AGROECOLOGY IN THE UNITED STATES: PATHWAYS TOWARD AGROECOSYSTEM REDESIGN AND AGRI-FOOD SYSTEM TRANSFORMATION

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In Chapter 1, I report the results from a field experiment conducted in Maryland and New York that compared the yield and quality trade-offs among four cultivars per winter cereal species (barley, cereal rye, and triticale) grown as forage and harvested at eight crop growth stages. Although barley cultivars maintained higher quality than cereal rye and triticale, yield was substantially lower. Cereal rye exhibited a desirable balance between yield and quality early in the season, whereas triticale provided the benefit of a slightly longer "harvest window" to obtain high-quality forage later in the season.

In Chapter 2, I assessed the effect of winter cereal cover crop cultivar selection among three species and cover crop termination-soybean planting date on cover crop growth stage and biomass, weed biomass, soybean density and yield, and cover crop reseeding in organically managed no-till planted soybean production. Differences among species indicated that triticale performed better than barley and as well as cereal rye in terms of biomass production, weed suppression, and soybean yield, but the effect of cultivar was inconsistent across response variables and sites.

In Chapter 3, I analyzed a national survey of organic fruit and vegetable farmers, which showed that fewer agroecological practices were used and a greater degree of "conventionalization" was observed on large farms. Intercropping, insectary plantings, and border plantings were at least 1.4-times more likely to be used on small

(0.4–39 cropland ha) than large (≥405 cropland ha) farms, whereas reduced tillage was less likely and riparian buffers were more likely on small than medium (40–404 cropland ha) farms.

In Chapter 4, I used a mixed-methods analysis of national survey results and findings from interviews with farmers in California and New York to assess the labor-intensity of agroecological practices. I showed that farmers who did not use agroecological practices perceived a greater labor requirement than farmers who had experience using a given practice; labor shortages were more problematic on medium and large farms; and the main strategy on large farms for managing labor-related challenges was to increase mechanization, despite already being the most mechanized farm type across sizes.

BIOGRAPHICAL SKETCH

As a broadly trained researcher, Jeffrey Andrew Liebert's work is drawn from natural and social science disciplines in the pursuit of a more sustainable, just, and equitable agri-food system. Jeff's scholarship has spanned dairy, grain, and fruit and vegetable systems, focusing on such topics as forage crop phenology, multi-tactic approaches to ecological weed management, the "conventionalization" of organic agriculture, the concept of meaningful work in agroecology, and the tension between socio-technical change and the labor-intensity of agroecological practices in the United States. Through this research, Jeff has collaborated with farmers, extension educators, crop consultants, NGOs, government agencies, and other scientists from around the world.

Born and raised on Vancouver Island, Jeff is from British Columbia, Canada. He completed his BSc at the University of British Columbia in the Global Resource Systems program, specializing in soil science and agroecology. At Cornell University, Jeff completed his MSc in agronomy, focusing on the use of agroecological management practices in organic grain systems. As a postdoctoral researcher in Canada, Jeff will continue to expand his interdisciplinary skillset by working with spatially explicit techniques to seek out synergistic relationships among biophysical, socioeconomic, and political drivers of sustainable and just agri-food systems.

In memory of my mum, Kathy Liebert.

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Some of the research that is described in this dissertation was conducted on the traditional homelands of the Gayogo̱hó:nǫ' (the Cayuga Nation). I am deeply grateful for the opportunity to conduct field experiments on this land, and I acknowledge that my future research can, and should, be more reciprocal through greater community engagement and collaboration.

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PROLOGUE

Just days ago, the United Nations Intergovernmental Panel on Climate Change (IPCC) issued a press release to coincide with the approval of The Summary for Policymakers of the IPCC Working Group III report, "Climate Change 2022: Mitigation of climate change." In blunt terms, the IPCC Chair Hoesung Lee stated, "We are at a crossroads. The decisions we make now can secure a liveable future." IPCC Working Group III Co-Chair Jim Skea added, "It's now or never, if we want to limit global warming to 1.5°C (2.7°F). Without immediate and deep emissions reductions across all sectors, it will be impossible." Despite the stark ramifications of failing to meet targeted reductions in greenhouse gas emissions, there are still opportunities for taking actions that can lead to a more just, equitable, and sustainable future. Given the centrality of food and agriculture to the Sustainable Development Goals, climate change mitigation and adaptation, and biodiversity conservation targets, transformative change throughout the agri-food system must be a priority.

Comprising over 40% of all land-use in the United States (US), agriculture has a profound impact on the environment and the ecosystem services upon which humans depend. As one of the greatest drivers of biodiversity loss (Newbold et al., 2015; Maxwell et al., 2016; IPBES, 2019), freshwater use (Wada et al., 2010), and greenhouse gas emissions (Campbell et al., 2017), industrial agriculture is also a primary cause of soil degradation (Montgomery, 2007; Amundson et al., 2015), nutrient loading (Robertson and Vitousek, 2009), and pollution from pesticide use (Gunstone et al., 2021). Such deleterious effects are not limited to the environment, with documented impacts on human health, well-being, and rural livelihoods as well (Lobao and Stofferahn, 2008; FAO and WHO, 2019; Carolan, 2022). In the US, industrial agriculture has yielded more than enough calories for everyone, yet nearly

14 million people were food insecure in 2020 (Coleman-Jensen et al., 2020) and many more than that subsist on "low-quality diets that cause micronutrient deficiencies and contribute to a substantial rise in the incidence of diet-related obesity and diet-related non-communicable diseases" (Willett et al., 2019). Calls to transform the entire agri-food system have become increasingly urgent as evidence detailing the scale and severity of the environmental, social, cultural, and economic repercussions due to inaction continues to mount (IPES-Food, 2016; HLPE, 2019; IPBES, 2019; IPCC, 2022).

The breadth and complexity of the social-ecological agri-food system challenges facing society has prompted a wide range of proposed solutions. Informed by socioeconomic and environmental interactions between distant coupled human and natural systems (i.e., telecoupling), some researchers have sought solutions through interdisciplinary scholarship, multi-stakeholder engagement, and careful attention to context-specific social, cultural, political, and historical dimensions (Díaz et al., 2019; IPBES, 2019; van Bers et al., 2019). Other scholars have framed alternatives pathways as outcome-oriented, taking a politically agnostic or "neutral" stance on the means with which one might use to achieve established goals (e.g., see Pretty et al., 2018). Through a political economy lens, however, this rationale leaves vastly unequal power relations among participants and decision-makers in the food system uncontested. Consolidated power and capital among a small group of actors—such as transnational agribusinesses, national and international supermarket chains, and the largest industrial farms—undermines claims of equality in a scale- and technology-neutral approach. Such an approach seems likely to uphold the status quo—further concentrating power, entrenching inequities, and fostering more oligopolistic features in the agri-food system—rather than inviting a paradigm shift.

One way to conceptualize the transition to more sustainable agricultural systems is to use the efficiency, substitution, redesign (E-S-R) framework (Hill, 1985). With this framework, practices are described as one of three types: efficiency (E) practices, which make more discerning use of external inputs; substitution (S) practices, which are used to replace less sustainable inputs or practices with more sustainable alternatives; or (R) redesign practices, which are used as part of an effort to reorient an agroecosystem towards management based on ecological processes, in order to prevent many of the problems associated with less-diversified cropping systems (Hill, 1985; Hill and MacRae, 1996). Although on-farm practices do not consistently align with these discrete categories, the E-S-R framework can help guide a transformational process, based on practice-use and farm management, towards more sustainable agricultural systems.

The E-S-R framework has also been broadened beyond agricultural production to describe "levels" of food system change (Gliessman, 2015, 2016; Wezel et al., 2020). In the extended framework, levels I, II, and III represent the implementation of E, S, and R practices, respectively; level IV involves local development of alternative food networks, shortened supply chains, food citizenship, and (re)connecting consumers and producers; and level V represents a global food system, built on the foundation of levels III and IV, that is based on principles of justice, equity, and participation (Gliessman, 2015, 2016; Wezel et al., 2020). This expanded framework classifies the levels in two ways. First, the levels are organized based on the scale at which they operate, with levels I–III at the agroecosystem (farm) scale and levels IV–V at the food system scale. Second, the levels categorize the approach to agriculture and food system transition, with levels I–II concerned with incremental improvements to how food is produced (without changing the political economy of the existing agri-food system) and levels III–V capable of unlocking transformative change throughout the entire agri-food system.

Given the urgency, magnitude, and the globally interconnected nature of the social-ecological challenges confronting society, there is a need to move beyond efficiency and substitution approaches to address the structural deficiencies in the agri-food system. As Hill (1985) noted nearly four decades ago, society expends the majority of resources, whether economic or knowledge-based, on trying to identify ways to ameliorate poorly designed, malfunctional systems. More recently, DeLonge et al. (2016) found that the distribution of public research funding is primarily geared toward research projects focused on enhancing efficiency (level I) and increasing yield, rather than being directed toward more transformative agri-food systems change. After evaluating projects funded by the United States Department of Agriculture (USDA) Research, Extension & Economics (REE) agency, the authors estimated that only 5–10% of the analyzed funds went to agroecology-based projects with transformative potential (levels III–V), which was the equivalent of 0.6–1.5% of the 2014 USDA REE budget (DeLonge et al., 2016). A 2017 survey of US scientists who focus on agroecology found that inadequate funding amounts and insufficient duration of projects were barriers to conducting more impactful research, which underscores the need for a dramatic shift in research and funding priorities (DeLonge et al., 2020). In the US, private research and development (R&D) spending by agricultural input industries alone (e.g., on crop seed and agrochemical development) exceeded the total amount spent on all agricultural research by the federal-state system of public R&D (Pardey et al., 2015; Fuglie et al., 2017). As agroecological practices are explicitly designed to reduce farmer dependency on off-farm inputs and private sector actors, this funding trend suggests that agroecologists in the US will need to be significantly more engaged in public policy and research advocacy.

In order to identify levers and leverage points that can foster transformative change in the agri-food system, researchers from a diverse array of disciplines have characterized the factors that make it so difficult to shift away from historically embedded trajectories. In a recent review of the literature on this topic, Conti et al. (2021) identified six themes that explain the observed resistance to change in dominant agri-food systems: "(i) technological persistence; (ii) misaligned institutional settings, policies and incentives; (iii) attitudes and cultures that cause aversion to change; (iv) political economy factors that skew the direction of change; (v) infrastructure rigidities; and (vi) research priorities, practices and dominant innovation narratives misaligned to the transformational change agenda." After categorizing the publications by research domain (agricultural systems, food systems, and socio-technical systems), it is notable that only 13% of publications from agricultural systems scholarship focused on the misalignment of research priorities to meet the clarion call for transformative change (Conti et al., 2021). This finding appears to reflect the institutional environment in which public agricultural research takes place. As Vanloqueren and Baret (2009) explain, the reluctance of scientists to pursue novel research themes that might better align with urgent societal needs is hindered by knowledge acquisition and training requirements, development of new networks, concerns about maintaining reputation or prestige, and access to adequate research funding. On this last point, public funding agencies predominantly fund low-risk research, which primarily describes research that does not challenge the status quo (Stephan, 2015). This situation depicts the mutually reinforcing, institutional lock-ins and path dependency of the dominant industrial agri-food system and agri-food research paradigm (IPES-Food, 2016; Hall and Dijkman, 2019; Conti et al., 2021).

The industrial agri-food system is also resistant to change due to its pervasive, highly authoritative legitimacy that is widely accepted in society. This firmly entrenched legitimacy—based on such processes as scientific validation and the language used in government policy—is an underappreciated factor that helps explain why industrial agriculture is difficult to displace and, in turn, why agroecology is challenging to bring to scale in the US (Montenegro de Wit and Iles, 2016). As members of networks, or “social carriers” (van der Ploeg, 2012), many farmers are leading the effort to overcome the social and political barriers to scaling out agroecology (U.S. Food Sovereignty Alliance, n.d.). Researchers, extension educators, and other practitioners can support the movement through scholar-activism and participatory, action-oriented, interdisciplinary science (Fernandez et al., 2012; Méndez et al., 2013; HLPE, 2019; Montenegro de Wit et al., 2021). It will also be critical that researchers avoid depoliticizing agroecology, severing the social movement from the science and praxis. Doing so will make agroecology more susceptible to co-optation, and greatly diminish its transformative potential (Gonzalez de Molina, 2013; Levidow et al., 2014; Gliessman, 2018).

Although my research does not directly engage with social movement actors, I understand agroecology to be an inseparable and holistic science, practice, and social movement (Sevilla Guzmán and Woodgate, 2013). At the interface between farm- and food-system scales, my work is centered on agroecosystem redesign, or level III of the agri-food system transformation framework. I take an interdisciplinary approach, drawing on theory and methodologies from natural (biophysical) and social science disciplines. The spatial scale of my work also spans regional experiments in the Northeast to research that encompasses the entire country. This scholarship shifts from a focus on two or four agroecological practices for the regional field experiments to eight agroecological practices for the multistate interviews and national survey. These agroecological practices include compost or manure use, intercropping, and insectary plantings, which are used at the within-field scale; reduced tillage, diverse crop rotations, and cover cropping, which are used at the field scale; and border plantings, and riparian buffers, which are used at the perimeter and landscape scales (Kremen and Miles, 2012). As the use of agroecological practices is a place-based approach to agroecosystem (farm) management, it is important to situate the research described in each chapter in the US context, whether by climatic conditions, political economic constraints, or other key factors.

In the Northeast, there has been a 71% increase in the observed frequency of heavy precipitation between 1958 and 2012, and both the frequency and intensity of heavy precipitation events are projected to continue increasing (USGCRP, 2018). Climate change in this regional context informed the conceptualization and design of the field experiments I report on in Chapters 1 and 2. In the Northeast, dairy farms have been under particular scrutiny as major contributors of non-point source pollution to impaired watersheds, such as the Chesapeake Bay. As the adoption of fall-sown cover crops has been limited among dairy farmers in the Northeast, planting winter cereals for home-grown forage is a potential way to decrease soil erosion and runoff, which will be particularly important given the expected changes to precipitation in the region. The field experiment for Chapter 1 was conducted in Maryland and New York, and the connection to agroecosystem redesign involved two agroecological practices: diverse crop rotations and cover cropping. In this study, I assess the trade-offs between yield and nutritive value among 12 winter cereal forages in organic dairy double-cropping systems. Four cultivars each for barley (*Hordeum vulgare* L.), cereal rye (*Secale cereale* L.), and triticale (× *Triticosecale* Wittm. ex A. Camus) were harvested at eight crop growth stages to assess the trade-offs between yield and quality in relation to winter cereal phenology.

In Chapter 2, my research shifts from organic dairy systems to organic grain cropping systems. Like dairy producers, grain farmers in the Northeast are also concerned about extreme precipitation increasing soil erosion and runoff, exacerbating adverse effects on aquatic ecosystems, delaying planting in the spring, and decreasing the number of days when fields are workable. Also conducted in Maryland and New York, this field experiment involved four agroecological practices important for agroecosystem redesign: composted manure applications, reduced tillage, diverse crop rotations, and cover cropping. Here, I conducted an experiment to analyze the effect of rolling (i.e., mechanically terminating) cover crops before, during, and after anthesis, and to evaluate the effects of species and cultivar selection on cover crop growth stage, cover crop biomass production, weed suppression, soybean density, soybean yield, and cover crop reseeding.

Expanding the focus from a regional to national scope, Chapter 3 is based on a nationwide survey of organic fruit and vegetable growers. This chapter, along with Chapter 4, involves all eight agroecological practices previously listed. Despite the heterogeneity of organic agriculture, researchers tend to describe organic farmers as a monolith. Yet, there is a growing concern that as organic food increases in popularity and large-scale conventional farmers enter the organic sector in pursuit of price premiums, organic agriculture is becoming more similar to industrial agriculture—a process known as "conventionalization." I use the results of this survey to determine whether farm size affects the use of agroecological practices, and to assess the degree to which conventionalization is occurring among organic farms in the US. I consider four common characteristics of conventionalization—lower crop diversity, greater mechanization, wholesale marketing, and non-local markets—along with findings on competition among farm sizes and farmers' interest in scaling up their operation.

Using a mixed-methods approach in Chapter 4, I interrogate the claim that agroecological practices are more labor-intensive than industrial farming practices, which has ramifications for scaling agroecology in the US. Here, I synthesize quantitative data from the national survey and qualitative data from my interviews with 49 fruit and vegetable farmers in California and New York. Given the long-term historical and political trends of cropland consolidation, mechanization, and a shrinking farm labor market in the US, I describe the influence of structural constraints on current recommendations to use agroecological practices. I analyze whether experience using an agroecological practice can affect farmers' evaluation of labor-intensity; if labor shortages are experienced differently by farm size; and how farm size might be related to the strategies that farmers are using to manage labor shortages, an increasing minimum wage, and other labor-related challenges.

Although this research can help establish greater legitimacy for agroecological practices in the US, agroecology will be more likely to flourish in this country if agroecologists can shift to more interdisciplinary research priorities, embrace different epistemologies, and learn from the successes and failures of social movements around the world. In the Epilogue, I reflect on potential limitations of my research, knowledge gaps, and point to future directions for research and policy that seek to realize a more sustainable and just food system for all.

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CHAPTER 1

TRADE-OFFS AMONG YIELD, QUALITY, AND HARVEST TIMING FOR TWELVE WINTER CEREAL CULTIVARS GROWN FOR FORAGE IN DAIRY DOUBLE-CROPPING SYSTEMS

1.1 ABSTRACT

Volatile feed costs and extreme weather events are contributing to greater economic risk and precarity throughout much of the United States dairy industry, especially among smaller-scale farmers. These challenges have prompted dairy farmers to seek ways to reduce feed imports without compromising milk production. Integrating winter cereals for forage as part of a double-cropping system is a potential solution, but increasing the amount of forage in dairy cow rations can reduce milk production if the forages are not managed for optimal quality. Here, results are reported from a field experiment conducted in Maryland (MD) and New York (NY) that compared the trade-offs among yield, quality (i.e., nutritive value), and harvest timing for four cultivars per winter cereal species—barley (*Hordeum vulgare* L.), cereal rye (*Secale cereale* L.), and triticale (× *Triticosecale* Wittm. ex A. Camus.)—grown as forage and harvested at eight crop growth stages. Mean yield at a commonly harvested growth stage, swollen boot (Zadoks 45), was 1.3, 2.2, and 2.2 Mg ha^{-1} in MD and 1.8, 2.5, and 2.9 Mg ha^{-1} in NY for barley, cereal rye, and triticale, respectively. Mean relative forage quality at the same growth stage was 180, 158, and 163 in MD and 179, 156, and 157 in NY for the three species. Cereal rye reached swollen boot stage earliest at both sites, followed by barley and triticale. The findings presented here can be used to improve double-cropping system performance and the synchronization of harvest timing with the specific needs of lactating dairy cows, dry cows, heifers, and calves.

1.2 INTRODUCTION

Over the past 30 years, the dairy sector in the United States (US) has experienced a 16-fold increase in consolidation (MacDonald et al., 2020). This transformational shift towards fewer, yet much larger, dairy farms is also characterized by a general movement of the industry towards the western region of the US (von Keyserlingk et al., 2013). Dairy farms in the northeastern US, including Maryland (MD) and New York (NY), are smaller (as measured by mean number of animals per farm) and tend to produce more feed grain and forage on-farm than dairies in the west (von Keyserlingk et al., 2013). With fluctuating feed costs and milk prices, turning a profit—especially while using environmentally sustainable soil and crop management practices and providing a high standard of animal welfare (von Keyserlingk et al., 2009)—can be elusive for many dairy farmers.

Operating an organic dairy can be more profitable than conventional management as the higher prices received for organic milk can outweigh the greater productions costs (e.g., inputs and labor) on organic farms, though farm size plays an important role (MacDonald et al., 2020). In 2016, for instance, organic dairy farmers who managed 50–199 cows received gross returns that were more than double those received by their conventional counterparts, and the difference was similar for farmers who managed 10–49 cows (MacDonald et al., 2020). Still, many of these relatively small-scale organic dairy farmers lost money (per unit of milk sold), which underscores the need to provide these farmers with technical support that might help them stay in business.

For small-scale organic dairy farmers managing herds of <100 cows in the US, >75% of their total operating costs are spent on feed, which is comprised of homegrown feed (54%), feed purchases (40%), and grazing (5%) (MacDonald et al., 2020). In contrast, larger operations purchase most of their feed. This decoupling of on-farm nutrient cycles, and the spatially disconnected production of feed and management of livestock on separate farms, has exacerbated concerns over the environmental impact and sustainability of dairy operations. Such farms have been under increasing scrutiny as significant contributors of non-point source pollution, particularly in relation to impaired watersheds, such as the Chesapeake Bay.

