability of all project instruments through field testing and pilot testing. The population of interest for this project was Vermont seed growers, defined for this study as individuals who grow seed for at least one food crop and are involved to varying degrees with formal and informal seed systems within the state.

We focus on Vermont due to its robust formal and informal seed networks. Although there are no generalizable statistics available at any scale regarding the presence of seed saving and sharing networks, previous research has shown that there are many seed savers within the state that are maintaining a high degree of crop diversity (Isbell et al. 2021). There are also several seed saving groups, such as the Upper Valley Seed Savers (Potter 2022). Additionally, Vermont is home to several alternative seed companies, the most prominent being High Mowing Organic Seeds, which is known across the US for its dedication to selling organic seed and first championing the *Safe Seed Pledge* (Helicke 2015).

To explore how the COVID-19 pandemic impacted formal and informal seed systems in Vermont, as well as to examine differences in adaptation response strategies between growers involved within each system, we developed a convergent mixed methods research design that utilized both quantitative survey data (n = 152) and semi-structured interview data (n = 31). A mixed methods case study was specifically chosen as this design is able to provide rich knowledge of the inner workings of a case that can reveal insight into broader dynamics, even if the findings themselves cannot be generalized (Stake 2013). As described in Creswell and Clark (2017), a convergent research design enables the merging of qualitative and quantitative results to facilitate the direct comparison of participants' perspectives gathered through various question formats. A convergent design entails data being collected and analyzed during a similar timeframe. The design, implementation, and analysis of quantitative and qualitative data thus occurred in unison and are reported together within this paper using a constant comparison technique (Lewis-Beck et al. 2003), which entails an iterative process of interpretation and reinterpretation of findings.

Quantitative data used for this paper rely on two surveys that shared common questions – one of which was embedded in a larger resilience survey focused on farmer responses to the COVID-19 pandemic conducted by the Center for Sustainable Agriculture, and another that was sent by the authors of this paper to existing seed grower networks. The first survey was deployed using the online software Qualtrics to commercial producers through listservs maintained by the Center for Sustainable Agriculture at UVM as well

as advertisements sent by the Northeast Organic Farming Association of Vermont (NOFA-VT) and UVM Extension. From this survey, a total of 61 complete responses were collected. The second survey, also deployed using Qualtrics, was sent to individuals known to be involved in informal seed networks and/or save their own seeds, as collected in 2019 for another research project. From this survey, a total of 100 responses were collected and merged with the previous 61 responses to create a single dataset. Of the 161 total responses across the two surveys, duplicates were removed, and 152 responses were deemed sufficiently complete to be used for analyses.

To create a sample of interviewees for qualitative data, the survey that provides the quantitative data for this paper, as well as former surveys conducted by the first and the second author, were used as a basis from which to sample individuals. Purposeful sampling was the main strategy used for obtaining an interview sample, although some snowball sampling was used to ensure a diverse representation of perspectives. The interview sample totaled 31 individuals who all are involved to some degree in seed growing, purchasing, and exchanging (as well as selling, in some cases) in the state of Vermont. Because the survey specifically sought out the opinions of commercial farmers as well as non-commercial growers, care was taken to create an interview pool that had adequate saturation of both non-commercially oriented (e.g., gardeners, seed savers, etc.) and commercially oriented (e.g., farmers and individuals who sell seed) perspectives.

Quantitative questionnaires

As informed by our resilience framework (Fig. 1), questions on the surveys sought to capture sourcing habits before and since COVID-19 to indicate potential disruptions in sourcing, specific barriers/constraints to accessing seed preferred seed, and adaptation strategies. Questions specifically collected data for five key Vermont crops (tomato, sweet corn, lettuce, squash, and garlic) based on USDA NASS (2017) Agricultural Census acreage data to capture information on important crops grown within Vermont. Although the crops chosen to study were not necessarily those which take up the most land in Vermont (in which case, silage crops would dominate), they are prominent horticultural crops in the state as indicated by the amount of acreage dedicated to them relative to other specialty crops.

These data were used to understand the resilience strategies and capacities of seed growers within the state, and if any factors (e.g., market orientation, sourcing diversity, the involvement in informal networks) contribute to the relative capacity of some individuals over others to be protected from challenges or (more generally) have their needs met by the seed system. These capacities, which we hypothesize contribute to resilience, are outlined in Table 1. Moreover, given that resilience has more to do with stability and adaptability after disruption rather than protection (i.e., not facing any issues at all) (Walker et al. 2004), we also collected data on how growers responded (or adapted) to barriers if they were encountered. Importantly, while sourcing data were collected only for five key crops, questions related to challenges in general, as well as adaptation strategies, asked respondents to reflect on all the crops they grow.

Qualitative interviews

All interviews followed an interview protocol created in the winter of 2020–2021 which was pilot tested with two key stakeholders similar to the sample of interest to enhance validity (Creswell and Clark 2017). Created to complement survey data, the interview protocol included questions related to a person's background in growing seeds as well as current practices, sourcing habits, experiences with COVID-19, and other challenging events. Thorough notes were taken during each interview along with interviews being audio recorded to ensure the completeness of the data gathered. Demographic data were also collected from each participant, including age, gender, income, and market involvement (i.e., if they sell seed, and approximately how much seed they purchase or obtain from sources other than their own production). Although not reported in Table 2, the interview group was composed primarily of White individuals, which although closely reflects the overall ethnic makeup of Vermont, importantly misses the contributions of people of color. The authors thus highly recommend that future work should particularly focus on groups that were not well-represented within this research such as people of color and immigrant communities, who are often important stewards of crop diversity through seed saving (Phillips 2016). Moreover, while we believe this research makes important contributions, care should be taken to not generalize findings to any population beyond our specific sample of individuals.