Winter cereals, such as cereal rye (*Secale cereale* L.), have been promoted for use as cover crops to improve soil health and decrease water pollution by reducing soil erosion, nitrate leaching, and phosphorus runoff (Staver and Brinsfield, 1998; Dabney et al., 2001; Dinnes et al., 2002; Blanco-Canqui et al., 2015; Thapa et al., 2018). Despite the numerous environmental benefits attributed to winter cereal cover crops (Snapp et al., 2005; Daryanto et al., 2018; McClelland et al., 2021; Wood and Bowman, 2021), adoption and consistent use is limited, though increasing (Wallander et al., 2021), throughout the US. Among dairy farmers in NY, for instance, the most common barriers to cover crop adoption include the concern that winter cereal cover crops will delay planting in the spring and the perception that cover crops provide no tangible short-term benefits (Long et al., 2013).

As an alternative to growing winter cereals as cover crops, the same winter-hardy species [e.g., barley (*Hordeum vulgare* L.), cereal rye, and triticale (× *Triticosecale* Wittm. ex A. Camus.)] can be planted in the fall and harvested in the spring as forage. When grown in tandem with a summer annual forage crop, such as sorghum [*Sorghum bicolor* (L.) Moench] or corn silage (*Zea mays* L.), this arrangement comprises a double-cropping system (i.e., two crops grown sequentially on the same parcel of land and harvested in the same calendar year). Compared with growing a summer annual forage crop alone, double-cropping with winter cereals can increase homegrown forage production (Brown, 2006; Heggenstaller et al., 2008, 2009; Fouli et al., 2012; Jemison et al., 2012; Ketterings et al., 2015), reduce the quantity and cost of imported feed (Kim et al., 2016; Veltman et al., 2018; Ranck et al., 2020), and increase feed inventory when it is typically low (Landry et al., 2019) or when extreme weather creates a forage shortage and emergency feed becomes a necessity (Ketterings et al., 2015). Compared with corn, winter cereals have more stable yields under drought conditions, and double-cropping enhances diversification, which reduces production risk (Rotz et al., 2002). Double-cropping systems also provide additional opportunities to spread manure, which can be helpful for land-limited dairy farmers or those with limited manure storage options. In these ways, double-cropping with winter cereals can improve environmental stewardship, productivity, and profitability.

Challenges to the practice of double-cropping still exist, however, with surveyed dairy farmers in NY reporting concerns about weather impacting both the timely establishment of winter cereal forages in the fall and timely harvest in the spring (Ketterings et al., 2015). In the same survey, more information about forage quality was among the highest ranked topics that farmers indicated would best support adoption or continued use of winter cereal forages (Ketterings et al., 2015). This is an important consideration as increasing the amount of forage in dairy cow rations can decrease milk production if the forages are not carefully managed for optimal quality. Consequently, dairy farmers will benefit from region-specific information and guidance for precise, yet flexible, crop management that balances yield and quality with harvest timing synchronized to meet livestock nutritional demands and the requirements for optimal main crop production in a double-cropping system. To this end, the objectives of our research were to (1) determine the yield and quality of winter cereals—four cultivars each for barley, cereal rye, and triticale—grown as forage when harvested at different crop growth stages, and (2) evaluate the trade-offs between yield and quality in relation to winter cereal phenology and harvest date.

1.3 METHODS

1.3.1 Site description

Conducted during the winter cereal field season of fall 2014 to spring 2015, our experiment consists of two sites in the Northeast region of the US: Beltsville, MD (39° 1’ N, 76° 55’ W; USDA plant hardiness zone 7a), and Aurora, NY (42° 43’ 54.4” N, 76° 39’ 02.6” W; USDA plant hardiness zone 6a) (USDA ARS, 2012). At the MD field site, the primary soil type is a Codorus-Hatboro silt loam (fine-loamy, mixed, active, mesic, Fluvaquentic Dystrudepts and Endoaqueptsz). Soil type at the NY field site is a moderately well-drained, calcareous Lima silt loam (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs), with partial tile drainage. Soil pH and soil organic matter were lower in MD at 5.7 and 1.7%, respectively, compared with 7.5 and 3.0% in NY.

The non-irrigated field sites in both MD and NY were under long-term conventional management prior to establishing our experiment. Wheat (*Triticum aestivum* L.) and sorghum were the preceding crops in MD and NY, respectively. The experiment was managed organically at both sites.

Precipitation diverged from the long-term mean at both sites throughout much of 2015, but the variability was particularly notable beyond day 120 (May 1) in NY, fluctuating from dry periods of little or no precipitation to periods of very heavy rainfall (Figure 1.1). Compared with the long-term mean temperature, daily mean temperature was generally cooler prior to the sampling period and warmer during the sampling period in MD and NY.

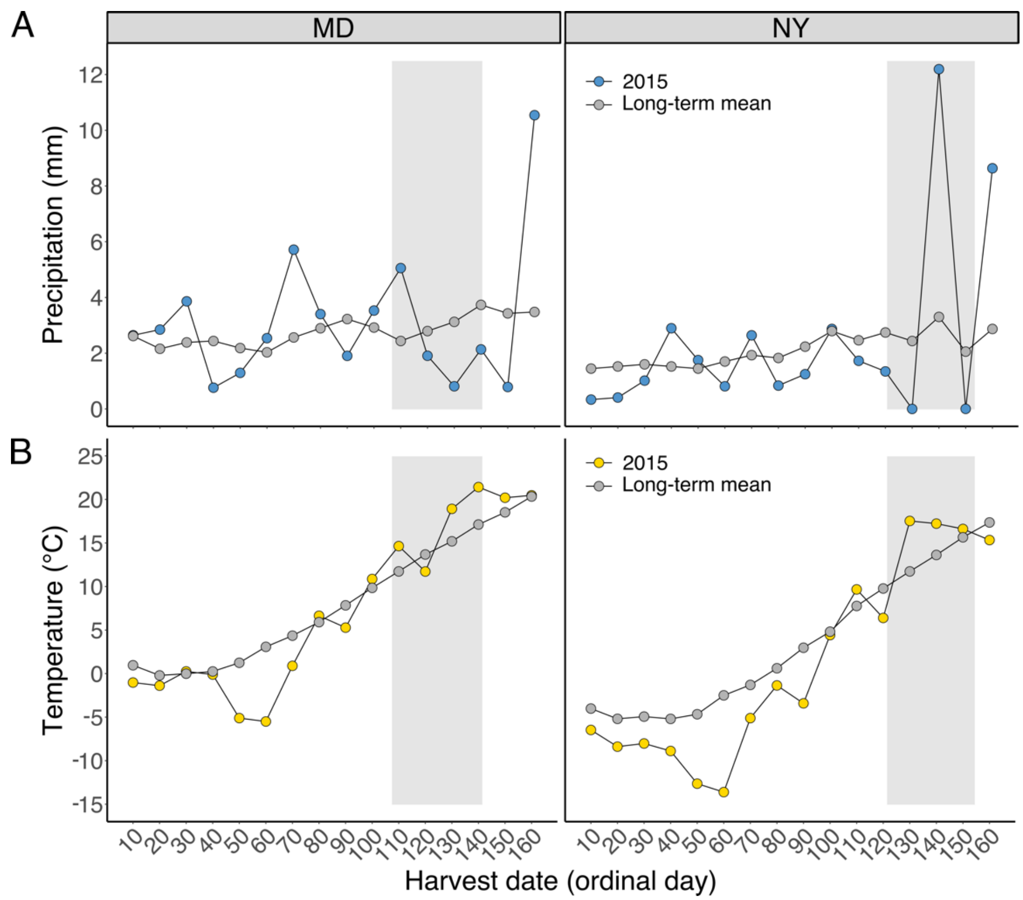

Figure 1.1 | Mean daily (A) precipitation (mm) and (B) temperature (°C) for Beltsville, MD, and Aurora, NY, in 2015 for each 10-day interval beginning January 1 (day 1) through June 9 (day 160). The long-term mean represents the mean daily precipitation or temperature summarized using the earliest year of recorded weather station data associated with each field site: 1941–2014 for MD and 1956–2014 for NY (Northeast Regional Climate Center, 2022). Shaded regions indicate the sampling period, ranging from the first to the last harvest date in each site.

1.3.2 Experimental design and field operations

Arranged in a randomized complete block design, the yield and quality of barley, cereal rye, and triticale cultivars were compared across eight sampling dates. Four cultivars per species were assessed: 'P-919,' 'Thoroughbred,' 'Valor,' and 'Verdant' barley; 'Aroostook,' 'Huron,' 'Lakeview VNS,' and 'Spooner' cereal rye; and 'NE426GT,' 'TriCal 718,' 'TriCal 815,' and 'TriMark 099' triticale. The variety-not-stated (VNS) cereal rye cultivar was from Lakeview Organic Grains in Penn Yan, NY, and will be referred to as ‘Lakeview VNS.’ The eight sampling dates occurred at four- to six-day intervals: day 107, 111, 117, 121, 125, 131, 135, and 141 in MD (i.e., April 17, 21, 27, and May 1, 5, 11, 15, and 21); and day 121, 125, 131, 135, 139, 144, 149, and 154 in NY (i.e., May 1, 5, 11, 15, 19, 24, 29, and June 3). Each site had of 48 plots (12 cultivars × 4 blocks), which were 24.4 by 6.1 m in both MD and NY.

Based on visual observations of nitrogen deficiency in the preceding sorghum crop in NY, poultry litter (5–4–3, N–P_2O_5–K_2O) was applied on the surface at a rate of 67 kg total N ha^{-1} prior to winter cereal planting, using a box-spreader. In MD, poultry litter was not applied. Winter cereals were drill-planted at a depth of 2.5 to 3.8 cm with 19-cm row spacing on September 19, 2014, in NY and October 2, 2014, in MD. Although some farmers do not prioritize early winter cereal planting dates, these dates were selected due to the importance of fall growing degree days for biomass production in the spring (Mirsky et al., 2009). Earlier fall planting dates are also compatible with the typical harvest timing for shorter-season summer annual crops, such as sorghum or corn silage.

All twelve winter cereals were seeded at an equivalent rate based on seed mass, with ‘Aroostook’ cereal rye as the reference cultivar. ‘Aroostook’ was selected as the reference because it is very winter-hardy, matures early in the spring, and produces high yields (Mirsky et al., 2009), which are all valuable traits for a winter cereal in a double-cropping system. Setting the reference seeding rate at 126 kg ha^{-1} of ‘Aroostook’ cereal rye, farm-scale seed drills were calibrated to plant an equivalent number of seeds per hectare for the other eleven cultivars, thereby accounting for differences in seed mass among the cultivars (Table 1.1). This approach resulted in adjusted seeding rates that ranged from 1% lower to 86% higher (kg ha^{-1}) than the ‘Aroostook’ reference (Table 1.1).

Table 1.1 | Seed mass (g seed^{-1}) and the adjusted seeding rate (relative to the reference cultivar, 'Aroostook' cereal rye) for all twelve winter cereal cultivars.

Species	**Cultivar**	**Seed mass**	**Adjusted seeding rate**
		g seed^{-1}	kg ha^{-1}
Barley	P-919	0.027	148
	Thoroughbred	0.033	183
	Valor	0.029	158
	Verdant	0.037	207
Cereal rye	**Aroostook**	**0.023**	**126**
	Huron	0.035	194
	Lakeview VNS	0.022	124
	Spooner	0.025	136
Triticale	NE426GT	0.037	203
	TriCal 718	0.041	229
	TriCal 815	0.038	210
	TriMark 099	0.042	235

1.3.3 Sampling protocols and lab procedures

Winter cereal biomass was determined by hand-clipping the plants 10.2 cm above the soil surface, mimicking typical machine harvest of winter cereal forages, within 20 by 100-cm sampling frames. Arranged perpendicular to the direction of winter cereal planting, the sampling frames spanned five crop rows. Biomass samples were collected at eight dates in the spring of 2015 between April and May in MD and May and June in NY. Immediately prior to biomass collection, the growth stage of the winter cereals was visually assessed and identified according to the Zadoks scale (Zadoks et al., 1974). The sampling events, which occurred at four- to six-day intervals, were selected to encompass a wide range of growth stages, including growth stages both earlier and later than the recommended harvest timing of swollen boot (Zadoks 45) for most winter cereals (Coblentz et al., 2018). These samples were obtained from eight locations within the randomly arranged plots. The sampling locations were systematically assigned during the experimental design phase to maximize the space between the samples and avoid both in-field sampling bias (e.g., poor growth avoidance) and edge effects from sampling too close to plot borders. Following each sampling event, the biomass samples were dried in forced-air ovens at 50°C for approximately one week and then weighed so that dry matter (DM) yield could be calculated.

The dried biomass samples were ground to 1-mm particle size in preparation for the forage quality analyses. The samples were then submitted to Dairyland Laboratories in Arcadia, WI, where Near Infrared Spectroscopy (NIR), supported by a robust database of cool-season grass forages, was used to analyze the winter cereals for crude protein, CP; acid detergent fiber, ADF; neutral detergent fiber, NDF; and 48-hour in vitro NDF digestibility, $NDFD_{48}$ (Marten et al., 1985; AOAC, 1990). For estimating NDFD, a single point in time (or endpoint) of 48 hours was selected to reflect NDF passage kinetics from the rumen (Coblentz et al., 2019).

1.3.4 Statistical analyses

All data were analyzed using R version 4.0.5 (R Core Team, 2021). Regression diagnostics were performed to ensure that there were no outliers or influential observations, that errors exhibited independence and residuals were normally distributed, and that there was homogenous variance (‘car’ package: Fox and Weisberg, 2019).

1.3.4.1 Yield

A linear mixed-effects model (‘lme4’ package: Bates et al., 2015) was used to predict yield (Mg DM ha^{-1}) as a function of three fixed effects: growth stage (Zadoks, 0-100, continuous), cultivar (12 levels), and site (2 levels). This model included the three-way and all two-way interactions among the fixed effects, along with each predictor as a main effect. Random effects included block (8 levels) and plot (96 levels). With unique designations for each factor level of block and plot, the random effects are equivalent to block and plot individually crossed with site (i.e., 4 blocks site^{-1} and 48 plots site^{-1}). The fixed effect associated with each subsample (collected in each plot at the eight sampling dates) is represented by growth stage in this model. To address the heteroscedasticity and non-normality of the residuals for yield, the response was square root transformed (McCune et al., 2002).

Analysis of variance ('lmerTest' package: Kuznetsova et al., 2017) was performed on the linear mixed-effects model. The marginal and conditional coefficients of determination (R^2) were also assessed ('MuMIn' package: Bartoń, 2020), which represent variance explained by the fixed effects and by both fixed and random effects, respectively (Nakagawa and Schielzeth, 2013). The difference between marginal slopes for each cultivar in the linear regression (i.e., pairwise comparisons or contrasts) was assessed with the Tukey Method to test the interactions ('emmeans' package: Lenth, 2021).

1.3.4.2 Forage quality

The University of Wisconsin Alfalfa/Grass Evaluation System (also known as MILK 2016) was used to calculate relative forage quality (RFQ), which is described as

$$RFQ = \frac{(DMI_{grass}, \%\ of\ BW)(TDN_{grass}, \%\ of\ DM)}{1.23}, \qquad [1]$$

where DMI_{grass} is the dry matter intake of a cool season grass as a percentage of body weight (Moore et al., 1999); TDN_{grass} is the total digestible nutrients for a cool season grass as a percentage of dry matter (Moore and Undersander, 2002); and the divisor, 1.23, is used to adjust the equation so that the mean and range are similar to Relative

Feed Value (Undersander et al., 2010). The effects of growth stage, cultivar, and site on RFQ were analyzed with the same linear mixed-effects model structure and analytical approach described for yield, except no transformation of the response was required. Although RFQ was evaluated as the primary measure of nutritive value for each winter cereal cultivar, supplemental analyses for the constituents of the summative RFQ metric—CP (% DM), ADF (% DM), NDF (% DM), and $NDFD_{48}$ (% NDF)—were also conducted in the same way as RFQ.

1.3.4.3 Crop phenology

Winter cereal phenological development was predicted with self-starting logistic models ('nlme' package: Pinheiro et al., 2021). The data were fit to a four-parameter sigmoidal (or "S-shaped") function, which can be described as

$$y(x) = ø_1 + \frac{ø_2 - ø_1}{1+e^{[(ø_3 - x)/ø_4]}}, \qquad [2]$$

where, given $ø_4 > 0$, $ø_1$ is the horizontal asymptote as x approaches ∞; $ø_2$ is the horizontal asymptote as x approaches $-\infty$; $ø_3$ is the value of x at the inflection point (i.e., the response is midway between the asymptotes at this x value); and $ø_4$ is a scale parameter on the x-axis (i.e., when $x = ø_3 + ø_4$ the response is approximately three-quarters of the distance from $ø_1$ to $ø_2$) (Pinheiro and Bates, 2000). As a four-parameter model did not fit the 'Aroostook' cereal rye data in MD, phenological development for this cultivar was predicted with a three-parameter sigmoidal function. The three-parameter logistic model is a special case of the four-parameter model in which one of the horizontal asymptotes ($ø_1$ or $ø_2$) is zero (Pinheiro and Bates, 2000).

1.3.4.4 Trade-offs

Farmers commonly use swollen boot stage (Zadoks 45) as a visual phenological indicator to time winter cereal harvest for forage. Using this growth stage as a baseline, percent change in yield and RFQ was calculated for growth stages that occur before and after Zadoks 45. Using the day associated with the earlier (Zadoks 39) and later (Zadoks, 51, 57, and 63) growth stages, the number of days earlier or later—relative to Zadoks 45—that a farmer would need to harvest to obtain forage at these specific growth stages was also determined. The trade-offs between yield and RFQ, and the timing (and length) of these phenology-based harvest dates, were all calculated using the estimated marginal means drawn from the previously described statistical models for yield, RFQ, and harvest date (day).

1.4 RESULTS AND DISCUSSION

1.4.1 Winter cereal yield

A three-way interaction among cultivar, growth stage, and site was observed (p = 0.005) for yield (Table 1.2), and all slopes were different from zero ($p < 0.0001$). As growth stage advanced, yield increased across all winter cereal cultivars. However, the rate of yield gain varied by cultivar, and these differences depended on site.

Table 1.2 | Analysis of variance for yield (Mg dry matter ha^{-1}) and relative forage quality (RFQ) as affected by winter cereal cultivar (all twelve), growth stage (Zadoks), and site (MD and NY).

Predictors	**Yield***	**RFQ**
	p-value	
Cultivar	0.0006	<0.0001
Growth stage	<0.0001	<0.0001
Site	0.0002	0.8149
Cultivar × Growth stage	<0.0001	<0.0001
Growth stage × Site	<0.0001	0.4141
Cultivar × Site	0.0212	0.2339
Cultivar × Growth stage × Site	0.0051	0.1355
Coefficient of determination		
Marginal	0.829	0.915
Conditional	0.848	0.917

* Yield (Mg DM ha^{-1}) was square root transformed to address heteroscedasticity.

In MD, yield ranged across sampling dates from 0.5 to 5.9 Mg ha^{-1} among barley cultivars, 0.8 to 7.4 Mg ha^{-1} among cereal rye cultivars, and 0.8 to 7.1 Mg ha^{-1} among triticale cultivars (Figure 1.2). As growth stage increased in MD, all barley cultivars produced lower yields than ‘TriCal 718’ triticale ($p \leq 0.03$). ‘Valor’ barley also gained less yield across growth stages (i.e., the slope was shallower) than all cultivars except ‘Verdant’ barley and ‘TriCal 815’ triticale. No slope differences were observed between any cereal rye and triticale cultivars in MD.

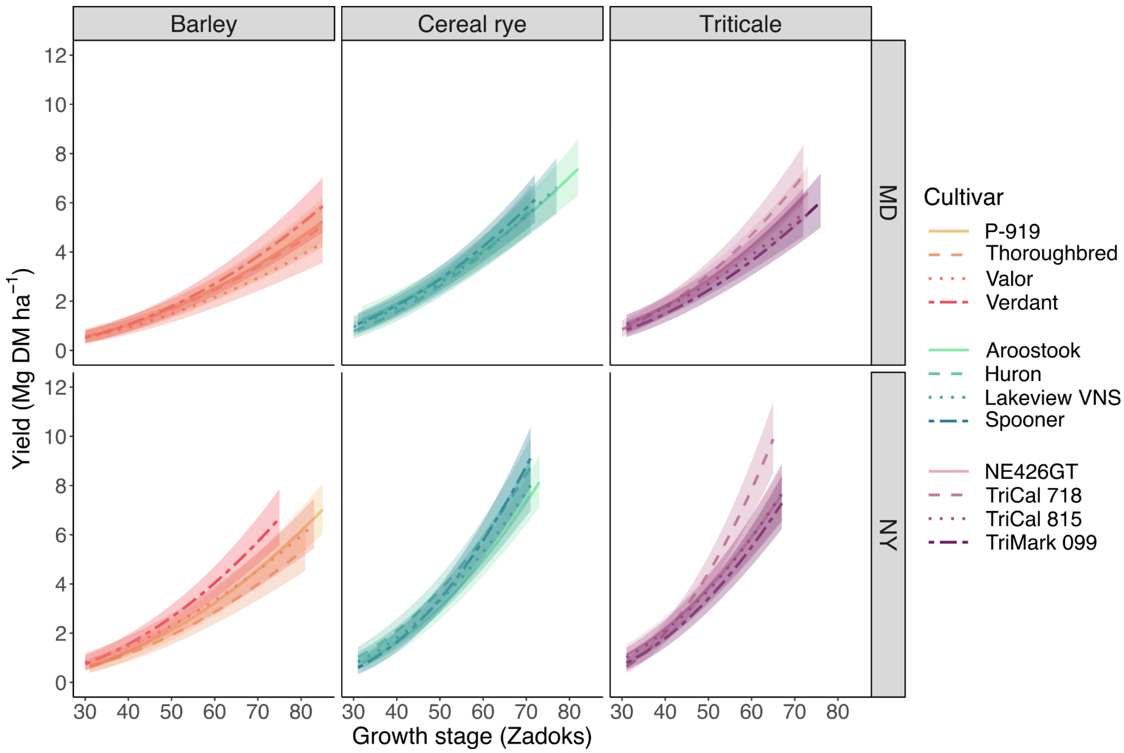

Figure 1.2 | The effect of winter cereal cultivar (four per species), growth stage (Zadoks), and site (MD and NY) on yield (Mg dry matter ha^{-1}). Yield has been back-transformed from the square root transformation. The shaded "ribbon" accompanying each cultivar slope (line) represents a 95% confidence interval. Analysis of variance and coefficients of determination for this linear mixed-effects model are presented in Table 1.2.

In NY, yield ranged across sampling dates from 0.6 to 7.0 Mg ha^{-1} among barley cultivars, 0.6 to 9.1 Mg ha^{-1} among cereal rye cultivars, and 0.6 to 9.9 Mg ha^{-1} among triticale cultivars (Figure 1.2). Yield gain differences across growth stage were also largely limited to barley cultivars in NY. 'P-919,' 'Thoroughbred,' and 'Valor' barley produced lower yield gains ($p \leq 0.003$) as growth stage advanced when compared with cereal rye and triticale cultivars. 'Verdant' barley, in contrast, yielded more similarly to cereal rye and triticale cultivars, although 'Spooner' cereal rye and 'NE426GT' triticale produced greater yield gains ($p \leq 0.009$) across growth stages than 'Verdant.' Intraspecific comparisons of yield gains exhibited no differences among the four barley cultivars. 'TriCal 718' triticale also emerged as a high-yielding cultivar in NY, producing greater yield gains ($p \leq 0.04$) than all other cultivars except

‘Spooner’ cereal rye (p = 0.2) and ‘TriCal 815’ triticale (p = 0.06).

After a period of vernalization and growth has advanced beyond the formation of a pseudostem (Zadoks 30), winter cereals make a transition from the vegetative to reproductive phase of development. The alignment of developmental stages during the reproductive phase—such as stem elongation (Zadoks 30–39), booting (Zadoks 40–49), ear emergence (Zadoks 50–59), anthesis (Zadoks 60–69), milk development (Zadoks 70–79), and dough development (Zadoks 80–89)—with seasonal conditions (temperature, radiation, and water availability) is essential for optimizing winter cereal yields (Hyles et al., 2020). Genotypic response and region-specific factors, such as latitude and day length (photoperiod), also interact with abiotic conditions and soil and crop management to influence yield in relation to growth stage (Slafer and Rawson, 1994). The addition of poultry litter (5–4–3) at fall planting in NY, for instance, might have contributed to the higher overall yields and CP content compared with MD (Supplementary Figure A1).

Among species, cereal rye is known to produce greater yields than triticale (Brown and Almodares, 1976; Helsel and Thomas, 1987; Kaspar and Bakker, 2015), which in turn is known to out-perform barley (Jemison et al., 2012). Lower barley yields are frequently reported in experiments located in more northern regions, due in part to its inferior winter hardiness. However, some research has reported that triticale produces greater yields than cereal rye (Tumbalam et al., 2016; Landry et al., 2019), which was observed in our experiment for ‘TriCal 718’ when compared with three of the four cereal rye cultivars.

The wide array of factors that affect winter cereal yield can make cultivar selection within a species an important decision. In our experiment, intraspecific yield differences were equivalent to, or larger than, interspecific differences (Figure 1.2). In other research comparing multiple cultivars per winter cereal species, yield differences among cultivars have been reported (Juskiw et al., 2000; Harmoney and Thompson, 2010; Kaspar and Bakker, 2015), though not consistently (Carr et al., 2004). Depending on the narrowness of the germplasm pool that cultivars are selected from, substantial differences may or may not be expected (Lyu et al., 2018).

Although this experiment did not compare the combined yields of a winter cereal and summer annual with a summer annual alone, numerous studies in the US (Brown, 2006; Heggenstaller et al., 2008, 2009; Fouli et al., 2012; Jemison et al., 2012; Ketterings et al., 2015; West et al., 2020) and abroad (Graß et al., 2013; Wannasek et al., 2019) have found that double-cropping systems tend to provide more biomass than single (or "sole") cropping systems, while also providing additional ecosystem services. It should be noted that some research has shown that growing a winter cereal prior to planting a summer annual crop can suppress the second crop in a double-cropping system. Most of this research has focused on cereal rye and corn silage double-cropping systems, with yield reductions in corn attributed to a reduction in soil nitrate or soil moisture (Krueger et al., 2011, 2012), negative effects of allelopathy (Raimbault et al., 1990; Tollenaar et al., 1992; Acharya et al., 2021), increased incidence of seedling disease (Acharya et al., 2017, 2020), or delayed planting (Darby and Lauer, 2002). In systems where soybean [*Glycine max* (L.) Merr.] follows a winter cereal, greater damage from insect pests has also been reported, although findings have been inconsistent (Inveninato Carmona et al., 2021). Although yields are important, dairy farmers must also consider the quality, or nutritive value, of a forage when making cropping system decisions.

1.4.2 Forage quality

The effect of winter cereal cultivar across growth stage did not vary by site for RFQ (p = 0.1), nor did site interact separately as a two-way interaction with cultivar (p = 0.2) or growth stage ($p = 0.4$) (Table 1.2). An interaction was observed, however, between cultivar and growth stage ($p < 0.0001$). All marginal slopes were different from zero ($p < 0.0001$). Key components of RFQ, such as CP, ADF, NDF, and $NDFD_{48}$, all followed expected trends (Khorasani et al., 1997) in relation to advancing crop maturity: CP decreased, ADF increased, NDF increased, and $NDFD_{48}$ decreased (Supplementary Figures A1–4, Supplementary Table A1). RFQ, however, will be the focus here as it represents a summative estimation of nutritive value.

As growth stage advanced, RFQ declined (Figure 1.3). In MD, RFQ decreased across sampling dates from 200 to 129 among barley cultivars, 216 to 41 among cereal rye cultivars, and 202 to 81 among triticale cultivars. In NY, RFQ decreased across sampling dates from 200 to 136 among barley cultivars, 205 to 64 among cereal rye cultivars, and 200 to 82 among triticale cultivars. At both sites, no differences in the slopes describing RFQ across growth stages were observed among the four barley cultivars ($p \geq 0.4$), but each barley cultivar maintained greater RFQ ($p < 0.0001$) as the plants matured compared with all cereal rye and triticale cultivars (i.e., the negative slopes were less steep for barley cultivars).

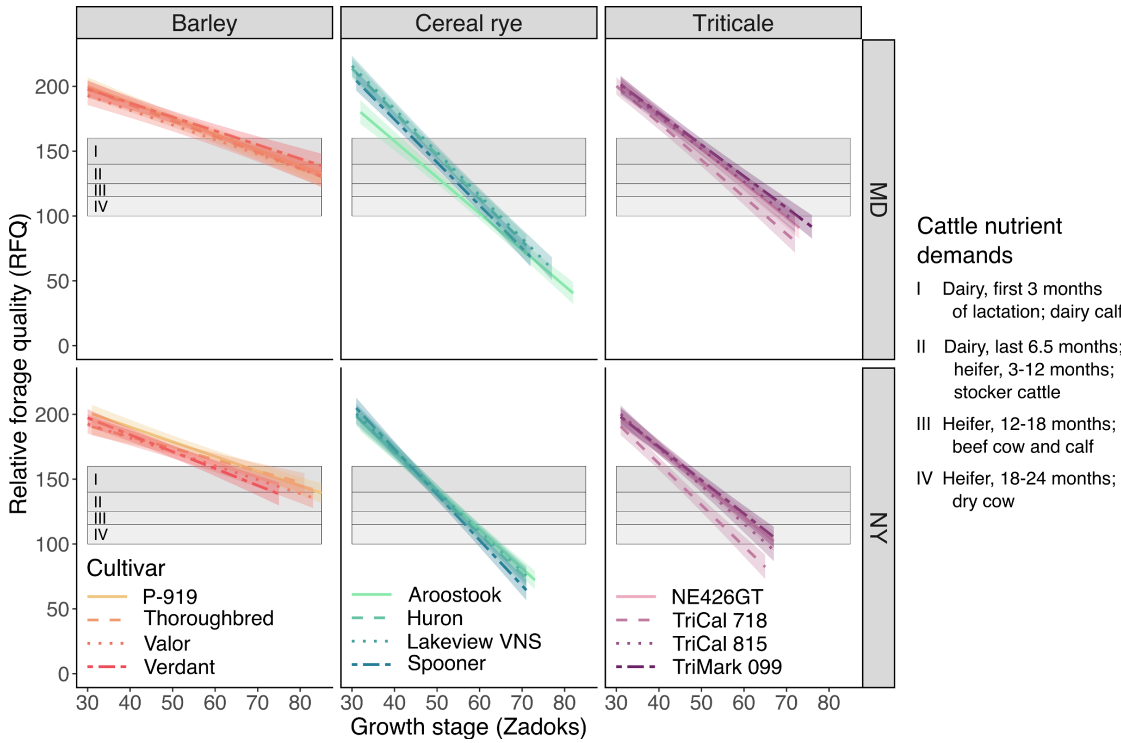

Figure 1.3 | The effect of winter cereal cultivar (four per species), growth stage (Zadoks), and site (MD and NY) on relative forage quality. The shaded "ribbon" accompanying each cultivar slope (line) represents a 95% confidence interval. Shaded rectangular areas indicate the recommended forage quality as it relates to the specific nutrient demands of an animal: (I) dairy cow (first 3 months of lactation) or dairy calf, RFQ 140 to 160; (II) dairy (last 6.5 months), heifer (3 to 12 months), or stocker cattle, RFQ 125 to 150; (III) heifer (12 to 18 months) or beef cow and calf, RFQ 115 to 130; and (IV) heifer (18 to 24 months) or dry cow, RFQ 100 to 120 (adapted from Ball et al., 2008). The ranges presented here show the minimum RFQ for each group (I to IV) to the minimum of the next group (with the exception of group I, as there is no group that has higher quality demands); the maximum values, which overlap with the next group (with the exception of group I), are not depicted in the shaded areas. Analysis of variance and coefficients of determination for this linear mixed-effects model are presented in Table 1.2.

In MD, the slope associated with 'Aroostook' cereal rye (-2.8 RFQ growth stage^{-1}) was not different from the other cereal rye ($p \geq 0.4$) and triticale ($p \geq 0.9$) cultivars, whereas 'Huron,' Lakeview VNS,' and 'Spooner' cereal rye exhibited a greater decline in RFQ (-3.3 RFQ growth stage^{-1} for all three cultivars) compared with 'NE426GT,' 'TriCal 718,' 'TriCal 815,' and 'TriMark 099' triticale (-2.4 to -2.9 RFQ growth stage^{-1}, $p \leq 0.02$). Among the four triticale cultivars, no differences were observed in MD ($p \geq 0.7$).

In NY, no differences between slopes were observed among cereal rye (-3.0 to -3.1 RFQ growth stage^{-1}) and triticale cultivars (-2.6 to -3.2 RFQ growth stage^{-1}), with two exceptions: 'Spooner' cereal rye exhibited greater RFQ decline (-3.5 RFQ growth stage^{-1}) compared with 'NE426GT' (-2.7 RFQ growth stage^{-1}, $p = 0.02$) and 'TriMark 099' (-2.6 RFQ growth stage^{-1}, $p = 0.008$) triticale. Although differences were detected when conducting pairwise comparisons of the slopes among cultivars at each site separately, it should be noted that interactions with site, and site as a main effect, did not help explain the variance for RFQ in our model (Table 1.2).

Compared with cereal rye and triticale cultivars, barley cultivars exhibited a notably smaller decline in RFQ as the crops advanced in maturity. For barley cultivars, this decrease ranged from 0.9–1.2 RFQ growth stage^{-1}, whereas cereal rye and triticale exhibited a 2–4-fold greater decline in RFQ growth stage^{-1}. Surprisingly, 'Thoroughbred' barley, which is a cultivar bred for grain, was of similar quality to the other three barley cultivars, which were bred as a dual-purpose grain and forage cultivar ('P-919') or explicitly for forage or grazing ('Valor' and 'Verdant'). Previous research has determined that barley has higher *in vitro* digestibility and lower acid detergent fiber, acid detergent lignin, and cell wall constituents than triticale (Cherney and Marten, 1982a). By separately analyzing each whole-plant yield component (e.g., leaf blade, leaf sheath, stem, and inflorescence) in winter cereal forages, greater digestibility of barley was found primarily as a result of highly digestible inflorescence comprising a greater proportion of the total dry matter across growth stages (Cherney and Marten, 1982b). Particularly at more advanced growth stages, other research has also found higher forage quality for barley compared with triticale (Khorasani et al., 1997; Lyu et al., 2018) or cereal rye (Helsel and Thomas, 1987), and triticale has been found to exhibit higher quality than cereal rye (Brown and Almodares, 1976). Although differences among cultivars within each species were not consistently detected in our experiment, intraspecific differences have been frequently reported when comparing the nutritive value of forage cultivars (Juskiw et al., 2000; Kim et al., 2016; Lyu et al., 2018).

Livestock have specific nutrient demands at different ages and reproductive stages. For example, dairy calves and dairy cows during the first three months of lactation have the highest nutritional requirements among cattle on a dairy farm (Ball et al., 2008). Meeting these high demands is a priority for farmers. High quality feed rations that fulfill such requirements, however, are typically the most expensive to purchase, as well as the most time-sensitive and challenging to manage and produce on-farm. Harvesting winter cereals for forage at swollen boot stage is common among dairy producers (Coblentz et al., 2018) because the nutritive value (e.g., RFQ) is typically high enough to feed to the most nutrient-demanding cattle on the farm, and the growth stage is reached relatively early in the growing season, thereby minimizing any delay in preparing the soil and planting the following crop. At swollen boot stage, RFQ ranged from 144–185 across cultivars and sites in our experiment (Figure 1.3). Based on previously defined thresholds (Ball et al., 2008), all cultivars maintained high enough RFQ to meet the nutrient requirements of the most demanding cattle (group I, Figure 1.3). However, not all cultivars performed equivalently when considering yield (Figure 1.2), the date at which swollen boot stage is reached, and length of the harvest window. These considerations are equally important if a farmer is seeking to produce forage for other cattle (groups II–IV) as well (Figure 1.3).

1.4.3 Phenological development and harvest windows

Located further south than NY, the MD site is in USDA Plant Hardiness Zone 7a (minimum temperature = -17.8°C). This hardiness zone has a greater minimum temperature threshold than Plant Hardiness Zone 6a (minimum temperature = -

23.3°C), which is associated with the NY site location (USDA ARS, 2012). Accordingly, all cultivars across the three species in MD—as described by three- and four-parameter logistic models (Supplementary Table A2)—reached swollen boot stage earlier in the year than in NY (Figure 1.4). The earliest and latest cultivars to reach swollen boot stage, however, were the same in both MD and NY: 'Aroostook' cereal rye reached swollen boot stage in 113 days (April 23) in MD and 128 days (May 8) in NY, while 'TriCal 718' triticale reached the same growth stage in 125 days (May 5) in MD and 141 days (May 21) in NY, which was 12 and 13 days later than 'Aroostook,' respectively.

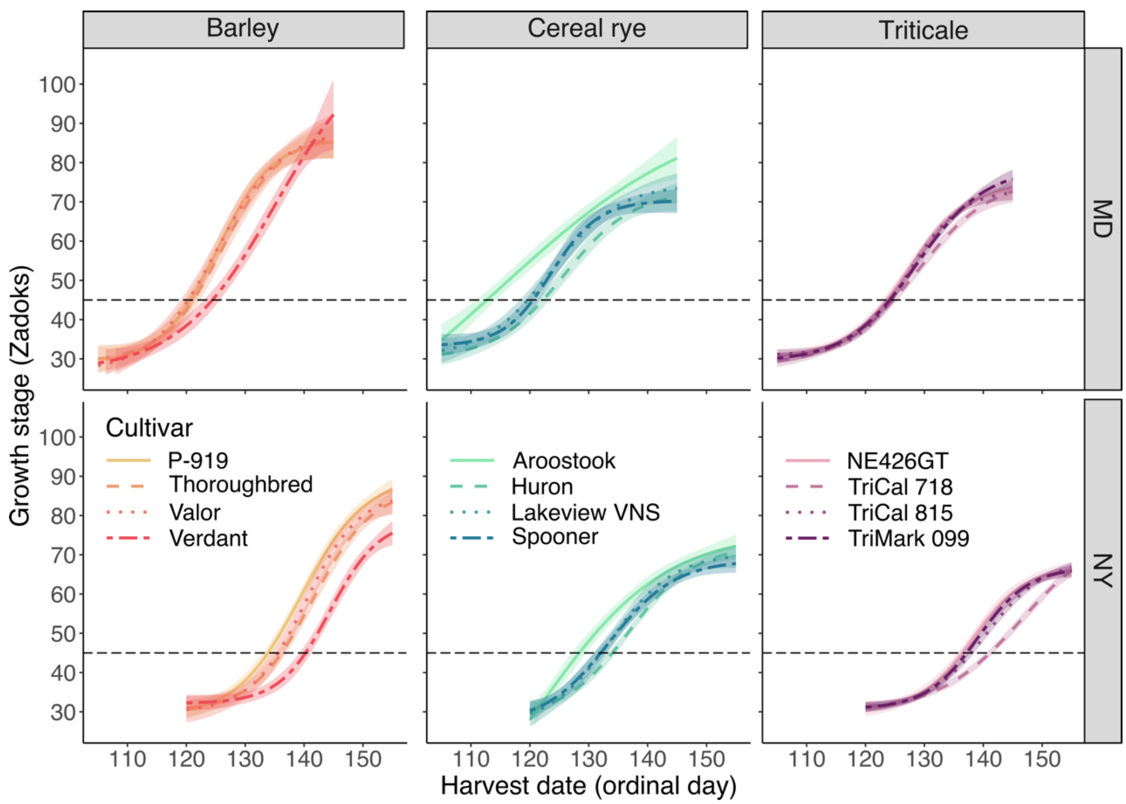

Figure 1.4 | Phenological development for barley, cereal rye, and triticale cultivars as described by the logistic models for the relationship between growth stage (Zadoks) and harvest date (ordinal day) in MD and NY. The shaded "ribbon" for each sigmoidal curve represents a 95% confidence interval. The horizontal dashed line indicates a common phenology-based harvest timing, swollen boot stage (Zadoks 45), for winter cereals grown for forage.

Within species, the mean number of days to reach swollen boot stage for barley, cereal rye, and triticale was 122, 119, and 124 in MD and 136, 132, and 138 in NY, respectively (Figure 1.4). Among the barley cultivars, 'P-919,' 'Thoroughbred,' and 'Valor' reached swollen boot stage approximately 4–5 and 4–6 days earlier than 'Verdant' in MD and NY, respectively. Among the cereal rye cultivars, 'Aroostook' reached swollen boot stage approximately 6–8 and 3–5 days earlier than 'Huron,' 'Lakeview VNS,' and 'Spooner' in MD and NY, respectively. And, among the triticale cultivars, no notable maturation differences were observed in MD, whereas 'NE426GT,' 'TriCal 815,' and 'TriMark 099' reached swollen boot stage approximately 3–5 days earlier than 'TriCal 718' in NY.

Early maturity is a valuable characteristic for a winter cereal forage, particularly in double-cropping systems. Using swollen boot stage as a baseline for comparisons across species, the average cereal rye cultivar reached the target growth stage 3–4 days earlier than the average barley cultivar, which in turn reached swollen boot stage approximately 2 days earlier than the average triticale cultivar. Similar outcomes were found by other researchers who compared at least two of the three species assessed in our experiment. For example, research conducted in Ontario, Canada, found that cereal rye reached swollen boot stage 4–8 days earlier than triticale (Landry et al., 2019), whereas a 5–6-day difference was observed, on average, in our experiment in the northeastern US. However, a much larger difference of 12–13 days is observed in our experiment if the earliest-maturing cereal rye cultivar ('Aroostook') is compared with the latest-maturing triticale cultivar ('TriCal 718'). This discrepancy between the maximum and minimum day values at swollen boot stage and the mean day values highlights the potential advantages, or disadvantages, associated with both species and cultivar selection.