Within the interview sample, the average amount of seed saved among this group was 32% of the overall stock that they planted, though this ranged from 1 to 100%. Additionally, about one-third of respondents indicated selling seed (usually on a very small scale) at some point in their lives. This reflects the fact that involvement in informal and formal seed systems varied widely with some being highly engaged in purchasing and selling seeds, and others obtaining seeds largely from their own stock or friends/neighbors.

Table 1 Survey Descriptive Statistics

Variable	Total n	Mean/Proportion[1]	SD
Demographics			
Commercial farmer[2]	148	0.49	-
Age	144	55.00	14.93
Black, Indigenous, or Person of Color (BIPOC)	136	0.18	-
Education			-
Income	138		-
Low	56	0.41	-
Medium	70	0.51	-
High	12	0.09	-
Acres owned and/or rented	139	35.26	111.75
Resilience Indicators			
Used Formal & Informal Source[3]	152	0.59	-
Only Used Formal source	152	0.09	-
# Sources Used Since COVID-19 (range: 1–6)	152	2.83	1.20
# Sources Used Before COVID-19 (range: 1–6)	152	3.30	1.41
Challenges (before COVID-19)			
Variety unavailable	152	0.43	-
Unable to get seeds with preferred characteristics	152	0.22	-
High cost	152	0.16	-
Species unavailable	152	0.16	-
Amount needed unavailable	152	0.14	-
Long wait time	152	0.11	-
Unable to place order	152	0.07	-
Challenges (since COVID-19)			
Variety unavailable	152	0.39	-
Long wait time	152	0.20	-
Species unavailable	152	0.18	-
Amount needed unavailable	152	0.17	-
Unable to place order	152	0.15	-
Unable to get seeds with preferred characteristics	152	0.15	-
High cost	152	0.08	-
Adaptation Responses (since COVID-19)			
Grew different variety	152	0.30	-
Found another source	152	0.26	-
Grew different species	152	0.18	-
Used own seed	152	0.15	-
Planted late	152	0.11	-
Took no response	152	0.05	-

[1]Categorical variables shown as proportion between 0 and 1 where 1 = presence and 0 = absence. [2]For the purposes of this survey, a commercial farmer was considered someone who sells more than $1,000 in agricultural products as per the USDA definition. [3] Formal sources include commercial seed companies and retail outlets, while informal sources include seed libraries/banks, neighbors, and friends.

Table 2 Demographics of Interviewees

Variable	Frequency	Percent
Gender		
Female	20	0.65
Male	11	0.35
Age		
18–30	3	0.10
31–50	11	0.35
50–70	10	0.32
70+	7	0.23
Seed System Involvement[1]		
Home gardener/ Homesteader	21	0.68
Seed librarian/ Seed group member	10	0.32
Commercial farmer/seed producer	8	0.26
Plant breeder/Seed company	4	0.13
Years Seed Saving		
0–5 years	6	0.19
6–15 years	6	0.19
16–25 years	10	0.32
26 + years	9	0.29

[1]Categories are not mutually exclusive.

Data analysis and reporting

All quantitative analyses were conducted using Stata v.17. Data were cleaned, labeled, and organized to enable descriptive statistics and preliminary analyses. Analyses followed the objectives of this study which seek to understand seed system resilience through both responses and capacities. As data were taken in the first year following the pandemic, the data particularly lend themselves to providing insight into short-term resilience (see Fig. 1; 'response' being a short-term temporal resilience indicator), but also provide initial insight into medium-term and long-term resilience through questions that asked growers about their challenges during COVID-19 relative to three years beforehand (with the intention of three years ago being a baseline that would illuminate potential pervasive challenges). Although our intention is to focus on seed system resilience, we use aggregated individual experiences as a basis for understanding overall seed system resilience, as former studies have also done (Adger 1997; Gil et al. 2017).

For qualitative data, the authors relied on an emergent coding approach to capture key themes that emerged from the 31 interviews. After interviews were transcribed, data were uploaded to the software NVivo v.16 for qualitative analysis. We first used within-case analysis before moving on to cross-case analysis to develop codes that correspond to 'meaning units' (Malterud 2012) such as quotes and remarks. As outlined by Creswell and Poth (2016) several steps were taken to reduce subjectivity and enhance the robustness of the data analysis process which includes continuous reflection before, during, and after each interview,

the creation of a list of significant statements coded by emergent theme, and a written composite description to summarize key-takeaways (the "essence") from the interviews and notes as a cohesive group.

A series of bivariate and multivariate analyses were used and compared with findings that emerged from interviews using the cross-comparison method (Creswell and Clark 2017). First, to determine how the COVID-19 pandemic impacted formal and informal seed systems in Vermont in the short- and medium-term, we report quotes that highlight common themes found throughout interviews on the topic of seed sourcing, connectivity, and other barriers immediately following COVID-19.. This is then backed by quantitative data to understand the extent of barriers faced during the pandemic, where McNemar tests are used to understand if the challenges faced before COVID-19 (in the three years prior to March 2020) were significantly different than challenges faced since COVID-19 (since March 2020). Information from interviews is also reported that focuses on what individuals thought the longer-term impacts of the pandemic might be on seed systems in the state.