As some dairy farmers might harvest a winter cereal that has matured beyond swollen boot stage, either to feed a specific cattle group or because timely harvest at swollen boot stage was not possible, it is important to consider winter cereal phenology past that target growth stage. The sigmoidal function of the logistic models indicates that the barley cultivars exhibit more rapid maturation than cereal rye and triticale cultivars following booting (Zadoks 40–49) and continuing through anthesis (Zadoks 60–69) or milk development (Zadoks 70–79) (Figure 1.4). For example, the barley cultivars reached quarter-complete anthesis (Zadoks 63) 0–1 day earlier than the average cereal rye cultivar despite arriving at swollen boot (Zadoks 45) 3–4 days later than the cereal rye cultivars. Similarly, barley cultivars reached quarter-complete anthesis 4–6 days earlier than triticale cultivars despite arriving at swollen boot stage just 2 days before the triticale cultivars.

Although the nonlinear models provide biologically realistic representations of winter cereal phenological development, applying these findings requires synthesis with yield and quality outcomes. Consequently, an evaluation of the trade-offs among yield, quality, and timing is an essential component of designing and managing the winter cereal forage component within a double-cropping system.

1.4.4 Trade-offs among yield, quality, and harvest timing

Relativizing the increases and decreases in yield and RFQ as percent change across growth stages provides a simple approach for comparing the outcomes of phenology-based harvest timing (Table 1.3). With swollen boot stage as the baseline, percent change in yield and RFQ—relative to this reference growth stage—are shown for multiple identifiable growth stages at 6-stage intervals (Table 1.3): when the flag leaf ligule just becomes visible (Zadoks 39), when the tip of the ear just becomes visible (Zadoks 51), when the ear is three-quarters emerged from the boot (Zadoks 57), and when anthesis is one-quarter complete (Zadoks 63). To increase the practical relevance of these changes, the trade-offs between yield and quality should also be considered in relation to the number of days that separate the growth stage differences (Table 1.3).

Table 1.3 | Change (%) in dry matter yield, change (%) in relative forage quality (RFQ), and change (number of days) in harvest date in relation to a common winter cereal harvest timing of swollen boot stage (Zadoks 45) for all barley, cereal rye, and triticale cultivars in MD and NY.

			Yield					RFQ					Harvest date				
			Growth stage (Zadoks)					Growth stage (Zadoks)					Growth stage (Zadoks)				
State	Species	Cultivar	39	45	51	57	63	39	45	51	57	63	39	45	51	57	63
			Change (%)					Change (%)					Change (day)				
MD	Barley	P-919	-27	–[*]	31	67	107	4	–	-4	-8	-12	-3	–	2	4	6
		Thoroughbred	-26	–	30	64	103	4	–	-4	-8	-12	-3	–	2	5	7
		Valor	-26	–	29	63	99	4	–	-4	-8	-12	-3	–	2	5	7
		Verdant	-29	–	34	73	117	4	–	-4	-7	-11	-4	–	3	6	8
	Cereal rye	Aroostook[†]	-24	–	27	57	89	12	–	-12	-23	-35	-4	–	4	9	14
		Huron	-28	–	33	71	113	12	–	-12	-24	-37	-4	–	3	7	11
		Lakeview VNS	-26	–	29	63	100	12	–	-12	-24	-36	-4	–	3	6	10
		Spooner	-26	–	29	63	99	13	–	-13	-25	-38	-4	–	3	5	9
	Triticale	NE426GT	-26	–	30	65	103	10	–	-10	-19	-29	-4	–	3	6	9
		TriCal 718	-30	–	35	75	120	11	–	-11	-22	-33	-4	–	3	7	10
		TriCal 815	-25	–	28	59	94	9	–	-9	-19	-28	-3	–	3	5	8
		TriMark 099	-27	–	32	68	109	9	–	-9	-17	-26	-4	–	3	6	9
NY	Barley	P-919	-29	–	34	74	118	4	–	-4	-7	-11	-3	–	3	5	7
		Thoroughbred	-28	–	32	68	109	3	–	-3	-6	-9	-3	–	3	5	7
		Valor	-25	–	29	61	98	4	–	-4	-7	-11	-3	–	2	4	6
		Verdant	-29	–	34	74	119	4	–	-4	-9	-13	-3	–	2	5	7
	Cereal rye	Aroostook	-35	–	42	91	147	12	–	-12	-23	-35	-3	–	3	7	12
		Huron	-32	–	37	81	130	12	–	-12	-24	-36	-4	–	3	6	10
		Lakeview VNS	-33	–	40	86	139	12	–	-12	-24	-36	-3	–	3	6	10
		Spooner	-38	–	48	105	171	14	–	-14	-27	-41	-4	–	3	7	12
	Triticale	NE426GT	-30	–	36	77	124	10	–	-10	-20	-30	-3	–	3	6	11
		TriCal 718	-41	–	52	116	191	13	–	-13	-26	-39	-5	–	4	7	11
		TriCal 815	-32	–	38	82	132	11	–	-11	-22	-33	-4	–	3	6	11
		TriMark 099	-34	–	41	90	146	10	–	-10	-19	-29	-3	–	3	6	11

[*] Swollen boot stage (Zadoks 45) is the reference growth stage from which all differences (change (%) in yield, change (%) in RFQ, and change (day) in harvest date) are calculated. As such, an en-dash (–) indicates no change.

[†] A three-parameter logistic model was used to describe the relationship between ordinal day and growth stage (Zadoks) for 'Aroostook' cereal rye in MD; this relationship was described with four-parameter logistic models for all other cultivars in MD and NY.

Prior to the yield plateau that is reached at advanced maturity, harvesting winter cereals at earlier growth stages results in lower yields and higher quality. Harvesting when the flag leaf ligule became visible, which occurred 3–5 days earlier than swollen boot stage, resulted in 27, 30, and 31% lower mean yields and 4, 12, and 10% greater mean RFQ for barley, cereal rye, and triticale cultivars, respectively, across sites. Given that all twelve cultivars at swollen boot stage maintained RFQ in excess of 160, which is the upper value of the required RFQ range for the most demanding cattle (group I, Figure 1.3), the trade-off with yield and timing might be undesirable for most farmers. However, a 27–31% yield reduction to gain an excessive or unnecessary 4–12% improvement in RFQ and 3–5 days for the following growing season (e.g., corn silage or sorghum) might appear more favorable if using those additional days for the subsequent crop resulted in greater yield and quality gains than the winter cereal yield loss. It is also worth noting that the spring is a particularly busy time of year for dairy farmers, and pre-boot harvesting might be preferred if a farmer is unlikely to harvest the winter cereal crop at swollen boot stage (or shortly thereafter) due to other farm tasks or projected weather impediments.

Delaying harvest 2–4 days until the tip of the ear becomes visible (i.e., a 6-stage delay to Zadoks 51) resulted in similar values for gains and losses as harvesting 3–5 days (6 growth stages) earlier, except inverted: at Zadoks 51, mean yields were 32–37% greater and mean RFQ was 4–12% lower across species and sites (Table 1.3). If harvest is delayed 6–14 days past swollen boot stage until the winter cereal crop reached quarter-complete anthesis (i.e., an 18-stage delay to Zadoks 63), mean yield gains would more than double at 109, 124, and 127% and mean RFQ would decrease by 11, 37, and 31% for barley, cereal rye, and triticale, respectively (Table 1.3). Across all barley cultivars, RFQ remains high enough to feed lactating cows in their first trimester or dairy calves (cattle group I) at quarter-complete anthesis, making the mean 109% increase in yield particularly attractive. Notably, barley cultivars reach quarter-complete anthesis in 6–8 days after swollen boot stage, which is quicker than cereal rye (9–14 days) and triticale (8–11 days). Still, barley cultivars were the lowest-yielding cultivars in the experiment (Figure 1.2).

Cereal rye and triticale cultivars exhibited large yield gains of 124 and 127%, respectively, when harvest was delayed until quarter-complete anthesis (Table 1.3). The trade-off with RFQ, however, was substantial with a 37% decline for cereal rye and a 31% decline for triticale compared with RFQ at swollen boot stage. Unlike the barley cultivars, none of the cereal rye and triticale cultivars maintained high enough RFQ at quarter-complete anthesis to meet the nutritional demands of cattle group I (140–160 RFQ). Instead, the RFQ at this later growth stage ranged from 93–106 for the cereal rye cultivars and 89–123 for the triticale cultivars across sites (Figure 1.3). Only 'Lakeview VNS' maintained >100 RFQ in both MD and NY at quarter-complete anthesis (9–14 days post-boot) among the cereal rye cultivars, whereas all triticale cultivars, except 'TriCal 718' in NY, met the nutritional demands of cattle group III (115–130 RFQ) or IV (100–120 RFQ) at the same growth stage (8–11 days post-boot).

At the cultivar level, the trade-off between yield and quality across growth stages is demonstrated by 'TriCal 718' triticale in NY. This cultivar produced over 9 Mg DM ha^{-1} at quarter-complete anthesis, which was more than all other cultivars ($p \leq 0.06$). At this growth stage, however, 'TriCal 718' exhibited a RFQ of 89, which was lower than all other triticale cultivars ($p \leq 0.06$), all barley cultivars ($p < 0.0001$), and no different from the cereal rye cultivars ($p \geq 0.2$).

1.4.5 Conclusion

This experiment has shown that while barley cultivars maintain higher RFQ than cereal rye and triticale, yield was substantially lower. With RFQ ranging from 144–166 at swollen boot stage across cultivars and sites, cereal rye was a strong candidate for obtaining a balance between yield and quality early in the season. Although the RFQ of cereal rye decreased quickly at growth stages beyond booting, the rate of decline for cereal rye cultivars (-2.8 to -3.5 RFQ per growth stage) was similar to triticale cultivars (-2.4 to -3.2 RFQ per growth stage). The yield potential for triticale was similar to cereal rye, but three of the four triticale cultivars produced more biomass at swollen boot stage than the barley cultivars. As with cereal rye, the RFQ of triticale declined more rapidly than barley. At later growth stages, however, triticale generally exhibited greater RFQ than cereal rye; this higher quality might provide the benefit of a slightly longer “harvest window” to obtain forage that is nutritionally suitable for multiple cattle groups. Overall, our results show that cereal rye cultivars are recommended if early harvest is the priority, triticale cultivars are recommended for farmers who seek greater flexibility in their harvest schedules, and barley cultivars are generally not recommended in more northern regions due to lower yields and lower cold tolerance.

To improve the performance of forage double-cropping systems for dairy farmers in the Northeast, numerous research pathways—focused on breeding, crop diversification and ecosystem services, and whole-system assessment—should be pursued, ideally in concert with one another. Genetic improvements to barley cold tolerance, which could indirectly improve yield potential, would be of great value to dairy farmers in more northern regions of the US given the sustained, high RFQ of barley cultivars. More research is needed on fall-planted mixtures of winter cereal species (e.g., Juskiw et al., 2000) and mixtures of winter cereals and legumes for spring-harvested forage (e.g., Carr et al., 2004; Lauriault and Kirksey, 2004). Continued research on summer annual forages that can serve as alternatives to corn silage will also be critical for providing farmers with more options for diversifying their cropping system (e.g., Lyons et al., 2019). The effect of grazing (Drewnoski et al., 2018) or harvesting (Blanco-Canqui et al., 2021) winter cereals, compared with incorporating or creating a mulch with the plant residue, is also under-researched as it relates to the delivery of various ecosystem services. To encourage the adoption of these systems, comparing the combined agronomic, environmental, and economic value—in total yield, quality, and ecosystem services—of double-cropping with single cropping is an effective approach (e.g., see Brown, 2006; Heggenstaller et al., 2008, 2009; Fouli et al., 2012; Jemison et al., 2012; Ketterings et al., 2015).

In the Northeast, winter cereals can serve as important sources of high-quality forage when feed inventories are low or when extreme weather events have disrupted feed and forage production in other regions of the US, causing feed shortages. Greater home-grown double-cropping forage production can reduce the environmental and economic costs associated with feed imports, help relocalize nutrient cycles, provide more opportunities for judiciously applying dairy manure, and increase both crop and non-crop biodiversity. With timely management, dairy farmers can synchronize winter cereal harvest with the specific nutritional requirements of the cattle on their farms.

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CHAPTER 2

TRITICALE PERFORMS AS WELL AS CEREAL RYE ACROSS COVER CROP TERMINATION DATES IN NO-TILL PLANTED SOYBEAN

2.1 ABSTRACT

Agroecosystem redesign is an important step towards transformative change in the agri-food system, whereby farmers ecologically reshape their operations using agroecological practices; however, support for such knowledge-intensive management is lacking. We conducted a field experiment in Maryland and New York to assess the effect of cover crop cultivar selection and cover crop termination-soybean [*Glycine max* (L.) Merr.] planting (roll-plant) date on cover crop growth stage, biomass, and reseeding; weed biomass; and soybean density and yield in organically managed no-till planted soybean production. Twelve winter cereal cultivars—four each for barley (*Hordeum vulgare* L.), cereal rye (*Secale cereale* L.), and triticale (× *Triticosecale* Wittm. ex A. Camus.)—were seeded at equivalent rates and terminated at four roll-plant dates. Although many cover crop cultivars had not yet reached the recommended growth stage for adequate termination (anthesis, Zadoks 60) at the earlier roll-plant dates, we observed greater soybean yields than at later dates and similar cover crop reseeding. Weed biomass was low across treatments despite cover crop biomass production below the recommended threshold of 8 Mg ha^{-1}, suggesting this threshold should be reevaluated for greater context-specificity. The effect of cultivar was often inconsistent, but differences among species indicated that triticale performed as well as cereal rye in terms of biomass production, weed suppression, and soybean yield. Our results show that triticale is a viable option for these cover crop-based systems, which provides farmers with another option to diversify their operations.

2.2 INTRODUCTION

Calls to redesign agroecosystems, as part of a strategy to improve the sustainability of agriculture and food systems more broadly, have suggested that farmers use agroecological practices to make transformative on-farm changes (Gliessman, 2016; Wezel et al., 2020). The implementation of agroecological practices, however, is not prescriptive. As such, there remains a need to provide more technical information to help farmers successfully redesign their agroecosystems, especially given that the redesign process relies on the concurrent use of many knowledge-intensive practices. Here, we describe an alternative approach to soybean [*Glycine max* (L.) Merr.] production that integrates both reduced tillage and cover cropping as agroecological practices. When used in concert with a more diverse crop rotation, this approach to soybean production can serve as a catalyst for agroecosystem redesign.

In organic no-till planted soybean production, winter cereal cover crops are typically rolled at anthesis to ensure adequate termination, and soybean is planted on the same day that rolling occurs (Mirsky et al., 2009). Although this approach can be effective for both cover crop and weed management, it delays soybean planting, which can limit yield potential (particularly in more northern regions) (Bastidas et al., 2008; Coulter et al., 2011). If winter cereal cover crops are terminated prior to anthesis, plants that survive the termination event (e.g., rolling or via other methods) can compete with soybean for light, nutrients, and water (Westgate and Singer, 2005). These cover crops can also produce viable seed that have the potential to become a weed in the subsequent crop in rotation (Keene et al., 2017); this can be a similar challenge when cover crop termination is delayed until after anthesis and viable seed is produced. Double-rolling winter cereal cover crops has the potential to improve termination when rolling occurs before anthesis (Keene et al., 2017; Champagne et al., 2021), and earlier rolling increases the length of the soybean growing season, thereby enhancing the yield potential.

Performance of this soybean production method is promising (Bernstein et al., 2014; Wallace et al., 2017; Vincent-Caboud et al., 2019a), but further optimization is required before farmer adoption is likely to increase. Previous work on cover crop management for no-till planted soybean has tended to focus on maximizing cereal rye (*Secale cereale* L.) biomass through seeding rate (Boyd et al., 2009; Ryan et al., 2011a), planting and termination date (Mirsky et al., 2011; Ryan et al., 2011a; Nord et al., 2012; Keene et al., 2017), and soil fertility (Ryan et al., 2011a; Mirsky et al., 2012, 2013). Cereal rye has frequently been used in this research because it produces a lot of biomass, matures relatively early in the spring, exhibits allelopathy, demonstrates good winter-hardiness, and the seed is widely available and often inexpensive (Bernstein et al., 2011; Ryan et al., 2011b; Reberg-Horton et al., 2012; Silva, 2014; Haramoto, 2019; Vincent-Caboud et al., 2019a, 2019b). There are, however, some drawbacks associated with such high biomass production, such as cover crop lodging (Liebert et al., 2017; Wallace et al., 2017); poor soybean seed placement through an excessively thick layer of mulch (Wagner-Riddle et al., 1994; De Bruin et al., 2005; Liebert et al., 2017); depleted soil moisture, which can inhibit soybean germination and reduce yield (Liebl et al., 1992; De Bruin et al., 2005; Wells et al., 2016); and greater soybean lodging (Smith et al., 2011).

Limited research has been conducted on the use of different winter cereal species (Liebert et al., 2017) and cultivars (Wells et al., 2016) in no-till planted soybean systems. Compared to cereal rye, barley (*Hordeum vulgare* L.) and triticale (× *Triticosecale* Wittm. ex A. Camus.) exhibit differences across a range of characteristics, some of which may or may not be advantageous for cover crop-based no-till planted organic soybean production. For example, barley is not as winter-hardy (cold tolerant) as cereal rye (Fowler and Carles, 1979), but it matures earlier in the spring, which might enable earlier termination (i.e., rolling) and soybean planting, potentially resulting in greater soybean yields. In contrast, triticale matures more slowly than cereal rye, reaching anthesis later in the spring, which might lead to more incomplete termination and greater reseeding the following spring (Keene et al., 2017). Differences in maturation timing, among other traits, provide opportunities to compare cereal rye with barley and triticale and identify trade-offs associated with cover crop species, and cultivar, selection.

We conducted an experiment to quantify soybean yield across a range of winter cereal cover crop species, cultivars, and cover crop termination (and thus, soybean planting) dates. Broadly, our objective was to assess the trade-offs among cover crop biomass, weed biomass, soybean yield, and cover crop reseeding that are associated with double-rolling cover crops before, during, and after anthesis. To this end, we evaluated three winter cereal cover crop species—barley, cereal rye, and triticale—and four cultivars of each species to determine the effect of species and cultivar selection on cover crop growth stage, cover crop biomass production, weed suppression, soybean density, soybean yield, and cover crop reseeding when double-rolled at four different dates.

2.3 METHODS

2.3.1 Site description

Our experiment was conducted in New York and Maryland, United States (US), in 2014 and 2015, comprising three site-years: NY 2014 (Aurora, NY; 42° 43’ 54.4” N, 76° 39’ 02.6” W), NY 2015 (Aurora, NY; 42° 44’ 13.2” N, 76° 39’ 18.1” W), and MD 2015 (Beltsville, MD, 39° 1’ N, 76° 55’ W). In NY, the experiment was carried out in different fields in 2014 and 2015. The primary soil type at both NY field sites is a moderately well-drained, calcareous Lima silt loam (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs), with partial tile drainage. In MD, the primary soil type at the field site is a Codorus-Hatboro silt loam (fine-loamy, mixed, active, mesic, Fluvaquentic Dystrudepts and Endoaqueptsz). Soil organic matter was higher in both NY site-years at 2.9% in 2014 and 3.0% in 2015 compared with 1.7% in MD. Soil pH was also higher in NY at 7.7 in 2014 and 7.5 in 2015 compared with 5.7 in MD.

The NY field sites are located in USDA plant hardiness zone 6a, whereas the MD site is in zone 7a (USDA-ARS, 2012). No irrigation was used in this experiment. In most site-years during soybean planting months (May or June), the field locations received more precipitation than the long-term mean, while mean monthly temperatures were similar to the long-term mean across site-years (Figure 2.1).

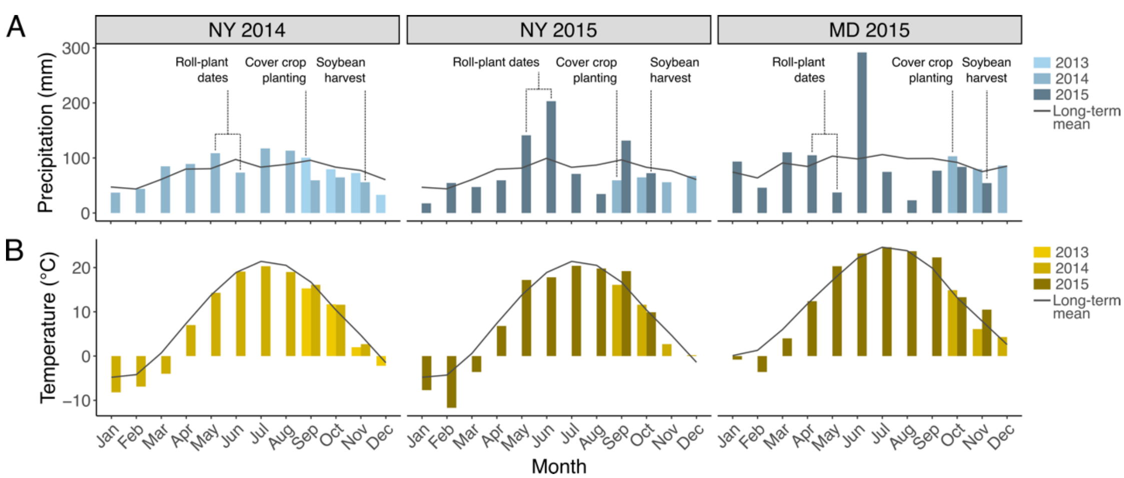

Figure 2.1 | (A) Total monthly precipitation (mm) and (B) mean monthly temperature (°C) from 2013–2014 for NY 2014, and 2014-2015 for NY 2015 and MD 2015. The long-term mean represents the average total monthly precipitation or mean monthly temperature beginning with the earliest year of recorded precipitation and temperature data for the given weather station each site-year: 1956 to 2014 for NY 2014 or 1956 to 2015 for NY 2015 and MD 2015 (Northeast Regional Climate Center, 2021).

In both NY and MD, the field sites were under long-term conventional grain crop production prior to the experiment. The preceding crop was corn (*Zea mays* L.) in NY 2014, sorghum [*Sorghum bicolor* (L.) Moench] in NY 2015, and wheat (*Triticum* *aestivum* L.) in MD. Our experiment was managed organically throughout each site-year.

2.3.2 Experimental design

A split-block design was used for this experiment. Twelve cover crop cultivars were arranged in a randomized complete block design with four replicates (blocks). Four roll-plant dates were laid perpendicularly across the twelve cover crop cultivars in each block, also in a randomized complete block design. At the interaction level, there were 48 experimental units (12 cultivars × 4 roll-plant dates) per block, or 192 experimental units per site-year. Each experimental unit, or plot, was 6.1 by 7.9 m in NY 2014, 6.1 by 6.1 m in NY 2015, 6.1 by 6.1 m in MD 2015.

The number of cultivars included in the experiment were equally distributed across three species—barley, cereal rye, and triticale—with four cultivars per species. The barley cultivars were ‘Verdant,’ ‘Valor,’ ‘P-919,’ and ‘McGregor.’ In 2015, ‘McGregor’ was not available and was replaced by ‘Thoroughbred’ in NY and MD. The cereal rye cultivars were ‘Huron,’ ‘Spooner,’ ‘Aroostook,’ and a variety-not-stated (VNS) cultivar from Lakeview Organic Grains in Penn Yan, NY, which will be referred to as ‘Lakeview VNS’ here. The triticale cultivars were ‘TriCal 718,’ ‘TriCal 815,’ ‘NE426GT,’ and ‘TriMark 099.’

The four roll-plant dates have been designated as Early, Early-mid, Mid-late, and Late, representing approximately one-week (four- to seven-day) intervals spanning mid-May to mid-June in NY and late-April to late-May in MD (Table 2.1).

Table 2.1 | Dates of major field operations (cover crop planting, cover crop rolling, soybean planting, and soybean harvest) and sampling (cover crop biomass, weed biomass, and soybean density) in NY 2014, NY 2015, and MD 2015.

Site-year	Date treatment	Cover crop planting	First roll and cover crop biomass sampling	Second roll and soybean planting	Weed biomass sampling and soybean population counts	Soybean harvest
NY 2014	Early	30 Sept. 2013	27 May 2014	31 May 2014	12 Sept. 2014	5 Nov. 2014
	Early-mid		31 May 2014	4 June 2014		
	Mid-late		4 June 2014	8 June 2014		
	Late		8 June 2014	12 June 2014		
NY 2015	Early	19 Sept. 2014	15 May 2015	22 May 2015	10-11 Sept. 2015	15 Oct. 2015 and 19 Oct. 2015
	Early-mid		22 May 2015	29 May 2015		
	Mid-late		29 May 2015	5 June 2015		
	Late		5 June 2015	12 June 2015		
MD 2015	Early	2 Oct. 2014	28 April 2015	7 May 2015	24-27 Aug. 2015	17-18 Nov. 2015
	Early-mid		6 May 2015	14 May 2015		
	Mid-late		13 May 2015	21 May 2015		
	Late		20 May 2015	27 May 2015		

2.3.3 Field operations and sampling protocols

In preparation for planting the cover crops, poultry litter (5–4–3, N–P_2O_5–K_2O) was broadcast-applied with a box-spreader at 56 kg total N ha^{-1} in NY 2014 and at 67 kg total N ha^{-1} in NY 2015. A higher rate of poultry litter was applied in 2015 based on visual observations of N-deficient sorghum, the preceding crop. Poultry litter was not applied in MD 2015. Cover crops were planted with 19-cm row spacing at a depth of 2.5 to 3.8 cm in September or October, depending on the site-year (Table 2.1). As 'Aroostook' cereal rye has been shown to reach anthesis earlier while also producing high amounts of biomass compared with other cereal rye cultivars (Mirsky et al., 2009, 2011), it has become one of the most common cultivars used in cover crop-based no-till planted soybean research (Mischler et al., 2010; Reberg-Horton et al., 2012; Wallace et al., 2018; Haramoto, 2019; Menalled et al., 2021). For these reasons, it was used as the reference cultivar upon which all other cultivar seeding rates were based. The reference 'Aroostook' seeding rate was 94 kg ha^{-1} in NY 2014 and 126 kg ha^{-1} in NY 2015 and MD 2015. A lower seeding rate was used in NY 2014 due to equipment limitations. Planting equipment was recalibrated for each cultivar so that an equivalent number of seeds was planted (per hectare), thereby accounting for differences in seed size and mass among the cultivars (Table 2.2). To achieve a seeding rate equivalent to 'Aroostook' for the other 11 cultivars, rate-adjustment ratios ranged from 0.99 to 2.09. Ratios less than one represent seeds that had less mass (g seed^{-1}) and required lower seeding rates (kg ha^{-1}) than 'Aroostook,' and ratios greater than one represent seeds that had more mass and required higher seeding rates (Table 2.2).

Table 2.2 | Seed mass (g seed^{-1}) for all 12 winter cereal cover crop cultivars. Seeding rate adjustment ratios, relative to the 'Aroostook' cereal rye reference cultivar, and the adjusted seeding rates (kg ha^{-1}) were calculated based on the different seed masses among cultivars.

		NY 2014			NY and MD 2015		
Species	**Cultivar**	**Seed mass**	**Seeding rate adjustment ratio**	**Adjusted seeding rate**	**Seed mass**	**Seeding rate adjustment ratio**	**Adjusted seeding rate**
		g seed^{-1}	cultivar : Aroostook	kg ha^{-1}	g seed^{-1}	cultivar : Aroostook	kg ha^{-1}
Barley	Verdant	0.040	1.98	186	0.037	1.64	207
	Valor	0.030	1.48	139	0.029	1.26	158
	P-919	0.029	1.45	136	0.027	1.18	148
	McGregor§	0.040	1.99	187	0.033	1.45	183
Cereal rye	Huron	0.028	1.37	129	0.035	1.54	194
	Spooner	0.027	1.34	126	0.025	1.08	136
	Aroostook	**0.020**	**1.00**	**94**	**0.023**	**1.00**	**126**
	Lakeview VNS	0.028	1.41	132	0.022	0.99	124
Triticale	TriCal 815	0.029	1.44	135	0.038	1.67	210
	TriCal 718	0.042	2.09	197	0.041	1.82	229
	NE426GT	0.031	1.52	143	0.037	1.61	203
	TriMark 099	0.040	1.98	186	0.042	1.86	235

§ In 2015, 'McGregor' barley seed was not available. It was replaced with another barley cultivar, 'Thoroughbred,' in both NY and MD.

A single rolling-crimping event is typically adequate to terminate winter cereal cover crops when the rolling occurs at or beyond anthesis, which corresponds to a Zadoks growth stage of ≥60 (Mirsky et al, 2009). However, one of our research objectives was to evaluate whether certain species or cultivars performed better, in terms of weed suppression and subsequent soybean yield, at earlier roll-plant dates. The winter cereals were double-rolled to improve control (termination efficacy) of any cultivars that had not reached anthesis, which would be more likely at the earlier roll-plant dates. For consistency, all species and cultivars across all roll-plant dates were rolled twice with a 3-m-wide roller-crimper filled with water for extra weight.

On the same day as the first cover crop rolling event (Table 2.1), cover crop biomass was collected just prior to rolling. To determine aboveground cover crop biomass, plants were clipped at the soil surface within 0.5-m^2 quadrats, samples were oven-dried at 50°C for approximately one week, and then each sample was weighed. Approximately one week (four to seven days) after the first rolling date, the cover crops were rolled a second time, and soybean was no-till planted at a depth of 3.8 cm with 76-cm row spacing through the cover crop mulch on that same day (Table 2.1). As the soil was particularly dry and hard in June 2014 (dates Early-mid, Mid-late, and Late for NY 2014), 726 kg of additional weight was added to the no-till planter to achieve the desired planting depth. No additional weight was required at any of the roll-plant dates in 2015 in NY or MD. Organic feed-grade soybean cultivar 'Viking O.2265' (maturity group 2.2) was planted in NY 2014 and an organic dual-purpose cultivar from the same maturity group, 'Viking O.2299N,' was planted in NY 2015 and MD 2015 because the cultivar used in 2014 was not available. As a cultural weed management tactic, a high planting rate of 741,000 seed ha^{-1} was used at all site-years to hasten canopy closure (Place et al., 2009; Liebert and Ryan, 2017; Menalled et al., 2021).

Weed biomass samples were collected approximately 13 to 17 weeks after soybean planting (Table 2.1), just before several dominant weeds in the experiment reached physiological maturity in a given site-year. Dominance was assessed as the most visually abundant species. Weeds were clipped at the soil surface within a 0.5-m^2 quadrat and separated according to dominant species: common ragweed (*Ambrosia artemisiifolia* L.) and all other weed species in NY 2014 and NY 2015, and giant foxtail (*Setaria faberi* Herrm.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and all other weed species in MD 2015. Weed biomass samples were dried and weighed as described for the cover crop samples. Soybean density was assessed by counting individual plants within a 0.5-m^2 quadrat on the same day that weed biomass samples were collected (Table 2.1). Soybean yield was determined by harvesting mature plants in the fall of 2014 and 2015 (Table 2.1) with a two-row plot combine and adjusting grain moisture to 13% in all site-years. In April 2016, cover crop reseeding from the cover crops rolled in NY 2015 and MD 2015 was assessed by visual estimates of percent ground cover. We did not conduct visual assessments of ground cover in spring 2015 for the NY 2014 site-year.

2.3.4 Statistical analyses

All analyses were performed using R version 4.0.5 (R Core Team, 2021). Linear mixed-effects models (‘lme4’ package: Bates et al., 2015) and analysis of variance (‘lmerTest’ package: Kuznetsova et al., 2017) were used to test relationships among roll-plant dates (4 levels: Early, Early-mid, Mid-late, and Late) and cover crop cultivars (12 levels: ‘Verdant’ through ‘TriMark 099’) as categorical predictors for six response variables: cover crop growth stage (Zadoks, 0–100), cover crop biomass (Mg ha^{-1}), weed biomass (Mg ha^{-1}), soybean density (plant ha^{-1}), soybean yield (Mg ha^{-1}), and cover crop reseeding (% cover). The interaction between roll-plant date and cover crop cultivar was tested in each model, along with the main effect of each predictor. Separate models were run for each site-year and response. The random effect structure in these models reflect the split-block research design, with block, roll-plant date nested in block, and cover crop species or cultivar nested in block as random effects. For the linear mixed-effects models, we present marginal coefficient of determination (R^2) and conditional R^2 (Nakagawa and Schielzeth, 2013), which represent variance explained by the fixed effects only and variance explained by both fixed and random effects, respectively (‘MuMIn’ package: Bartoń, 2020).

Regression diagnostics were used to evaluate model assumptions of constant variance among residuals (homoscedasticity) and normal distribution of the residuals (normality). These assumptions were assessed by plotting the conditional studentized residuals versus the fitted values and a normal quantile plot of raw conditional residuals, respectively (‘redres’ package: Goode et al., 2021). Normal quantile plots for each of the random effects were also produced to visually assess their distribution. Diagnostic plots (such as Cook’s distance and plotting residuals against leverage) were also used to investigate whether there were any outliers or influential observations (‘car’ package: Fox and Weisberg, 2019). As the residuals for weed biomass were severely heteroscedastic and non-normal, the response was log-transformed. The lowest nonzero value of weed biomass differed from one by more than an order of magnitude, so we did not add a constant of one to the data before the log transformation as that is known to compress the low end of the scale (McCune et al., 2002). Instead, we used a generalized procedure to better preserve the original order of magnitudes in the data and retain values of zero when the initial values were zero (McCune et al., 2002). Given that min(x) is the smallest nonzero value in the data; int(x) is a function that truncates x to an integer; c is an order of magnitude constant, which is equivalent to int(log(min(x)); and d is the decimal constant, which is equivalent to $\log^{-1}(c)$, then the transformation is

$$b_y = log\left(x_y + d\right), \quad [1]$$

where x_y is the original value from the data set and b_y represents the adjusted value that replaces x_y (McCune et al., 2002). As a modification from the procedure described by McCune et al al. (2002), the constant (c) was not subtracted from the transformation, which allowed us to back-transform the estimated marginal means to the original response scale ('emmeans' package: Lenth, 2021).

Estimated marginal means of the factor levels for the categorical predictors, roll-plant date and cover crop cultivar, were obtained and compared with a Tukey's honest significant difference (HSD) test ('emmeans' package: Lenth, 2021), thereby correcting for the family-wise error rate. For all linear mixed-effects models, custom contrasts were built to test for differences among cover crop species (barley, cereal rye, and triticale). Specific factor level means were pulled out to create vectors with a one assigned to the factor level mean of interest and a zero to all other factor levels. In this way, vectors could be combined and averaged: barley comprises 'Verdant,' 'Valor,' 'P-919,' and 'McGregor' or 'Thoroughbred;' cereal rye comprises 'Huron,' 'Spooner,' 'Aroostook,' and 'Lakeview VNS;' and triticale comprises 'TriCal 815,' 'TriCal 718,' 'NE426GT,' and 'TriMark 099.' Then, differences in the mean response of the custom groups (i.e., species) were assessed.

2.4 RESULTS AND DISCUSSION

2.4.1 Cover crop growth stage

An interaction between roll-plant date and cover crop species was observed in NY 2014 ($p = 0.004$), NY 2015 ($p < 0.0001$), and MD 2015 ($p < 0.0001$) (Table 2.3). Across site-years, cover crop growth stage generally increased as termination date advanced, but the mean increase in growth stage varied by cultivar across the roll-plant dates (Supplementary Table B1).

Table 2.3 | The effect of roll-plant date (Early, Early-mid, Mid-late, and Late dates) and cover crop cultivar (four cultivars per species) on cover crop growth stage (Zadoks), cover crop biomass (Mg ha^{-1}), weed biomass (Mg ha^{-1}), soybean density (plant ha^{-1}), soybean yield (Mg ha^{-1}), and cover crop reseeding (% cover). An analysis of variance was conducted for each linear mixed-effects model, and the marginal and conditional coefficient of determination are presented. Estimated marginal means for the main effects, including the average cultivar effect (i.e., species), were compared with a Tukey's HSD test.

		Cover crop growth stage			Cover crop biomass			Weed biomass*			Soybean population			Soybean yield			Cover crop reseeding		
		Site-year			Site-year			Site-year			Site-year			Site-year			Site-year		
	Predictor	NY 2014	NY 2015	MD 2015	NY 2014	NY 2015	MD 2015	NY 2014	NY 2015	MD 2015	NY 2014	NY 2015	MD 2015	NY 2014	NY 2015	MD 2015	NY 2014	NY 2015	MD 2015
			p-value			*p*-value			*p*-value			*p*-value			*p*-value			*p*-value	
	Date	<0.0001	<0.0001	<0.0001	0.0004	<0.0001	<0.0001	0.0114	0.0071	0.1202	<0.0001	0.0003	<0.0001	0.0019	0.0010	0.0006	—	0.4527	0.0209
	Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0097	<0.0001	0.0005	0.0178	0.5235	0.6498	0.6078	0.0302	0.0005	0.2117	—	0.0008	<0.0001
	Date × Cultivar	<0.0001†	<0.0001	<0.0001	0.1516	0.5655	0.9058	0.2601	0.1255	0.1803	0.8223	0.6960	0.6672	0.0164	0.7694	0.4703	—	0.4514	0.0008
	Marginal R^2	0.843	0.964	0.989	0.611	0.739	0.661	0.492	0.403	0.317	0.531	0.361	0.289	0.444	0.456	0.244	—	0.314	0.597
	Conditional R^2	0.859	0.971	0.991	0.808	0.803	0.773	0.576	0.524	0.584	0.657	0.413	0.338	0.718	0.761	0.862	—	0.559	0.825
			Zadoks			Mg ha^{-1}			Mg ha^{-1}			plant ha^{-1}			Mg ha^{-1}			Cover (%)	
	Date																		
	Early	53 -‡	44 -	36 -	2.30 b	3.33 c	2.94 d	0.56 ab	0.02 b	0.27	560,965 a	536,954 a	614,785 b	2.79 -	3.13 a	4.42 a	—	10	24 -
	Early-mid	58 -	54 -	55 -	2.61 b	3.63 c	3.89 c	0.45 b	0.01 b	0.35	689,718 a	633,415 a	638,797 b	2.75 -	3.27 a	4.27 a	—	10	18 -
	Mid-late	64 -	70 -	66 -	3.30 a	5.95 b	4.92 b	0.47 b	0.05 ab	0.72	613,129 a	616,027 a	595,741 b	2.64 -	3.06 a	3.60 b	—	8	15 -
	Late	72 -	75 -	77 -	3.63 a	7.50 a	5.76 a	0.85 a	0.13 a	0.27	233,568 b	418,136 b	705,864 a	2.18 -	2.54 b	3.39 b	—	9	18 -
	Cultivar																		
Barley	Verdant	44 -	57 -	58 -	1.40 b	3.82 c	4.03	0.51 bc	0.03 abc	0.15	604,849	597,397	657,012	2.85 -	3.22 ab	4.41	—	9 abc	22 -
	Valor	66 -	67 -	62 -	1.71 b	4.26 bc	3.83	1.01 a	0.16 ab	1.14	574,298	578,767	653,287	2.30 -	2.68 c	3.76	—	12 ab	32 -
	P-919	71 -	70 -	64 -	2.31 b	4.55 bc	4.02	1.05 a	0.14 ab	1.22	557,653	553,927	623,479	2.34 -	2.71 bc	2.93	—	9 abc	38 -
	McGregor¶	61 -	64 -	63 -	1.50 b	3.75 c	3.81	0.99 a	0.47 a	1.18	573,799	570,073	665,706	2.53 -	2.68 c	2.91	—	7 bc	24 -
Cereal rye	Huron	66 -	61 -	56 -	3.89 a	5.63 ab	4.40	0.49 bc	0.03 abc	0.31	485,618	522,878	663,222	2.82 -	3.05 abc	4.78	—	6 c	2 -
	Spooner	65 -	63 -	58 -	3.53 a	6.03 a	4.34	0.64 ab	0.02 abc	0.43	535,298	495,554	627,205	2.49 -	3.12 abc	4.24	—	9 abc	12 -
	Aroostook	66 -	66 -	67 -	3.67 a	5.41 ab	5.04	0.58 abc	0.03 abc	0.47	521,359	529,088	625,963	2.57 -	2.97 abc	4.47	—	12 ab	33 -
	Lakeview VNS	64 -	63 -	59 -	3.55 a	6.32 a	4.99	0.59 ab	0.01 bc	0.10	500,522	525,362	618,511	2.57 -	2.95 abc	4.30	—	7 bc	2 -
Triticale	TriCal 815	59 -	55 -	54 -	3.41 a	5.39 ab	4.92	0.30 cd	0.00 c	0.12	465,746	589,945	619,753	2.72 -	3.30 a	3.77	—	12 abc	11 -
	TriCal 718	56 -	52 -	53 -	3.52 a	4.91 abc	4.66	0.58 abc	0.04 abc	0.31	435,938	546,476	639,625	2.59 -	2.98 abc	3.39	—	8 abc	25 -
	NE426GT	62 -	57 -	55 -	3.51 a	5.57 ab	4.31	0.49 bc	0.05 abc	0.26	511,700	543,992	658,254	2.57 -	3.07 abc	3.95	—	13 a	10 -
	TriMark 099	62 -	57 -	55 -	3.51 a	5.61 ab	4.17	0.21 d	0.00 c	0.38	525,362	560,137	613,543	2.74 -	3.30 a	4.12	—	12 ab	10 -
	Species																		
	Barley	60 -	64 -	62 -	1.73 b	4.09 b	3.92 b	0.86 a	0.13 a	0.71	578,905	575,041	649,871	2.51 -	2.82	3.51	—	9 ab	29 -
	Cereal rye	65 -	63 -	60 -	3.66 a	5.86 a	4.69 a	0.57 ab	0.02 b	0.28	511,038	560,137	633,725	2.61 -	3.02	4.45	—	8 b	12 -
	Triticale	60 -	55 -	54 -	3.49 a	5.37 a	4.52 a	0.36 b	0.01 b	0.25	484,686	518,220	632,794	2.65 -	3.16	3.81	—	11 a	14 -

* The response, weed biomass, has been log-transformed for these linear mixed-effects models, and the estimated marginal means for weed biomass have been back-transformed from the log transformation. More detail about the log transformation is presented in the Methods.