Then, considering reports in the US of heightened gardening demand and concurrent restrictions of non-commercial growers purchasing seed, another set of McNemar tests were conducted to determine if barriers and capacities were different for commercial growers versus non-commercial growers. A set of binary logistic regressions were also conducted to determine how individuals responded to barriers, controlling for informal and formal seed system involvement, commercial orientation, as well as types of challenges faced to understand how market and seed system involvement may influence which capacities growers did (or did not) have access to during the pandemic. To reduce autocorrelation errors, challenge variables used for these regressions were aggregated into three types: *seed type challenges* which included "species unavailable," "variety unavailable," "amount needed not available," and "unable to obtain seed with preferred characteristics," *cost challenges* which were composed of only "high cost," and *time challenges* which included "long wait time" and "unable to place order," as based on eigenvalues. These data were compared to interview data which focused on how individuals navigated seed systems during the pandemic, highlighting similarities and differences in responses between commercial and non-commercial growers.

Findings

COVID-19's impact on seed systems in Vermont: formal system challenges

Our survey found that 52% of growers sampled reported having some difficulty accessing seed during the spring of 2020. Qualitative findings reinforce this split and suggest these disruptions occurred mainly through formal channels, with many growers reporting delays, shortages, and other general supply chain disruptions, but others expressing hardly any issues at all. As one grower summarized, "*The month of April [2020] was crazy because no one could get seed. Everyone decided they wanted to be a gardener, and no one could get seed because all the seed companies shut down*" (female, 42, farmer and seed company owner). Indeed, many growers highlighted increased interest in gardening during the pandemic both among new and established gardeners alike, which they hypothesized to cause an uneven supply and demand for seed in Vermont. As one grower expounded:

> "When things become uncertain and certainly COVID was, you know, an uncertainty…one of the things people do is they plant gardens because … [they realize] 'that's one thing that, you know, I can grow some of my own food and, you know, have a little more food security in that way.' And certainly, on top of that with COVID, just because so many people were just stuck at home, I think also people were like, 'Oh, I don't know what to do. I'll plant a garden.' So, there's no question that seed sales, like, went through the roof during COVID in large part because of the home garden" (female, 44, plant breeder).

For some growers, this increase in demand meant that sourcing became more difficult for them as established growers. As one interviewee expressed in relation to sourcing in both 2020 and 2021: "*I probably bought less seed than I would have normally, just because so many of the varieties that I wanted to get were backordered. And didn't necessarily get substituted.*" (female, 38, home-gardener). This was reported among many other growers (both commercial and non-commercial) as well as they recalled certain popular varieties being out of stock earlier than they usually anticipated them to be. However, most growers stated that they did eventually get what they wanted – but simply had to wait longer than in previous years. Moreover, other growers expressed that they felt like seed shortages were made out to be more serious than they actually were. As one grower reported, "*Well, it's funny - there were a lot of threats online. Like "we're way behind" [but] we didn't*

really have any problems - not any big problems" (female, 75, home-gardener).

When comparing insight from interviewees with quantitative data from our two surveys, what appears is that even though more than half of our survey sample had some difficulty accessing seeds after the onset of the pandemic, many of the issues they faced were not markedly different than in the three years prior. As displayed in Fig. 3, only such issues as "long wait time for order" and "unable to place order" were found to be significantly worse ($p < 0.01$) since the pandemic. Our data also indicate that the issue of "high cost" fell from 16% of respondents before COVID-19, to half of that since COVID-19 ($p < 0.05$) – perhaps due to the prevalence of free seed packets and seed starting kits being distributed by public offices and non-profits throughout the state of Vermont during the same time. In comparison, the most common sourcing challenge "variety unavailable from usual source" (Before Covid p = 43% Since Covid p = 39%) was not found to be significantly more or less difficult than in previous years, despite interview findings indicating that growers had difficulties with finding certain varieties. However, this nonsignificant quantitative finding does reflect comments from interviewees about the dwindling diversity available from seed companies over the last few decades, with one grower recalling that this was the reason that he started to save seed. As he recalled, "*I began to see that some of my favorite varieties were disappearing from the seed catalogs, they were suddenly no longer available*" (male, 70, seed saver and seed group member). Moreover, another interviewee attributed seeing this loss to eventually deciding to start producing seed for his small seed company, stating that "*many varieties have disappeared, thousands and thousands of varieties, which is too bad because they really can't come back without people maintaining them*" (male, 38, farmer and seed company owner).