† The interaction between date and cultivar had a significant effect on cover crop growth stage across all site-years, soybean yield in NY 2014, and cover crop reseeding in MD 2015. Comparing the estimated marginal means for the main effects (grey text) is misleading and not advised. Instead, refer to Supplementary Table B1 to see comparisons of the estimated marginal means among cultivars, within each roll-plant date.

‡ Different lowercase letters within the same site-year for a given predictor (date or cultivar) indicate differences ($p < 0.05$) among the estimated marginal means based on a Tukey's HSD test. The same *post hoc* means comparison has also been applied to the estimated marginal means for each of the three species, which represent the average of the four cultivars for a given species. No letters indicate no significant differences. A hyphen (-) indicates no means comparisons were conducted due to the presence of a significant ($p < 0.05$) interaction. An em dash (—) indicates no data were available for that site-year.

¶ In 2015, 'McGregor' barley seed was not available. It was replaced with another barley cultivar, 'Thoroughbred,' in both NY and MD.

Pooled over cultivar, cereal rye was more mature than barley and triticale at the Early date across all site-years. Barley, however, matured more quickly than both cereal rye and triticale at later rolling dates, surpassing the mean growth stage of triticale at the Mid-late date and both cereal rye and triticale at the Late date in 2015. The mean growth stage of barley was greater than triticale at the Late date in NY 2014 as well. Consistently, triticale did not reach a greater mean growth stage than barley or cereal rye across all dates and all site-years.

In NY 2014, cereal rye reached anthesis (Zadoks 60 or above) at the Early rolling date, whereas triticale and barley reached anthesis at the Early-mid rolling date (four days later) and the Mid-late rolling date (eight days later), respectively. In NY 2015, cereal rye again reached anthesis earlier than barley and triticale, this time at the Early-mid rolling date compared with the other two species at the Mid-late rolling date (seven days later). In MD 2015, barley reached anthesis earliest at the Early-mid rolling date, compared with both cereal rye and triticale at the Mid-late rolling date (seven days later).

Numerous studies have shown that physically terminating a winter cereal cover crop with a roller-crimper is increasingly effective between anthesis, Zadoks 60, and soft dough stage, Zadoks 85 (Mirsky et al., 2009, 2011, 2012; Wells et al., 2016). Rolling a cover crop prior to anthesis can result in incomplete termination, which can have implications for both weed biomass and soybean yield. In contrast, delaying termination until after anthesis can provide enough time for the winter cereal cover crop to produce viable seed, which can potentially contaminate the subsequent crop in rotation, essentially serving as a weed.

2.4.2 Cover crop biomass

As roll-plant date advanced, cover crop biomass increased across site-years (Table

2.3). From the Early to Late date, mean cover crop biomass increased 0.11 Mg ha^{-1} day^{-1} from 2.30 to 3.63 Mg ha^{-1} in NY 2014, 0.35 Mg ha^{-1} day^{-1} from 3.33 to 7.50 Mg ha^{-1} in NY 2015, and 0.24 Mg ha^{-1} day^{-1} from 2.94 to 5.76 Mg ha^{-1} in MD 2015. Mean cover crop biomass did not reach the recommended threshold of 8 Mg ha^{-1} (Teasdale and Mohler, 2000; Mirsky et al., 2012, 2013) at any of the roll-plant dates, nor with any of the cultivars, across site-years. When pooled over cultivars, barley produced 53 to 50%, 30 to 24%, and 16 to 13% less biomass than cereal rye and triticale in NY 2014, NY 2015, and MD 2015, respectively (Table 2.3). Cereal rye and triticale produced similar amounts of biomass, and none of the cultivars within or among species consistently produced the most or the least biomass across site-years. In addition to our own findings, other research has demonstrated that less than 8 Mg ha^{-1} of cover crop biomass can still provide adequate weed suppression. In another study conducted in the Northeast, barley produced 2.8 to 3.5 Mg ha^{-1} less biomass than cereal rye, depending on the termination date, yet weed biomass was not greater (Wallace et al., 2017).

Among the cultivars we assessed, some required substantially more seed—up to 2.09-times more—to achieve an equivalent seeding rate (kg ha^{-1}) to the reference cultivar, 'Aroostook' cereal rye (Table 2.2). The mean seed mass for the barley cultivars was 73 and 38%, 76 and 74%, and 37 and 20% greater than the 'Aroostook' cereal rye seed mass for barley, triticale, and the three other cereal rye cultivars in 2014 and 2015, respectively. Such differences can have economically significant ramifications, especially as the price per unit (i.e., bag of seed) can also vary a lot. For example, it cost $268 to seed 210 kg ha^{-1} of 'TriCal 815' triticale, which was the equivalent of seeding 126 kg ha^{-1} of 'Aroostook' cereal rye for just $97. Seed cost, however, is strongly affected by certification status (e.g., certified organic vs. untreated non-organic), and farmer demand and availability, among other market forces.

In an organic no-till planted soybean experiment conducted in the upper Midwestern US and Southern France, ‘Aroostook’ cereal rye and ‘NE426GT’ triticale produced similar amounts of biomass, but cereal rye provided greater weed suppression and was associated with greater soybean yields (Vincent-Caboud et al., 2019b). This result was broadly attributed to stronger allelopathy, better winter-hardiness, and earlier flowering (anthesis) in cereal rye. In our experiment, we did not observe differences in cover crop biomass, weed biomass, or soybean yield when comparing cereal rye and triticale species (pooled over cultivar) or individual cultivars (Table 2.3). Importantly, however, we used cultivar-specific seeding rates based on mass (Table 2.2). Vincent-Caboud et al. (2019) used a single seeding rate of 201.75 kg ha^{-1} for the cereal rye and triticale cultivars, which would have resulted in approximately 36% fewer seed ha^{-1}—a difference of over three million seeds—for ‘NE426GT’ triticale compared with ‘Aroostook’ cereal rye based on the mean seed masses for the same cultivars that we used for our mass-based seeding rates (Table 2.2). This discrepancy in seed mass (and size) between cereal rye and triticale and the resultant cover crop density might help explain why cereal rye was associated with lower weed biomass and higher soybean yields compared with triticale in the Vincent-Caboud et al. (2019) study. Notably, other research has shown that higher seeding rates, while not resulting in greater biomass, tend to decrease weed biomass (Boyd et al., 2009; Ryan et al., 2011a).

2.4.3 Weed biomass

Across site-years, weed biomass responded inconsistently to roll-plant date (Table 2.3). We observed an effect of roll-plant date in NY 2014 (p = 0.002), a marginal effect in NY 2015 (p = 0.06), and no effect in MD 2015 (p = 0.2). Mean weed biomass was lowest at the Early-mid (0.45 Mg ha^{-1}) and Mid-late (0.47 Mg ha^{-1}) dates in NY 2014, and at the Early (0.02 Mg ha^{-1}) and Early-mid (0.01 Mg ha^{-1}) dates in NY 2015. Cultivar selection, however, affected weed biomass across site-years ($p \leq 0.008$). In NY 2014, triticale cultivar 'TriMark 099' was associated with the lowest mean weed biomass at 0.21 Mg ha^{-1} across roll-plant dates (Table 2.3). 'TriMark 099' performed well again in NY 2015, though eight other cultivars also provided similar weed suppression that year. Although the overall effect of cultivar was significant in MD 2015 (Table 2.3), differences among cultivars were not detected after applying the Tukey's HSD *p*-value adjustment (Table 2.3).

Pooled over cultivar, cereal rye and triticale were the most weed suppressive in both years in NY, although weed biomass was similar for cereal rye and barley in NY 2014 (Table 2.3). Weed biomass associated with cereal rye and triticale was 33 to 58%, 85 to 90%, and 60 to 65% lower than barley in NY 2014, NY 2015, and MD 2015, respectively (Table 2.3).

As other researchers have discussed, enhancing the weed suppressive ability of winter cereal cover crops involves more than simply manipulating management practices to maximize biomass production (Ryan et al., 2011a; Mirsky et al., 2013; Wortman et al., 2013; Halde and Entz, 2016). Although some researchers have found that allelopathy is a contributing mechanism for the weed suppressive ability of cereal rye (Reberg-Horton et al., 2005; Schulz et al., 2013; Boselli et al., 2021), a similar explanation is not typically assigned to observations of barley and triticale cultivars achieving similar weed suppression to cereal rye (Wallace et al., 2017), sometimes at lower amounts of cover crop biomass (Table 2.3). Numerous characteristics of winter cereal cover crop species that might help explain differences in weed suppressive ability, such as specific leaf area as it relates to light interception and mulch decay as it relates to physical and biochemical weed suppression, require more research. A functional trait-based approach appears promising in this regard (Gaba et al., 2014; Storkey et al., 2015; Wood et al., 2015). In addition to cover crop considerations, optimizing weed management in organic no-till planted soybean production also involves soybean cultural practices.

2.4.4 Soybean density

Roll-plant date affected soybean density across site-years ($p \leq 0.0003$), while cultivar did not ($p \geq 0.5$). A substantially lower soybean density was observed at the Late roll-plant date, compared with the three earlier dates, in NY 2014 and 2015 (Table 2.3). Compared to the collective mean soybean density for the Early, Early-mid, and Mid-late dates together (as there were no differences among them), the soybean density at the Late date was 62 and 30% lower in NY 2014 and NY 2015, respectively. Although the soybean density at the first three dates were also similar in MD 2015, comparing the collective Early, Early-mid, and Mid-late mean with the Late date mean exhibited the opposite relationship: the mean number of soybean plant ha^{-1} increased by 15%. Cover crop species and cultivar selection did not affect soybean density across site-years. It is unclear why soybean density was so much lower at the Late date in both years in NY and higher in MD.

Soybean is a highly plastic crop with numerous compensatory mechanisms for maximizing seed production (i.e., yield). At lower within-row plant densities, soybean has been shown to maintain yield per unit area by producing a greater number of lateral branches, pods, and seeds per plant, among other forms of compensatory growth (Board, 2000; Cox et al., 2010). Still, research has shown that increasing soybean density well beyond planting rates recommended for tillage-based organic or conventional soybean production (Cox et al., 2019) can result in yield gains (Liebert and Ryan, 2017; Menalled et al., 2021).

The importance of soybean density on soybean yield is also partially explained by the role it plays in reducing weed biomass. It is well-established that higher (denser) plant populations result in earlier canopy closure, which can help suppress weeds via light interception and shading (Mohler, 1996; Weiner et al., 2001). The effectiveness of increasing soybean planting rates, and thus stand densities, to help suppress weeds has been demonstrated in other organic no-till planted soybean research. Both Liebert and Ryan (2017) and Menalled et al. (2021) observed greater weed suppression as soybean density increased. Also, as soybean yield increased asymptotically with increasing soybean density in both experiments, the higher seed costs associated with higher planting rates can potentially be offset by the price premium obtained for organic soybean, especially food-grade cultivars. Champagne et al. (2021) also found that moderate yield gains can offset additional input costs in these production systems due to organic price premiums.

2.4.5 Soybean yield

An interaction between roll-plant date and cultivar was observed for NY 2014 (p = 0.02), but not for NY 2015 (p = 0.8) or MD 2015 (p = 0.5) (Table 2.3). Interpreting the interaction for NY 2014, a difference between barley cultivar 'Valor' and triticale cultivar 'TriMark 099' was detected at the Late date (Supplementary Table B1). For 8 of the 12 cultivars in NY 2014, the Late date soybean yield was lower than the yield obtained at the Early date, which was the most common difference identified by the pairwise contrasts.

In 2015, roll-plant date affected soybean yield in NY (p = 0.001) and MD (p = 0.0006), whereas cultivar selection only had an effect in NY 2015 (p = 0.0005). Soybean yield decreased at later roll-plant dates in both NY and MD 2015 (Table 2.3). In NY 2015, triticale cultivars 'TriCal 815' and 'TriMark 099' resulted in greater soybean yields than barley cultivars ‘Valor,’ ‘P-919,’ and ‘Thoroughbred;’ otherwise, most other cultivars were associated with soybean yields that did not differ from each other (Table 2.3). We did not observe an effect of cover crop cultivar or species on soybean yield in MD 2015.

Terminating a winter cereal cover crop and no-till planting soybean earlier in the season provides a longer period for soybean to increase grain yield. Unless soybean is no-till planted into a standing winter cereal cover crop (Bernstein et al., 2014), extending the soybean growing season requires shortening the cover crop season, thereby constraining cover crop biomass production. Aside from the implications for weed suppression, terminating winter cereal cover crops before they reach anthesis can result in incomplete termination and a volunteer cover crop—which would typically be considered a weed—in the subsequent crop in rotation, among other potential agronomic consequences. Despite producing the least, or among the least, amount of cover crop biomass at the Early date, weed biomass was lower compared with the latest roll-plant dates. As such, it appears that the earlier roll-plant dates were associated with some of the lowest cover crop biomass production, lowest weed biomass, and greatest soybean yield.

2.4.6 Cover crop reseeding

Although we could not assess whether double-rolling improved cover crop termination relative to a single rolling event, we could evaluate the effect of rolling, in terms of reseeding, across termination timings and cover crop cultivars and species in NY 2015 and MD 2015. Cover crop cultivar differences on reseeding were observed in NY 2015 (Table 2.3). More ground cover of reseeded cover crops was associated with triticale cultivar ‘NE426GT’ (13%) compared with cereal rye cultivar ‘Huron’ (6%), but no other differences among cultivars were detected, nor did the effect of roll-plant date affect cover crop reseeding in NY 2015. Pooled over cultivars, triticale led to more reseeding in the following spring than cereal rye, while the reseeding associated with barley was no different than cereal rye or triticale (Table 2.3).

In MD 2015, an interaction was observed between roll-plant date and cover crop cultivar ($p = 0.0008$). Mean reseeding ground cover ranged from <1 to 48% across date and cultivar combinations. Pooled over cultivars, an interaction between roll-plant date and species was not detected. Differences in mean ground cover among roll-plant dates were not strictly chronological as more ground cover was associated with the Early date (24%) compared with the Mid-late date (15%), but the Late date (18%) was no different than the Early date. Among species, greater mean ground cover was observed with barley at 29%, compared with cereal rye and triticale at 12 and 14%, respectively.

Broadly, percent ground cover was greatest at the Early roll-plant dates across most cultivars in NY 2015 and MD 2015, decreased through the Early-mid and Mid-late dates, and then increased at the Late date. This general pattern was also observed in an organic rotational no-till experiment conducted in the Mid-Atlantic region of the US (Keene et al., 2017). As the authors note, rolling before anthesis stimulated some tillering, which then continued through vegetative and reproductive growth stages, producing seed that emerged in the following spring (Keene et al., 2017). In our experiment, rolling at the Early date, even with two rolling events, often did not flatten the cover crops, except for beneath the tractor tires where down pressure was greater than the water-filled roller-crimper. These incompletely terminated plants were able to continue kernel development. At the Mid-late date in NY 2015 and MD 2015, all species had at least reached anthesis (Zadoks 60). This roll-plant date corresponds to the lowest mean percent ground cover for both site-years in spring 2016, although not statistically different (at a 95% confidence level). Delaying rolling until the Late date allowed growth stages to reach the end of anthesis to early dough (Zadoks 69 to 83) in NY 2015 and nearly early milk to soft dough (Zadoks 72 to 85) in MD 2015; as such, kernel development was able to reach the final stages of development and produce viable seed while rolled flat on the soil surface. Consequently, percent ground cover increased slightly, compared with Early-mid and Mid-late dates.

As Keene et al. (2017) discuss, volunteer cover crops can contaminate the subsequent crop in a rotation, which can have undesirable agronomic and economic consequences. Tillage associated with seedbed preparation following soybean harvest, however, can reduce volunteer winter cereal cover crops the next spring (Keene et al., 2017). Beyond reseeding and crop contamination, we have shown that cover crop termination timing, and thus the timing of soybean planting, affects cover crop biomass, weed biomass, soybean density, and soybean yield (Tables 2.3–2.4).

2.4.7 Conclusion

In this experiment, we assessed the effect of roll-plant date and winter cereal cover crop cultivar and species on cover crop growth stage, cover crop biomass, weed biomass, soybean density, soybean yield, and cover crop reseeding. Across all site-years, cereal rye reached more advanced growth stages, on average, than barley or triticale at the Early date. In contrast, barley matured more quickly than cereal rye and triticale at later rolling dates. Despite these differences, we observed multiple benefits associated with terminating all three species prior to anthesis, including adequate weed suppression and greater soybean yields.

Pooled over cultivar, cereal rye produced more biomass on average than barley, but not triticale, across roll-plant dates at each site-year. This did not, however, result in better weed suppression with cereal rye each site-year, nor were consistent differences observed between cereal rye and barley for soybean density and yield.

Unlike barley, triticale performed as well as cereal rye in terms of biomass production, weed suppression, and soybean yield. Although triticale was not the first species to reach anthesis at either site in 2015, the slower maturation rate only resulted in the greatest reseeding in NY. In terms of management flexibility, slower maturity can also be an advantage for farmers who decide to harvest their winter cereal for forage as a more slowly maturing winter cereal provides a longer harvest window for capturing high-quality forage during a busy time of the season (Liebert et al., 2022). As cover crop-based no-till planted soybean production can be particularly challenging to manage during dry springs (Crowley et al., 2018), the option of harvesting a winter cereal as a forage provides farmers greater adaptability when using winter cereal cover crops.

Overall, these results suggest that researchers and farmers in the Northeast and Mid-Atlantic should consider triticale as a viable option for cover crop-based no-till planted soybean production. It is worth reiterating that previous research in which the substantial differences in seed mass between cereal rye and other winter cereal species (or cultivars) were not accounted for might have attributed superior performance to cereal rye that was confounded, at least in part, by very different plant densities. Ideally, an economic analysis should accompany future cover crop comparisons as well.

Cover crop biomass did not reach, let alone exceed, 8 Mg ha^{-1} across all treatments and site-years. Although we acknowledge the legacy effects of previous soil and crop management in our experiment, the relatively low weed biomass observed across a wide range of cover crop biomass levels still suggests that the recommended cover crop biomass threshold should be reconsidered. As with all agroecological practices, however, recommendations should not be prescriptive or decoupled from location and context. Future research should identify adequate cover crop biomass levels across a range of pedo-climatic zones, both at research stations and on-farm, in collaboration with farmers.

Relatively low crop diversity on grain farms can limit crop rotation options, which presents a major barrier to adoption and successful management given the importance of timing in these systems. Technical agronomic support will be critical for such knowledge-intensive practices, but many farmers need additional assistance to diversify and redesign their operations (Mortensen and Smith, 2020), such as access to regional processing facilities or new markets. In order to shift incremental improvements in on-farm management towards more transformative agroecosystem redesign (Gliessman, 2016; Wezel et al., 2020), participatory, interdisciplinary research (Méndez et al., 2013), in collaboration with farmers and policymakers, will be essential.

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CHAPTER 3

GET BIG OR GET OUT? HOW FARM SIZE AFFECTS THE USE OF AGROECOLOGICAL PRACTICES ON ORGANIC FARMS IN THE UNITED STATES

3.1 ABSTRACT

Organic agriculture outperforms conventional agriculture across several sustainability metrics due to more widespread use of agroecological practices instead of synthetic fertilizers and pesticides. However, increased entry of large-scale farms into the organic sector has prompted concerns about input substitution and agroecosystem simplification. We examine this shift in organic agriculture by estimating the use of agroecological practices across farm size and comparing indicators of conventionalization. Results from our national survey of 542 organic fruit and vegetable farmers confirm that fewer agroecological practices are used and a greater degree of conventionalization is observed on large organic farms. Intercropping, insectary plantings, and border plantings were at least 1.4-times more likely to be used on small (0.4–39 cropland ha) compared with large (≥405 cropland ha) farms, whereas reduced tillage was less likely and riparian buffers were more likely on small compared with medium (40–404 cropland ha) farms. Since decisions about management practices can drive environmental sustainability outcomes, policy should support small (and medium) farms that already use agroecological practices while encouraging increased use of agroecological practices on larger farms.

3.2 INTRODUCTION

Transformative changes are urgently needed to increase the sustainability of agriculture and food systems (Wanger et al., 2020). In the United States, the prevailing "conventional" model of agriculture is input-intensive and narrowly focused on maximizing crop yield. Landscape and management simplification, product standardization, and consolidation of farms and agribusinesses have resulted in tremendous production outputs, but the associated practices have also been a major driver of biodiversity loss (Newbold et al., 2015), soil degradation (Amundson et al., 2015), water pollution (Robertson and Vitousek, 2009), and greenhouse gas emissions (Campbell et al., 2017), and ultimately can contribute to the loss or serious degradation of arable lands (Kremen and Merenlender, 2018).