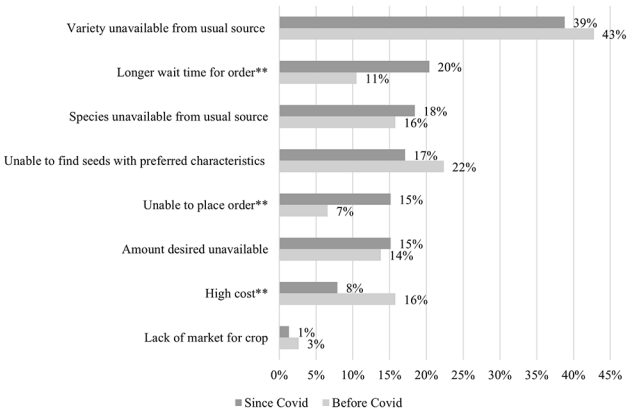

Fig. 3 Proportion of respondents indicating various challenges in the three years before March 2020 (before COVID-19) versus in the months following (since COVID-19) (n = 152). Note: **$p < 0.05$

Issues in sourcing seed specifically following the onset of the COVID-19 pandemic thus point to disruptions in formal seed supply chains, considering that Fig. 3 indicates the most significant change in challenges was the ability to place and receive orders, which may have hindered the ability of some growers to obtain seed over others. Moreover, seed growers who sell seeds or work for seed companies helped illuminate some of the difficulties on the other side of the supply chain by describing an overwhelming situation and simultaneous uncertainty. As one seed company employee summarized, *"… on the one hand, I think you saw a real increase in drive for seed sales for home gardens, but we saw a lot of, you know, customers that their accounts or wholesale accounts or restaurant accounts where they totally lost their market for the year*" (female, 44, plant breeder).

Other seed growers who sell their seed described a similar boom in their sales for garden seed, with one stating that *"…it's been a challenge to keep a good stock of seed and not sell out… and kinda, like, offer more than one variety of different things, for sure, because of the pandemic*" (female, 42, farmer and seed company owner). Moreover, as explained by another grower, "*So many people are gardening, so many people want my seeds that they sell very well. I think the COVID pandemic has encouraged people to buy more seeds. And some people are very interested in buying local and supporting local producers and small businesses*" (female, 74, farmer and seed company owner). Indeed, demand for seed even convinced one farmer that he could potentially switch full-time from being a market grower of produce to a full-time seed producer. In reflecting on how the pandemic ultimately impacted him, he responded by stating the following:

> "I think I've just increased my customer base. Yeah, we say like long term impacts [of COVID-19] sounds negative. But it's like, no, I think it's good. I think people know I'm around, they know that these interesting, rare varieties have gotten into more people's hands. So that's really good. I think it has helped to refine my focus on the farm … it's helped to kind of like narrow in a little bit and said, you know, we'll leave the market gardening to other people and we'll just focus on seeds and home consumption" (male, 38, farmer and seed company owner).

This sentiment of increasing interest in seeds and gardening was shared among many interviewees, although not everyone agreed on whether this momentum would continue. Although growers cited increased interest in self-provisioning as one of the key positive impacts of the pandemic on Vermonters, many shared that they thought this would turn out to be temporary, with people eventually going back to

normal after the effects of the pandemic are no longer so directly inhibiting to other (less isolated) activities. That said, speculation on the long-term effects of the pandemic varied widely, with some also thinking COVID-19 might be able to act as a catalyst for future change.

COVID-19's impact on seed systems in Vermont: informal system challenges

As displayed in Table 1, 91% of those surveyed indicated having used an informal source in the last three years – indicating a sample with high informal seed system involvement. However, 59% of individuals reported using both informal and formal sources in the last three years, highlighting an overall reliance on both formal and informal sources for seed. Although the former section focused on the formal sector (which undoubtedly gained the most attention within the popular media during the pandemic), interviewees generally described difficulties in exchanging and sourcing seed within informal seed systems as well, principally due to connectivity issues brought on by public health measures to slow the spread of COVID-19. Many home-gardeners described a double-edged repercussion of COVID-19 whereby they found themselves having a lot more time to devote to their gardens, but also felt extremely isolated, undoubtedly due to social distancing measures taken during the early months of the pandemic. For instance, one interviewee stated that "*I had more time to garden last year than I ever had before because I didn't go anywhere. So, my garden was great*" (female, 75, home-gardener), but also expressed an inability to connect with other gardeners due to the pandemic and a general lack of networks: "*I don't have anybody, which is sort of sad.*" Indeed, this captured the sentiment of many others, especially considering the high proportion of interviewees who are above fifty years old (p = 55%) and thus of greater risk of serious illness from COVID-19.

Despite challenges with connecting with other gardeners and farmers face-to-face, many growers nonetheless tried to help their communities access seeds through a variety of outlets. While many growers who were interviewed reported not having much personal difficulty obtaining seeds, they acknowledged that others in their community did – especially those with minimal growing experience or low incomes. In response, community initiatives proliferated across the state of Vermont. As described by interviewees, initiatives took several forms, from small acts of giving as in the case of one interviewee who described setting out a basket on her front porch full of seeds that she had saved available for anyone in her neighborhood to take, to larger cross-state initiatives such as one in which a seed saving group created a free online seed catalog directed at low-income Vermonters. Seed librarians also described seeking out new ways to reach out to people in need of seeds which included creating a better online presence, handing out seed-starting kits for popular varieties, and mailing out seeds to schools and individuals who requested them. One seed library even originated during the pandemic, with one of the founders stating that "*my hope would be that communities could save seeds together, that would be my ideal*" (female, 68, home-gardener and seed librarian).

Many growers also viewed the pandemic as an opportunity to reach out to individuals who previously might not have been interested in growing food or seed saving: "*Last year, our group had talked about ways in which we could share seeds given the pandemic and people…you know, we kind of knew that it was an opportunity to not only guide people towards growing their own food but educate them about the importance of seed saving and get local seeds in their hands*" (male, 38, farmer and seed company owner). Indeed, acknowledging the increased interest in growing food, paired with difficulties in sourcing seed in 2020, several growers discussed using the pandemic as an opportunity to promote the informal seed sector, which many felt was being underutilized long before the pandemic. In fact, increased awareness of seed saving came up within interviews as one of the most prominent medium-term recovery strategies of the pandemic, often inspiring growers to save more for subsequent years than they might have before. As stated by one grower, "*It [COVID-19] makes me more interested in growing more seed this year but also to keep educating other people about the importance of saving seeds because we don't need to be dependent on seed catalogs for our seeds*" (female, 60, home-gardener).

Ultimately, growers cited varied difficulties that occurred in both the formal and informal system due to the pandemic: uncertainties in sourcing, lack of availability, and difficulties in connecting with others that required alternative ways to disseminate and source seed than in previous years. That said, growers who interacted within the formal system did not express extreme difficulty in sourcing that limited their ability to grow what they wanted – a quality also seen in those involved in sourcing and distributing seed through the informal system.

Resilience capacities: differences between commercial and non-commercial growers

As illuminated by comparing quantitative and qualitative data from before and during the pandemic, commercial farmers and non-commercial growers likely went into the pandemic with different abilities and resources to navigate formal and informal seed systems during the public health crisis. Using McNemar tests again to examine the change

in proportion of barriers both before and since COVID-19, Table 3 emphasizes how barriers differed between commercial and non-commercial growers. These findings demonstrate that non-commercial growers in our sample were significantly more likely to be unable to place seed orders ($p < 0.01$) and wait a long time for orders ($p < 0.05$) since COVID-19 in comparison to commercial growers, but also had less trouble with high costs ($p < 0.05$), perhaps due to higher degrees of involvement in informal seed systems. In comparison, commercial growers did not have has much trouble in 2020 versus previous years, except in terms of obtaining species from their usual sources ($p < 0.10$). Moreover, robustness checks to assess the impact of other demographic factors (age, income level, and race) were not significant – suggesting that these differences in barriers likely have more to do with the ability to access various system capacities as determined by market positionality rather than individual capacities of growers themselves.

Interestingly, the inability to obtain certain species was not as explicit within interview findings: while some expressed shortages of varieties, total lack of species availability did not occur for most individuals – and when it did, those growers sought out other sources to fulfill their needs. That said, many growers, in general, did express difficulty in finding certain species such as garlic and potatoes during COVID-19 – two relatively easy-to-grow and popular species among both veteran and new growers alike. Moreover, while only brought up a few times, some growers did point to being unable to find entire crop species they wanted in organic or open-pollinated varieties through formal sources, which one grower pointed out was particularly important for farmers running Community Supported Agriculture (CSA) businesses to attract customers. Ultimately, this divergence suggests that interactions with formal and informal seed systems following the pandemic (regardless of commercial or non-commercial status) varied widely across samples in some areas.

Additionally, many non-commercial growers were unable to order seeds until later in the spring as many seed companies prioritized commercial growers. Within interviews, many non-commercial growers described long wait times to obtain the seed that they ordered, as triangulated with quantitative findings shown in Fig. 3. For example, one grower recalled:

> "So, the first year, really when things hit and got kind of crunched, we, luckily, had our big order in with [seed company] early. And, so, that was really unaffected. But then sometimes I'll make a follow-up order because I forgot something, and I did, I had forgotten something and I tried to make an order, and they were actually not taking orders from home gardeners, they were only taking orders from commercial farms at that time, I think in 2020. And, so, I appreciate that, I think that was a smart move for them to make. And worthy too, like of course we need to make sure that our commercial farms get the seed first. So, I appreciated that but also, you know, had to wait, you know, for those forgotten seeds that I eventually did get" (male, 43, homesteader).

Table 3 McNemar's Tests for Challenges between Commercial and Non-Commercial Growers

	Chi2 Statistic	
Challenge	Non-Commercial (n = 75)	Commercial (n = 70)
Lack of market for crop	0.00	1.00
High cost	**-6.23****	1.00
Amount desired unavailable	1.00	1.32
Unable to place order	**8.07*****	0.07
Unable to find seeds with preferred characteristics	0.20	1.80
Species unavailable from usual source	1.00	**3.56***
Longer wait time for order	**4.76****	2.00
Variety unavailable from usual source	0.18	2.13

Note: *p < 0.10, **p < 0.05, ***p < 0.01

Indications of adaptive, absorptive, and transformative capacities

Although both qualitative and quantitative findings suggest that commercial and non-commercial growers faced divergent challenges to their seed sourcing, our findings suggest that these challenges ultimately did not result in a difference in abilities to adapt. To confirm this, we ran a series of binary logistic regressions where the dependent variables were potential responses ("grew a different species," "planted late," "found another source of seed," "grew a different variety," and "used own seed stock") and the independent variables were whether or not an individual identified as a commercial farmer and whether they used at least one informal source. The controls were time, seed type, and cost challenges. The findings from these models were all insignificant except for one – the fact that individuals (regardless of commercial orientation) who used an informal source of seed were more likely to respond to challenges by using their own seed stock ($p < 0.01$). What this suggests is that growers (commercial or non-commercial) were ultimately able to respond positively using a variety of capacities in the face of challenges to accessing seed, with only 5% of growers indicating that they did nothing to respond to challenges.