As a series of mutually enabling trends, synthetic fertilizer and pesticide use, mechanization, and farm size have increased since the 1940s. Fewer farmers are now working larger farms, a change that was encouraged by policy, and research and development. Championing this transition in the 1970s, former US Secretary of Agriculture, Earl Butz, declared that farmers should "get big or get out" (Krebs, 1992). Since then, the average size of US farms has increased. By 2000, the balance had shifted management of the majority of cropland from small- and medium-scale farmers to large-scale farmers on operations of at least 405 ha. As a result of market forces and policies that disproportionately reward economies of scale and particular commodity crops (Mortensen and Smith, 2020), the majority of cropland is now managed on large farms, primarily at the expense of medium farms (Figure 3.1).

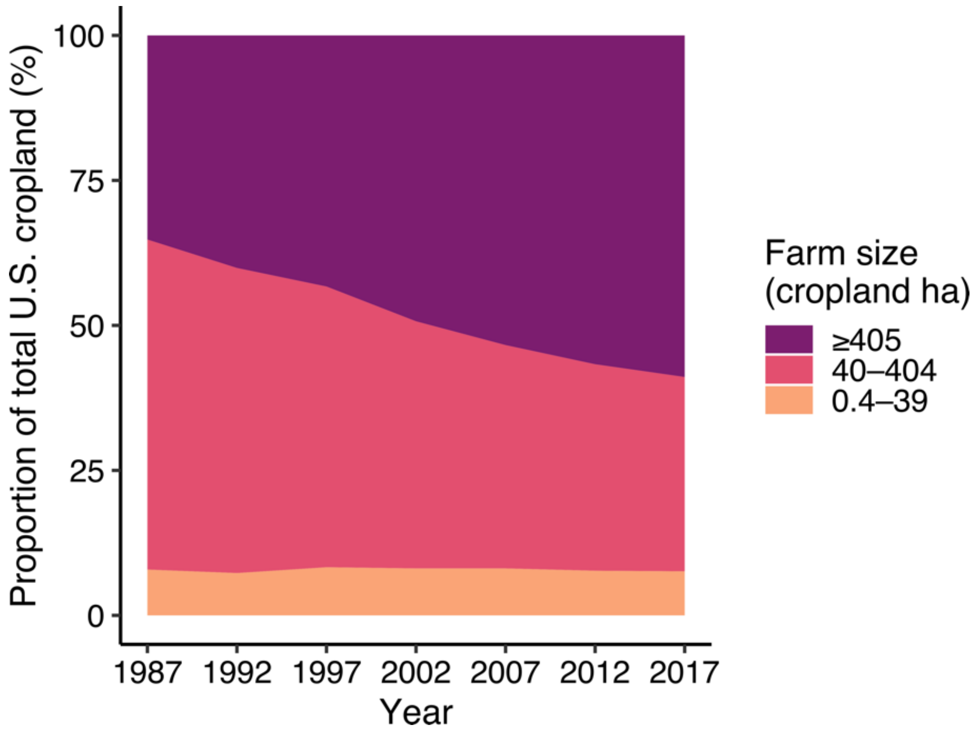

Figure 3.1 | The proportion of total cropland managed by farms in different size categories: 0.4–39, 40–404, and ≥405 ha. Farm size categories are adapted from the 2017 Census of Agriculture (see Methods). Data represents all crops farms in the US (USDA NASS, 2019b).

In the US, organic farms are smaller (135 ha), on average, than conventional farms (180 ha) (USDA NASS, 2020a, 2020b). Over 2.2 million hectares of farms and ranches are certified organic, with 1.4 million hectares dedicated to crop production. Though it comprises less than 1% of all farmland in the US, organic agriculture has been promoted as a management approach that can help ameliorate the deleterious effects associated with conventional agriculture (Reganold and Wachter, 2016; Muller et al., 2017). Compared to conventional production, organic farming performs better across a wide array of sustainability metrics—such as energy use, soil quality, and the provision of ecosystem services—largely through the use of practices that support biodiversity and minimize negative impacts on the environment (Reganold and Wachter, 2016; Lori et al., 2017; Seufert and Ramankutty, 2017). These benefits reflect the focus of the USDA National Organic Program (NOP) standards, which were designed to maintain or enhance soil health and “promote ecological balance” (Leahy, 1990). Many of the practices commonly used on organic farms are also characteristic of agroecology and other alternative approaches to agriculture. Agroecology can be described as a scientific discipline, suite of practices, and social movement (Wezel et al., 2009). Though the focus is on practices here, we understand agroecology to integrate these three dimensions.

3.2.1 Agroecological practices

Agroecological practices aim to maintain the ecological integrity of farming systems, which in turn provide ecosystem services such as nutrient cycling, pollination, and biological pest control (Bommarco et al., 2013; Kleijn et al., 2019; Tamburini et al., 2020). Such services not only undergird the resilience and adaptive capacity of a farming system, but they can also reduce the need for off-farm inputs. In this study, we focused on eight agroecological practices that range from above- to below-ground, and within-field to landscape-level implementation: compost or manure application, intercropping, insectary plantings (e.g., flower strips), reduced tillage (i.e., a decrease in tillage intensity or frequency), diverse crop rotations (≥3 crops), cover cropping, border plantings (e.g., hedgerows), and riparian buffers (Figure 3.2).

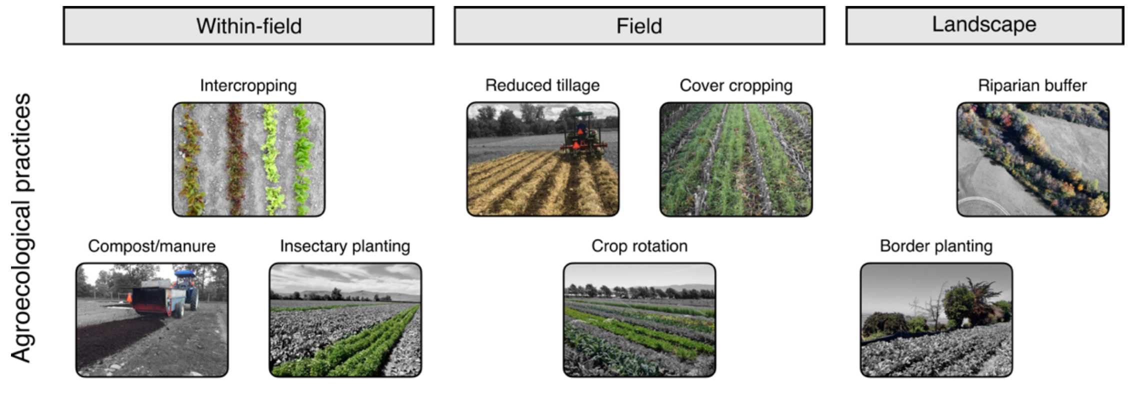

Figure 3.2 | Agroecological practices organized by their typical on-farm scale of application. Based on previous reviews of agroecological practices (Kremen and Miles, 2012; Wezel et al., 2014), this categorization scheme, ranging from within-field to perimeter and landscape-level application, is common. Some practices can be implemented at multiple scales or combined across scales to create a "diversified farming system" (Kremen and Miles, 2012).

As biological diversity is a key element in ecosystem function and maintenance, it is notable that all eight practices support greater above- or below-ground biodiversity (Kremen and Miles, 2012). Implementing a complex crop rotation is among the most fundamental practices in this regard. Diversified crop rotations reduce yield loss and the risk of crop failure under climatic stresses, as well as increase yields during more productive growing conditions (Bowles et al., 2020). Complex crop rotations can also limit the frequency and severity of pest outbreaks, support more diverse soil biota, and enhance nutrient cycling, among other benefits (Bommarco et al., 2013; Tamburini et al., 2020). With intercropping and cover cropping, leveraging plant functional traits through crop species and cultivar selection and management can yield a range of ecosystem services, including weed suppression and nitrogen fixation (Wood et al., 2015; Faucon et al., 2017). The application of compost or manure enhances numerous indicators of soil health (D'Hose et al., 2014), such as organic matter (Fließbach et al., 2007) and soil microbial community composition and activity (Francioli et al., 2016). Reducing the intensity or frequency of tillage can also improve soil health through increased aggregate stability, microbial biomass C, and soil respiration, among other characteristics (Willekens et al., 2014; Blanco-Canqui and Ruis, 2018; Nunes et al., 2020). Diversifying an agroecosystem with floral strips (i.e., insectary plantings) and semi-natural, perennial, or other flower-rich habitats along field edges (i.e., border plantings) can enhance pest control and pollination services (Chaplin-Kramer et al., 2013; Kremen and Merenlender, 2018; Dainese et al., 2019; Martin et al., 2019; Albrecht et al., 2020), though context and landscape complexity are important mediating factors (Karp et al., 2018). Riparian buffers also provide habitat for beneficial organisms and movement corridors or stepping stones for wide-ranging species, but they are primarily used by farmers to prevent sediment, nutrient, and pesticide transportation off-site via runoff(Zhang et al., 2010).

As these agroecological practices are applicable to all types of farm management, organic farms that use multiple practices in combination can serve as a model for transforming agriculture (Reganold and Wachter, 2016; Eyhorn et al., 2019; Tamburini et al., 2020). However, as cropland becomes increasingly consolidated among fewer farmers and market opportunities entice conventional farmers to enter into organic production, concerns about the “conventionalization” of organic agriculture have emerged (Buck et al., 1997; Guthman, 2000, 2004).

3.2.2 Conventionalizing organic agriculture

The process by which organic agriculture is becoming more similar to the dominant industrial model of farming has been termed “conventionalization” (Buck et al., 1997). The conventionalization process can be characterized by larger farm size, simplified agroecosystems, greater mechanization, standardized crop production, and a reliance on input substitution (i.e., replacing a prohibited input with an NOP-approved input) (Guthman, 2000, 2004). Social, economic, and political consequences of conventionalization include the use of more non-family labor, less full-time farmworker employment, increased contract growing, a decline in direct marketing, vertically integrated supply chains, and a weakening of organic standards (Constance et al., 2008; Darnhofer et al., 2010).

Similar to the trends observed among all farms in the US, the consolidation of land among a decreasing number of increasingly large farms has also occurred in the organic sector. Due to conventionalization, organic agriculture is bifurcating into two distinct groups: large-scale operations mass-producing a few crops for wholesale and small- to medium-scale farms using more ecological practices to grow a diverse array of crops for direct sale. In 2017, crop farmers who primarily sold organic products managed 49% of organic cropland while representing 73% of all farms with NOP-certified sales. In contrast, farmers who primarily sold non-organic products managed the remaining 51% of organic cropland, but they represented just 27% of all farms with NOP-certified sales (USDA NASS, 2019a, 2019b). In other words, a small number of large-scale farming operators—predominantly conventional but whose operations include a small fraction of organic land—manage the majority of organic cropland in the US.

Some researchers have emphasized the importance of distinguishing between different types of organic management (Ponisio et al., 2015; Seufert and Ramankutty, 2017; Tamburini et al., 2020), but such differentiation is still uncommon in empirical studies. Universally ascribing benefits or drawbacks to organic agriculture might obscure the uneven potential among organic farms of varying sizes and management types to contribute to the transformation of agriculture. This lack of distinction among organic farms could, in turn, mislead research agendas or hinder more effective policy interventions. If organic agriculture is to scale up in a way that avoids many of the drawbacks of conventional production, it will be important to better understand the effects of conventionalization on organic farms. We use the results from a national survey of organic fruit and vegetable farmers to discern whether relationships exist between farm size and the use of agroecological practices and to assess the degree to which conventionalization is occurring among organic farms in the US.

3.3 METHODS

3.3.1 Survey design

The survey questions were initially developed to address our broad research objectives and the associated knowledge gaps we identified in the literature. As we designed the survey instrument, we also created an interview guide, which was comprised of themes, questions, and prompts that were similar to the survey questions. We used this interview guide to conduct semi-structured in-depth interviews with 10–12 farmers in both California and New York. Written informed consent was obtained from all interview subjects who participated in this study. The Cornell Institutional Review Board for Human Participants (IRB) approved our study (Protocol ID #1612006859).

The interviews provided detailed responses and valuable insight, informing our questionnaire revisions. After these modifications, the questionnaire was tested by a diversity of small- to large-scale farmers from multiple US states. Feedback from this phase was then integrated into a final set of revisions. Numerous question types were used throughout the survey, including multiple choice, text entry, rank order, and matrix tables with Likert-scale response options.

3.3.2 Survey distribution

Created with the Qualtrics online survey platform, our electronic survey was accessible with a computer, tablet, or smartphone. We primarily used maximum variation sampling (also known as "heterogeneous sampling"), which is a sub-type of non-probability purposive sampling. We used this sampling procedure because probability sampling was not possible for our population of interest, and it was important for our research objectives to obtain responses from organic fruit and vegetable farmers who managed a wide range of farm sizes and were characterized, potentially, by varying degrees of "conventionalization."

To ensure that we minimized sampling bias and obtained a sufficient sample of respondents who represented small- to large-scale farmers across a range of conventionalization, we used a highly diverse and purposeful survey outreach approach. This strategy included posting survey invitations on farmer listservs; publishing invitations through various social media platforms, on farming-focused websites, and in electronic agricultural newsletters; promoting the survey through trade magazine interviews; contacting farmers directly with email addresses obtained from extension educators, grower associations, non-governmental organizations, and public databases; and through referral (snowball) sampling.

While some of these outreach efforts reached organic farmers of all sizes (e.g., USDA Organic Integrity Database), others were more specific. For example, obtaining farmer email addresses from farmers' market managers across the country provided access primarily to small-scale organic farms as large-scale organic farmers typically sell their produce through wholesale markets. To reach large-scale farms, for example, we promoted our survey through extension educators at land-grant universities who often work with medium- and large-scale farmers (with the exception of specific "small farms" programs); crop consultants, who tend to do contract or salaried work for larger farms; farm bureau contacts, some of whom serve on state boards with large-scale farmers; and grower-shipper associations, which cater to large, vertically integrated farms.

Once started, the survey could be completed over any number of sessions within a two-week timeframe. As many farmers left the survey open and returned to it multiple times, an accurate calculation of the average length of time required to complete the survey was not possible. Although the survey remained live between February and November 2018, the outreach and distribution efforts were intermittent, rather than continuous, throughout that time period.

3.3.3 Data preparation

A total of 1,264 responses from farmers across the US were obtained. Using R version 4.1.1 (R Core Team, 2021), incomplete surveys were filtered out. More specifically, any surveys that did not include responses to questions about farm size, management type, or crops grown were excluded as these data were required for the analyses in this paper. Next, we organized the respondents into two management types, conventional, which we excluded from the analyses in this paper, and organic. Here, organic management represented a composite of several subcategories from the survey, including any combination of the following: farmers who are certified organic, farmers who use organic management practices but are not certified, farmers who are managing land in transition to organic certification, and farmers who manage some land conventionally and some land organically. Among this organic management group (referred to collectively as "organic farmers" or "small-scale farmers," "medium-scale farmers," or "large-scale farmers" in-text), we filtered out farmers who did not grow any fruits or vegetables. In addition to those who exclusively produced fruits or vegetables, we retained farmers who produced a mix of fruits or vegetables and field or grain crops. We refer to all of these farmers as "fruit and vegetable farmers" for simplicity.

Based on the amount of cropland under production, the responses were then organized into one of three farm size categories: 0.4–39, 40–404, or ≥405 ha. Each of these categories combined several size groups used in the USDA 2017 Census of Agriculture. Our small-scale category (0.4–39 ha) matches the USDA group (<40 ha), which represents a farm size group that was relatively stable over the past three decades with a slight 0.3% decrease in the proportion of cropland managed. Our medium-scale category (40–404 ha) combines three USDA groups (40–80, 81–201, and 202–404 ha), which represents a farm size group that experienced a 23.4% decrease in the proportion of cropland managed. Our large-scale category (≥405 ha) combines two USDA groups (405–809 and >809 ha), which represents a farm size group that experienced a 23.7% increase in the proportion of cropland managed. All three USDA farm size groups that comprised our medium-scale category saw a decrease and both USDA farm size groups that comprised our large-scale category saw an increase over the three-decade period. Combining farm size groups with consistent long-term trends (e.g., all decreasing or all increasing) allowed us to visualize the broader trend of cropland consolidation (Figure 3.1) more clearly, as well as conduct meaningful contrasts among farm size groups. This data preparation process yielded 542 responses from farmers across 43 states for use in our statistical analyses. The representativeness of this sample is supported by the similar demographic composition observed when comparing our national sample with the demographic characteristics reported in the USDA 2017 Census of Agriculture for organic farmers (Supplementary Table C1).

3.3.4 Statistical analyses

All analyses and visualizations were completed in R version 4.1.1 with the following packages: 'tidyverse' (Wickham et al., 2019), 'lme4' (Bates et al., 2015), and 'emmeans' (Lenth, 2021). The total number of practices used was summarized with violin plots. The width of these visualizations represents the observation frequency (i.e., width increases as observation number increases). We also predicted the average number of agroecological practices in use on farms of varying size. Based on a linear model in which the number of practices used was the response and farm size was the predictor, we calculated estimated marginal means, which are equally weighted means of the predictions, and 95% confidence intervals.

Binomial logistic regression was used to predict the probability of whether a farmer does or does not use a given agroecological practice. In the survey, respondents were asked whether they currently use, previously used, or never used each of the eight practices. For riparian buffers, a fourth option was available, "not applicable," so that the responses from farmers without waterways on or adjacent to their farm would not confound the responses from farmers who had never used the practice. Also, farmers who exclusively produced woody perennials, such as fruit and nut trees, were excluded from the analysis of crop rotation. The lifecycle of such crops precludes typical crop rotation. Responses from farmers who previously used a practice, but no longer do so, were grouped with farmers who had never used a practice before. Thus, our binary response variable was current use (1) and current disuse (0).

The response was predicted by an interaction between practice (8-levels: compost or manure application, intercropping, insectary planting, reduced tillage, crop rotation, cover cropping, border planting, and riparian buffer) and farm size (3-levels: 0.4–39, 40–404, and ≥405 ha), with anonymized respondent identification as a random effect. After establishing a reference grid, which included all combinations of the categorical predictors, we used the binomial logistic regression model to estimate the mean on the response scale for each combination in the reference grid. This process yielded estimated marginal means and 95% confidence intervals. Note that for binomial logistic regression, the confidence intervals are asymmetrical due to the asymptotic nature of the minimum and maximum values for predicted probabilities (i.e., at $y = 0$ and $y = 1$, respectively). Pairwise comparisons (i.e., contrasts) by farm size (Supplementary Table C2) and by practice (Supplementary Table C3) were conducted to compare the estimated marginal means with one another. We note that interpretations of these contrasts were not based exclusively on the threshold of $p < 0.05$ (see Wasserstein and Lazar, 2016; Krueger and Heck, 2019; Wasserstein et al., 2019).

To assess whether there were any associations between farm size and a specific indicator of conventionalization, Fisher's exact test (R Core Team, 2021) was used. This test can accommodate contingency tables (i.e., a table with I rows for categories of X and J columns for categories of Y, or $I \times J$) that are larger than 2×2 (Agresti, 2013). Fisher's exact test is also preferred over Pearson's chi-squared test when the sample size is relatively small or when one or more cells in a contingency table has an expected frequency of five or less (Agresti, 2013), which was the case in some of our 3×4 tables (Supplementary Table C4). Farm size categories (0.4–39, 40–404, and ≥405 ha) were the rows and (potential) conventionalization indicator responses (four discrete choices as a possible survey response) were the columns. For these tests, the null hypothesis is that there is no association between the two categorical variables, farm size and the (potential) conventionalization indicator.

The six questions related to conventionalization focused on crop diversity (number of crops in rotation: 1–2, 3–9, 10–29, or ≥30 crops), mechanization (proportion of farm work that is mechanized: 0–25, 26–50, 51–75, or 76–100%), market channel (wholesale as a proportion of total sales: 0–25, 26–50, 51–75, or 76–100%), distribution (distance from farm to the final point of sale: <16.1, 16.1–161, ≥161 km, or unknown), competition (most difficult farm types to compete with: large conventional, large organic, small-medium organic, or small-medium conventional), and scaling (interest in increasing their farm size: definitely yes, probably yes, probably no, or definitely no). After assessing whether farm size and the (potential) conventionalization indicators were associated (Supplementary Table C4) using Fisher's exact test (two-sided) with each contingency table of counts (n), we calculated proportions (%) as a more easily interpretable metric for this analysis.

3.4 RESULTS

A total of 542 fruit and vegetable farmers from 43 states completed our survey. These farmers include exclusively organic producers, as well as those who manage mixed operations of conventional and organic cropland. We refer to all of these farmers as "organic farmers." Compared with the 2017 Census of Agriculture data on organic farmers (USDA NASS, 2019a), the demographics of our survey respondents were similar (Supplementary Table C1).