These insignificant quantitative findings can be further explained by our qualitative findings, which suggest that growers generally did not have that much difficulty dealing with sourcing issues caused by the pandemic. For instance, one grower who could not obtain a variety she wanted stated that "*it's not that big of a deal*" and that that she was not devastated because "*you know that you can try again other years*" (female, 38, home-gardener), which relates to the ability of some growers to absorb shocks and continue growing in one way or another. Moreover, the average gardening/farming experience of individuals interviewed was 16.7 years, indicating substantial experience responding and to seed system dynamics within the state that, along with established networks, can also contribute to their adaptive capacity. For instance, interviewees who reported not facing significant barriers often attributed their lack of challenges to purchasing seed early (in the winter, prior to pandemic scares in spring 2020), saving at least some of their own seed (32% on average across the 31 growers interviewed), and established connections with other growers both within the state and outside of it. As recalled by one grower in response to a question asking him about the ramifications of COVID-19:

> "I guess it just made us feel really fortunate. I mean, there's always things we do well and things we screw up, but people who are like, 'Oh, my gosh, like, we might have to grow our own food,' like, and they're starting now from a place we started at 16 years ago or 17 years ago. So, I just felt really blessed that we've been working on this thing. And people are like, 'Where are we gonna' get potatoes?' I'm like, 'Oh, my God.' I was talking to my mom, she could not find potatoes in the height of [the pandemic] …like, 'Mom, I have pounds. I have, like, dozens and dozens of pounds of potatoes.' … So, I just felt really blessed" (male, 43, home-gardener).

Indeed, many growers told similar stories, while also acknowledging their capacity to adapt due to a learned understanding of seed supply chains which are inherently dependent on many external factors. For this reason, despite widespread challenges in the seed system, interviewees generally expressed feeling very privileged in their access to seeds, networks, and knowledge to fare well during the pandemic. However, many also discussed how, despite their privilege, they felt like problems would continue to persist within the seed system at local to global scales. As recalled by one grower in response to a question about if she anticipated supply chain issues to get better post-COVID-19:

> "Well, yeah, you would think that seed companies would sort of like ramp up, but I know there's just because they're living things that you can't always, you know, some things take two years to produce and there's all the different, various supply chain issues. There's fires out West. There's, you know, all kinds of factors that seem to be interrupting the supply chain" (female, 46, farmer).

Because of these challenges, interviewees seemed mixed about their feelings concerning the future – with some expressing a deep desire to instigate change in any small way they could (e.g., seed saving, being involved in seed libraries or being in solidarity with global seed movements), and others feeling discouraged. That said, many saw the COVID-19 pandemic as a wake-up call, with the majority of growers interviewed discussing how they hoped that people new to gardening and farming would help deepen awareness surrounding issues such as seed company consolidation and the loss of crop genetic diversity. As one grower stated in response to why he thought seed saving and informal seed systems were important to him, he responded by saying that he thought it was important "*to break the grip that global corporations have on not only our food supply but on our seed supply*" and that "*it [seed saving] feels very fundamental, it also feels kind of revolutionary, in a way*" (male, 70, seed saver and seed group member).

In the end, what these quantitative and qualitative findings suggest is that, in general, growers were able to adapt using both formal and informal channels and by drawing on different capacities that were most easily available to them given their role within the agri-food system. At the same time, these data also suggest the prevalence of pervasive issues within the overall seed system that growers are increasingly recognizing and, in some instances, seeking to transform.

Discussion

The effect of COVID-19 on informal and formal seed systems

Despite the acute and chronic challenges facing seed systems in Vermont during the COVID-19 pandemic, this research highlights how the capacities of seed systems in the state were leveraged by various seed system actors to allow for adequate response strategies. As the data demonstrate, seed systems in Vermont were subject to substantial challenges: in formal systems, this took the form of supply chain disruptions that meant long wait times for seed orders and shortages for certain species and varieties; in informal

systems, uncertainty came from social distancing measures that meant less reliance on traditional methods of interacting and exchanging seeds. However, despite 52% of the survey sample indicating having some trouble obtaining seed directly following the onset of the pandemic, a lack of significant differences in challenges pre-COVID versus since-COVID (Fig. 3), combined with interview data that indicate challenges faced by growers were minimal, suggests that the pandemic simply compounded issues in seed sourcing that already existed rather than introducing many new ones. In relating these findings to our conceptual framework (Fig. 2), what this suggests is that, at least in the short term, the ability of individuals within Vermont's seed systems to recover indicates a strong potential for adjustment and stabilization to settle on a stable post-COVID state that is very akin to the pre-COVID state. In and of itself, this finding is promising: the data suggest that growers fared well because, in many cases, they were able to lean on both informal and formal sources of seed which helped to shield them from shocks as well as adjust with relative ease. These data also highlight how engaging with growers involved in both commercial and non-commercial seed sourcingmay be key to connecting informal and formal seed systems, and in doing so help create a robust holistic seed system that is better equipped to deal with disruptions.

Neither formal nor informal seed systems in isolation are likely to be as resilient as a system that acknowledges, supports, and actively employs both. The reason for this can be gleaned from Fig. 1, which highlights the fact that formal and informal seed systems are structurally distinct; whereas formal seed systems depend on a vertical exchange of seed from one point to another, informal seed systems rely on horizontal exchanges based on social networks between households, with no specific endpoint. For this reason, it makes sense that the main challenge we found within formal seed systems had to do with disruptions in the supply chain, and the main challenge within informal seed systems was a reduced ability for individuals to connect. Supply chain disruptions are a major issue within food systems in general, potentially causing major reverberations from the point where it first occurs to all the way up the supply chain (Béné 2020). In comparison, social interactions were limited by the pandemic, which can constrain the ability of some households to exchange seeds or obtain seeds from local sources (de Boef et al. 2021).

However, while both informal and formal seed systems were found to face challenges and struggle to a certain degree, informal seed systems did show a greater ability to adapt. In the case of Vermont seed systems directly following the COVID-19 pandemic, the disruption in the seed supply chain required time to fix (resulting in the long wait times our data have shown), but individuals engaged in the informal seed system could still identify alternative ways to exchange seed not requiring face-to-face interactions. As qualitative data from growers within the state exemplifies, growers took many steps to support their communities in accessing seeds. Whether by offering extra seed to neighbors, shifting seed library ordering strategies to accommodate social distancing measures, or facilitating free-seed online ordering programs, growers leaned into informal seed systems to meet increased demand for seed when formal systems had to wait for supply chains to adjust. This research thus provides initial evidence that even in highly industrialized contexts like the US, informal seed systems provide an essential source of seed, especially during a crisis (McGuire and Sperling 2013; Zimmerer and de Haan 2020; Sperling et al. 2020). While the findings of this study should be tested in future studies through other case studies in the Global North, they provide the important groundwork to hypothesize that informal seed systems constitute an important, yet often overlooked, source of seed for growers in the Global North.

Furthermore, the data presented in this paper also suggest ample opportunities for formal and informal seed systems to find connection points, which can help support access to seed as previous findings have already stressed (Sperling et al. 2010; Lopez Noriega et al. 2021; Vernooy et al. 2022). Principally, our data show that not only are many individuals already using both formal and informal channels but that increased interest in gardening due to the pandemic can be a catalyst for other individuals to get more involved in seed systems as well. Considering that seed production takes several years of planning, potentially limiting the stock of seeds available in the formal system to pre-pandemic projections (or potentially worse, since many companies have had to deplete their stocks to supply orders (Nabhan and Kaufman 2020)), informal seed systems can help supplement consumer demand. In terms of resilience, informal seed systems are thus fundamentally complementary to formal systems because they provide greater redundancy, an important yet often overlooked component of resilience (Walker 2020). In general, seed security can be enhanced if growers have multiple options to source their seeds (Batur et al. 2021). On their own, informal seed systems are highly redundant (Fig. 1) considering that many households perform the task of seed production. In comparison, formal seed systems are often not redundant, as demanded by their vertically arranged structures (Kliem and Sievers-Glotzbach 2022). Because of this, creating cross-sector collaborations between informal and formal systems is not only in the best interest of individuals (in the sense of enhancing choice, satisfying preferences, and providing multiple options) but of companies who depend on germplasm from the informal system in the first place (Wattnem 2016).

Differences in capacities and responses by commercial and non-commercial growers

After reviewing our qualitative and quantitative findings together, what emerged was that commercial and non-commercial growers faced divergent challenges after the onset of the COVID-19 pandemic. For non-commercial growers, this often meant longer wait times to obtain seed from commercial companies. This finding is supported by popular accounts in the media which described commercial companies as giving preference to their commercial customers (Held 2021). Qualitative findings also support this, although add nuance in that many growers (regardless of their involvement with formal and/or informal seed systems) were able to eventually get what they needed. In general, these data support the well-known fact that agricultural producers use both informal and formal seed systems to meet their needs, and illustrate how interactions with these systems vary depending on the types of crops needed and the market orientation of the grower (Sperling et al. 2010). For instance, just as our findings showed that commercial growers may have gotten preferential treatment in that they faced issues with ordering seeds, our findings also showed greater flexibility of non-commercial growers to switch what they were growing or use alternative sources of seed. This showcases the importance of both multiple seed sources, as well as established social and community ties, to the adaptive and absorptive capacities of individuals (Folke et al. 2010; Kliem and Sievers-Glotzbach 2022).

When comparing the response strategies to challenges of commercial farmers and non-commercial growers, what can be clearly seen is that these two groups of growers are working with different capacities. That is, the way they navigate seed systems is importantly distinct. As one example, commercial farmers are much more subjected to economic pressures than non-commercial growers, who often view growing as leisure rather than a component of sustaining their livelihoods. For this reason, seed saving among commercial growers is perhaps much less practical, as is using a seed library as a source of seed (seed libraries usually only maintain small collections of seed), leaving commercial growers with fewer viable sourcing options. These limitations faced by commercial growers may be why interviewees generally expressed being happy that commercial companies were giving farmers preferential treatment during the pandemic. However, these findings should not be interpreted such that commercial farmers are better off using formal channels and non-commercial growers should always use informal channels. While many of those interviewed felt particularly lucky in that they were able to overcome challenges to their seed sourcing relatively easily – whether through formal or informal seed channels, both still expressed the prevalence of systemic challenges that no one system is necessarily equipped to handle.

Seed system resilience

While the data show that certain challenges such as waiting a long time to place and receive seed orders from commercial companies worsened due to the pandemic, other common barriers such as the unavailability of species, varieties, and seeds with certain characteristics (e.g., organic, open-pollinated) did not appear to worsen significantly yet were among the most common challenges faced by growers. Qualitative data support these findings, suggesting seed system vulnerability in the short-term had to do with slow-moving supply chains that could not adapt quickly to changing demand, while in the long-term seed systems face pervasive challenges such as formal systems not being able to adequately reflect the preferences of the growers who purchase from them. In one sense, these findings can be taken as positive: the fact that certain challenges did not worsen is indeed beneficial to many stakeholders, suggesting overall resilience. Yet, in another sense, the findings from this study illuminate that so many challenges were so pervasive in the first place. For example, more than a third of respondents to our survey indicated that, regardless of COVID, they had difficulty obtaining seeds for preferred varieties in the last three years (Fig. 3). Interestingly, Table 3 also shows that commercial farmers are significantly more likely to face challenges in obtaining preferred species from sources they use. This is again supported by qualitative findings, with many growers discussing the prevalence of systemic issues rather than those specifically associated with COVID-19. Given the shift towards specification and privatization in seed systems in the last fifty years (Howard 2022), these findings are not unsurprising but foreground the need to support seed networks which are driven by the demands of their diverse stakeholders rather than the market – an essential component of seed system resilience as discussed in the literature thus far (Vernooy et al. 2019).

Finally, while the quantitative findings help highlight challenges, these data also underscored the desire of individuals to make changes. As outlined in Folke et al. (2010), acknowledging and making deliberate actions towards change (i.e., transformative capacity) is also an essential yet often overlooked component of resilience within SES. Again, while our findings suggest certain stability of current seed systems, it should be remembered that this is not necessarily positive if it simply perpetuates negative outcomes. Drawing on Kliem and Sievers-Glotzbach (2022), ensuring resiliency in seed systems should entail not just that the system is stable, but that it is just and contributes positively to SES from the immediate to long term. Recognizing the

complementarity of formal and informal seed systems provides a pathway to enhanced resilience without compromising the needs, goals, and ambitions of the individuals that rely on seeds for their food, livelihoods, and well-being.

Considering the importance of diversity and supporting the preferences of growers for both seed system resilience and sovereignty (Etten et al. 2017; Vernooy et al. 2019; La 2021; Kliem and Sievers-Glotzbach 2022), the findings of this paper underscore the need to bolster seed systems by ensuring that they are reflective of the goals, values, and needs of the growers who use them. As found throughout resilience literature, diversity and redundancy are two incredibly important avenues to supporting sustainable, equitable, and resilient systems (Walker et al. 2004; Folke et al. 2010; Cabell and Oelofse 2012 Béné 2014; Walker 2020). Relating this to seed systems specifically: While formal seed systems have undoubtedly been given priority in development initiatives and dominate throughout the Global North, informal seed systems provide an important alternative to growers that can help complement the formal system, suggesting that seed system plurality (i.e., supporting the coexistence of both informal and formal systems) may be one way to help address systemic challenges in formal and informal systems alike, including issues such as eroding agrobiodiversity and under-connected social and economic networks. Despite misconceptions that informal seed systems maintain lower quality seed than the formal system (Coomes et al. 2015) or are only important for conservation (rather than immediate use) purposes (Batur et al. 2021), informal systems can provide diverse germplasm to the formal sector (thus addressing the lack of preferred variety and species challenges that came up during this research), which can be improved or multiplied before being put back into the informal sector to disseminate, thusenhancing the availability and quantity of seed available through non-commercial channels. This is already being done in many countries across the Global South with success (Wattnem 2016; Sperling and McGuire 2013; Lopez Noriega et al. 2021).

Conclusion

The COVID-19 pandemic has undoubtedly affected the world in profound ways and simultaneously challenged the systems on which individuals and communities depend for food. As exemplified by cross-disciplinary studies in the last few years (Béné 2020; Niles et al. 2021; O'Hara and Toussaint 2021) and as supported by this study, food and seed systems in the US were not immune. Local and regional seed systems have been challenged due to worldwide shortages, supply-chain disruptions, and social distancing measures which have hindered the ability of many growers to obtain seed (Poudel et al. 2020). Globally, seed system disruptions have most notably been seen within the formal sector, but informal systems have also faced their fair share of uncertainty (de Boef et al. 2021), highlighting the fact that dependence on any one source makes growers vulnerable to seed insecurity – already a well-known fact that seed system scholars have emphasized (Zimmerer and de Haan 2020; Sperling et al. 2020).

At the same time, findings from this study illuminate the fact that, despite some challenges to seed sourcing caused by system deviations during the pandemic, Vermont growers ultimately were able to meet their seed needs by drawing on a diverse array of sources and capacities within informal and formal seed systems. While there were some differences in the degree of challenges faced by commercial and non-commercial growers (namely in terms of wait times to purchase seeds), our findings highlight an overarching need to address systemic challenges to bolster seed system resilience in the long term. This would include giving equal weight to informal and formal seed systems in the US to ensure a robust seed stock that is not only stable but can adequately meet the needs and preferences of both commercial and non-commercial growers (Vernooy et al. 2019). As our findings suggest, informal systems provided an important source of seed for many during the pandemic, as well as showcased the ability of communities to adapt to difficulties in obtaining seed through the formal sector. Interpreting these insights with the resilience framework developed for this study (Fig. 2) provides a foundation to build future studies which seek to interrogate the relationships between various seed system capacities and seed system resilience for both the short and long term. Furthermore, our findings suggest that perhaps a stable system does not necessarily entail a perfect system – leaving ample room to continue questioning what (if at all) a truly just, sustainable, *and* resilient seed system may look like.

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