Responses to our survey were categorized into three farm size groups: 0.4–39, 40–404, and ≥405 ha. We refer to these categories as small (n = 394), medium (n = 109), and large (n = 39) farms for convenience, while being aware that such qualitative descriptors differ significantly across the US. In our sample, the percentage of farmers in each farm size category who managed mixed operations was 7% (small), 28% (medium), and 72% (large). On these mixed operations, the mean percentage of cropland that was under organic production was 45% (small), 33% (medium), and 25% (large). The farm size categories were adapted from the 2017 Census of Agriculture (USDA NASS, 2019b) to align with the 30-year trend of cropland consolidation (Figure 3.1). In our survey, farm sizes based on cropland ranged from 0.4 to 9,737 ha, with a mean size of 8, 128, and 1,904 cropland ha for small, medium, and large farms, respectively. Farmers who did not grow any fruits or vegetables were excluded from the analyses. As such, the farmers represented here grow as few as a single fruit or vegetable crop to more than 50 different species. Mixed cropping systems of fruit or vegetable production with field crops, grains, forages, or livestock are also included.

3.4.1 Practice-use among organic farmers

Farmers who managed small or medium farms used more than five out of eight agroecological practices on average (Figure 3.3), which was a greater number of practices than large-scale farmers (small vs. large, $p = 0.0004$, and medium vs. large, $p = 0.02$). Over half of the small- and medium-scale farmers used at least six of the eight agroecological practices.

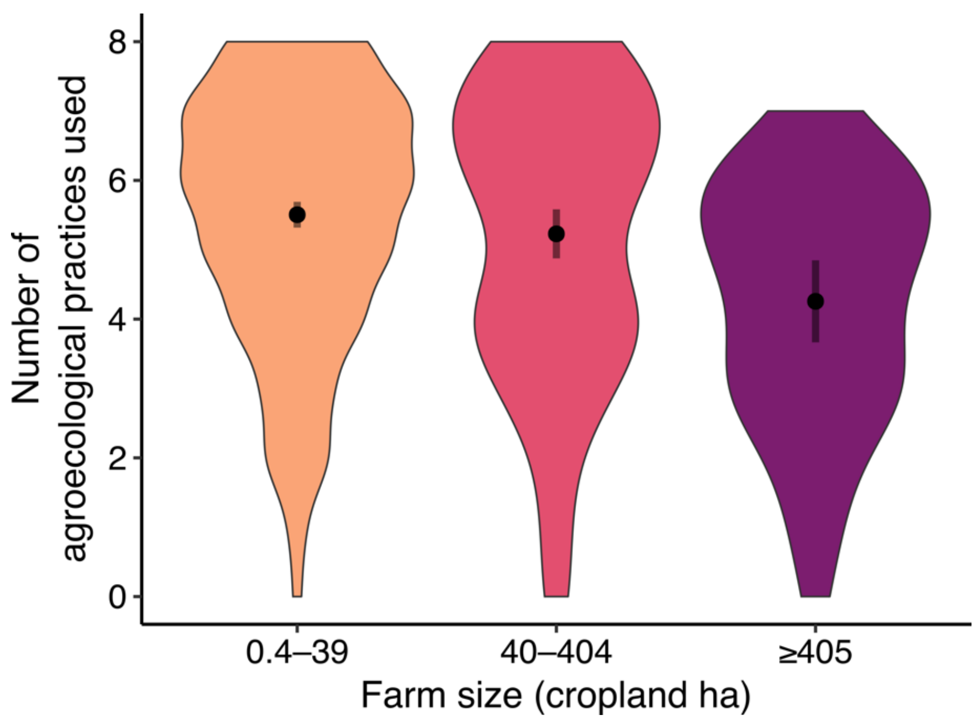

Figure 3.3 | Average number of agroecological practices used by farm size (cropland ha). Violin plots display the distribution of the data whereby the width indicates the observation frequency. Estimated marginal means (points) are accompanied by 95% confidence intervals (bars).

The relationship between farm size and the use of specific agroecological practices varied among (Figure 3.4, Supplementary Table C2) and within

(Supplementary Table C3) size categories. Across all three size groups, the probability that an organic farmer uses a diverse crop rotation, cover cropping, or riparian buffers is over 75% (Figure 3.4). The use of border plantings, in contrast, has among the lowest predicted probability (<63%) across farm sizes. When averaged over all eight practices, small-scale farmers exhibit the highest probability of practice-use (79%), with all practices more likely than not to be used among this size category (i.e., all probabilities are >50%, Figure 3.4). In contrast, large-scale farmers are associated with the lowest average probability of practice-use (65%), as well as the only two practices that organic farmers of any size are less likely to use than not use: insectary plantings at 29% (p = 0.03) and border plantings at 30% (p = 0.04).

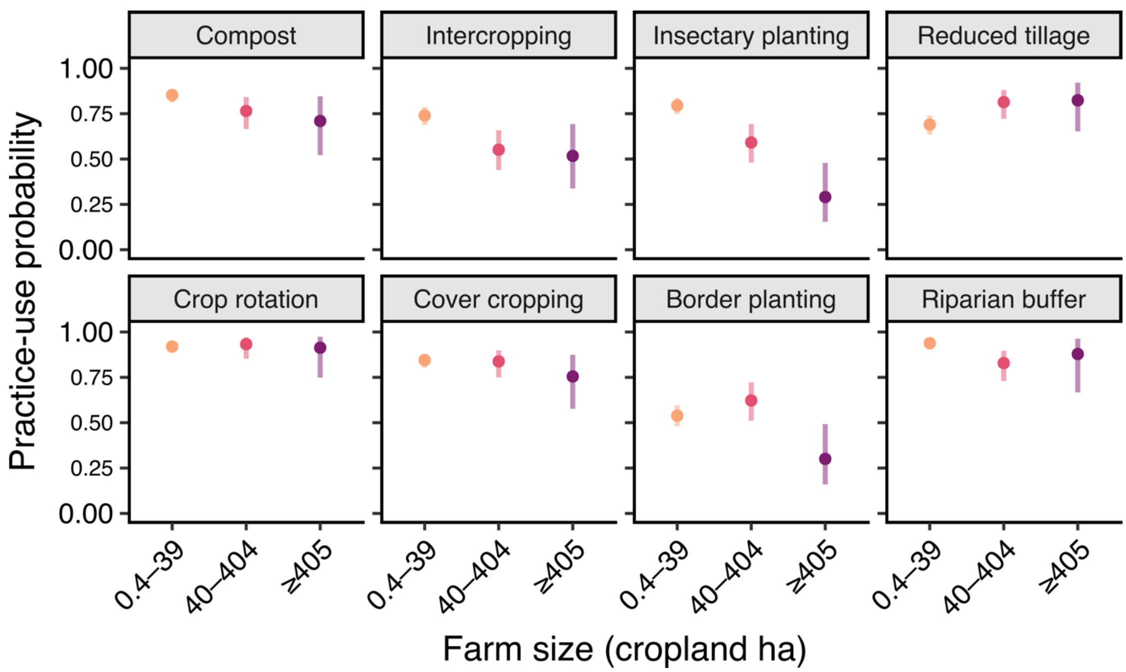

Figure 3.4 | Predicted probability that a farmer does use (y = 1) or does not use (y = 0) a given agroecological practice among farm size (cropland ha) categories. Estimated marginal means are presented for each practice-size interaction, and accompanying bars are 95% confidence intervals.

The use of compost, diverse crop rotations, and cover crops exhibit no differences among farm sizes within each practice (Figure 3.4, Supplementary Table

C2). The only practice that shows a positive relationship with farm size is the implementation of reduced tillage, increasing from 69 to 81% as farm size increases from small to medium ($p = 0.06$, Figure 3.4).

For intercropping, small-scale farmers are more likely to use the practice (74%, Figure 3.4) than either medium- (55%, Figure 3.4; $p = 0.004$, Supplementary Table C2) or large-scale farmers (52%, Figure 3.4; $p = 0.04$, Supplementary Table C2). The effect of farm size on the use of insectary plantings is even more pronounced (Figure 3.4): the probability of planting flowers to attract pollinators or natural enemies markedly declines from 80% among small-scale farmers to just 29% among large-scale farmers ($p < 0.0001$). Using border plantings is also less likely among large-scale farmers compared with small- and medium-scale farmers (Figure 3.4, Supplementary Table C2). Farmers in the smallest farm size category are most likely to use riparian buffers if a waterway, such as a stream or drainage ditch, is present on or adjacent to their farmland.

Practice-use among medium-scale farmers was generally intermediate. Whereas small-scale farmers were more likely to use intercropping, insectary plantings, and riparian buffers than medium-scale farmers ($p \leq 0.008$), reduced tillage emerged as the only practice more likely to be used on medium than small farms ($p = 0.06$). Medium-scale farmers were, however, more likely to use both insectary plantings and border plantings than large-scale farmers ($p \leq 0.02$).

3.4.2 Indicators of conventionalization

Four features commonly ascribed to conventionalization were assessed in the survey: low crop diversity, high mechanization, wholesale marketing, and non-local markets. Together, these qualities describe an industrialized farm that uses a standardized, highly mechanized management approach to mass produce a relatively small number of crops for export-oriented wholesale markets. Among the survey respondents, these attributes are generally associated with larger farms (Figure 3.5).

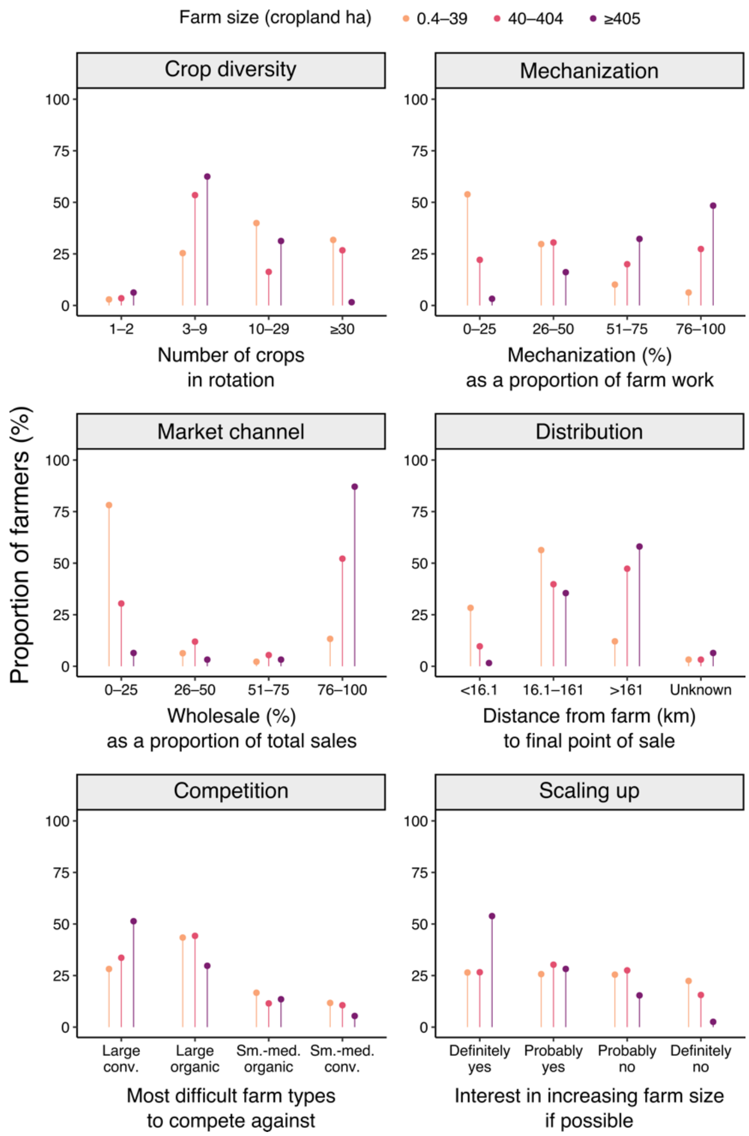

Figure 3.5 | Comparing potential indicators of conventionalization among organic farms of different size (cropland ha). Points represent the percentage of surveyed farmers within a size category who selected a specific response among a discrete number of choices for a given survey question. The questions presented here focused on crop diversity (number of crops in rotation), mechanization (proportion of work that is mechanized), market channels (wholesale as a proportion of total sales), distribution (distance to market), competition with other farmers (size and management type), and scaling up (interest in increasing farm size). See Supplementary Table C4 for the associated contingency tables.

Large-scale organic fruit and vegetable farmers managed the least diverse crop rotations overall, though the majority of these farmers grew 3–9 crops in a typical rotation (Figure 3.5). While nearly one-third of both small- and medium-scale farmers produced 30 or more crop species, no large-scale farmers managed similarly diverse rotations. The proportion of mechanized farm work increased as farm size increased. Among small-scale farmers, 54% managed their farm with little to no mechanization (0–25%), whereas just 3% of large-scale farmers did the same (Figure 3.5). Conversely, around 6% of small-scale farmers managed highly mechanized (75–100%) operations, compared with 48% of large-scale farmers.

Wholesale markets, which include selling to processors or distributors, local or regional food hubs, and cooperative commodity markets, were the primary destination for fruits and vegetables grown on large farms: nearly 90% of large-scale farmers sold over three-quarters of their produce wholesale (Figure 3.5). Direct sales, such as farmers' markets, farm stands, or community-supported agriculture programs, comprised over three-quarters of total sales for 74% of small farms, 30% of medium farms, and less than 7% of large farms. Relatedly, nearly 30% of the produce grown on small farms was sold to consumers within a 16-km radius around the farm, with just 12% transported further than 160 km (Figure 3.5). In comparison, none of the crops grown on large farms were sold to consumers within 16-km of the farm, and nearly 60% was shipped beyond a 160-km radius.

Farms of contrasting sizes market their crops in dissimilar ways, potentially serving different consumers. Notably, however, only 17% of small-scale (organic) farmers claimed that other small- or medium-scale organic farmers were their biggest competitors (Figure 3.5). Over 40% of small-scale (organic) farmers reported that competition from large organic farms presented the greatest threat, followed by 28% who designated this role to large conventional farms. Among large-scale (organic) farmers, over 50% indicated that large conventional farms were their greatest competition.

In our survey, respondents were asked if they would increase the size of their farm if possible—that is, if all barriers were removed in a hypothetical situation, would they increase the size of their farm? Among small farms, the responses were evenly distributed at around 25% for each option (Figure 3.5). More than half of all large farms indicated that they would "definitely" increase the size of their farm with just 3% definitive about not doing so.

3.5 DISCUSSION

Overall, most of the organic farmers in our survey used multiple agroecological practices in a wide variety of combinations. Small-scale farmers were able to adopt many of these practices, though usually not all eight concurrently, while large-scale farmers adopted fewer agroecological practices in general. Other research has shown that organic farmers are likely to use agroecological practices, though many studies do not explicitly distinguish practice-use among organic farms of different sizes (Gomiero et al., 2011; Kremen and Miles, 2012; Wezel et al., 2014; Lori et al., 2017; Eyhorn et al., 2019; Tamburini et al., 2020). In a national survey that grouped all organic farms together, it was reported that 29% of organic farmers maintain habitat for beneficial insects (USDA NASS, 2020a); however, our analyses demonstrate that farm size is an important factor for predicting the use of insectary plantings. While the probability of using insectary plantings is 29% for large-scale farmers, it is much higher at 59 and 80% for medium- and small-scale farmers, respectively. Similarly, large-scale farmers are less likely (30%) to use border plantings compared with medium- (62%) or small-scale (54%) farmers.

The use of insectary plantings provides an illustrative example of how barriers to using agroecological practices can vary substantially by farm size. For instance, crop pollination services have been found to decrease exponentially as the distance from an insectary planting increases (Albrecht et al., 2020). In our survey, the average field size for large farms, at 41 ha, is not only 25-times larger than the average field size on small farms, but also greater than the largest possible small farm in that category. This disparity has inherent management implications for optimizing pollination services, as well as for biological pest management (Martin et al., 2019). Though flower strips are generally scalable (Tittonell et al., 2020), large-scale farmers must consider trade-offs that a small-scale farmer might not contend with to the same degree. Integrating enough flower strips or border plantings to countervail the suppressive effects of both low semi-natural habitat abundance and low edge density (i.e., perimeter-area ratios) on functional biodiversity might present a greater challenge for large-scale farmers, although landscape composition and configuration can interact in complex, context-specific ways (Tscharntke et al., 2012; Martin et al., 2016; Haan et al., 2020). Still, taking land out of production is a likely concern on farms of any size, exacerbated by short-term leases and the high value of farmland in many important growing regions in the US.

In addition to cropping system constraints, marketing can present uneven barriers that differentially affect large- and small-scale growers. Large-scale farmers tend to sell their produce wholesale, thus receiving a lower price per unit than those who sell directly to consumers. To access some wholesale markets, farmers must comply with third-party food safety standards that can be more stringent than national guidelines (Olimpi et al., 2019). In these instances, compliance has resulted in the removal of non-crop vegetation and a notable simplification of agroecosystems (Karp et al., 2015). Landscape simplification has been shown to reduce both natural enemy and pollinator richness, indirectly affecting pest control and pollination, resulting in lower crop production (Dainese et al., 2019). Together, these factors have the potential to affect large-scale farmers negatively through reduced prices, habitat removal, and lower yields. Although small-scale farmers engage with different markets, buyers can still demand that they obtain some form of food safety certification (Olimpi et al., 2019); unless they are exempt from these demands, small-scale farmers face prohibitively high costs to comply—costs that are substantially greater than the costs of compliance for large-scale farms—given the high fixed costs relative to sales (Bovay et al., 2018).

3.5.1 Conventionalization, competition, and certification

Large-scale organic farms in our survey exhibit multiple characteristics of conventionalization, including differences in the use of agroecological practices. These attributes suggest a bifurcation based on traits concomitant with size: larger farms demonstrate a greater degree of conventionalization than smaller farms. In early conventionalization research outside of the US, it was suggested that the bifurcated sectors—large-scale production for export markets and small-scale production for local markets—coexist in a dependent relationship in which target markets are both separate and complementary (Coombes and Campbell, 1998). Despite small and large organic farms serving different consumer niches (Hughner et al., 2007), small-scale farmers in our survey reported a disproportionately high degree of competition from large organic farms. This threat might represent a "farm-gate price-squeeze" (Smith and Marsden, 2004), driven by the entry of large-scale farmers into an organic market with few powerful buyers (i.e., oligopsony), providing products at a lower cost due to scale efficiencies (Howard, 2016).

The overall, though uneven, dilution of organic standards (Arcuri, 2015; Seufert et al., 2017)—leading to some products less differentiated from their conventionally produced counterparts—accommodates, if not encourages, increased entry by larger farms (Guthman, 2004). This mainstreaming of organic agriculture has been co-facilitated by big-box retailers and the large-scale farmers who have access to processors, distributors, and national wholesale markets, thereby introducing organic products to a much greater number of people, often at a lower cost (Guthman, 2019). Yet, the entry of these large farms can depress the price premium obtained for organic produce, thereby discouraging the very farmers who are most motivated by profitability from converting to organic production (Guthman, 2019).

In the US, reversing the attenuation of organic standards and evolving them beyond minimum requirements (Seufert et al., 2017) to include measurable social and ethical dimensions might help minimize the economic pressure from large farms, but not without consequences for the price of organic products and growth in the sector. Alhough some alternative certification schemes have been developed to explicitly address social justice shortcomings, others still eschew the inclusion of more rigorous social and ecological principles in favor of regulation compliance, which has been central to the critiques of the NOP (Guthman, 2004, 2019; Darnhofer et al., 2010; Jaffee and Howard, 2010; Seufert et al., 2017). The alternative certifications that do seek to redress the absence of strong commitments to social sustainability typically frame their principles in contrast to conventionalized organic standards. As such, voluntary adoption of these alternative certifications seems more likely among small- and medium-scale farmers, many of whom indicated that large organic farms posed the greatest competition (Figure 3.5). In contrast, elective uptake of these more rigorous certifications seems less likely among the large-scale farmers that the organic standards have been softened to accommodate.

It should be noted that the features of organic farms described in this paper cannot be extrapolated to other production regions with different socio-economic or political contexts. We also agree with other researchers (Coombes and Campbell, 1998; Lockie and Halpin, 2005; Campbell and Rosin, 2011) who have detailed the limitations of using binary metrics in a heterogeneous organic sector. A large farm is not inherently less attuned to environmental stewardship, animal welfare, or farmworker justice than a small farm, just as small-scale farmers are not intrinsically or universally more ecologically or socially virtuous.

Identifying the use and disuse of agroecological practices helps illustrate the differences among organic farms, but it does not reveal *why* or *how* the practices are being used. While the reasons why agroecological or similar practices are used has received significant attention from researchers (Prokopy et al., 2019), the different ways in which farmers implement these practices—particularly across farm sizes—is not well understood or documented. Such variations in the application of a given practice can have profound implications for the delivery of ecosystem services, or disservices, as well as the transformative potential of the farming sector as a whole.

3.5.2 Redesigning agroecosystems

Although organic agriculture can serve as a model for transforming agriculture, heterogeneity within organic agriculture in terms of agroecological practice-use and conventionalization highlights the need for a guiding framework that acknowledges the influence of farm size. Conceptualizing the transformation of agriculture as a series of discrete steps can be a valuable analytical approach, despite simplifying the complexity inherent in the process (Gliessman, 2016; Pretty et al., 2018). One such framework for envisaging a shift towards increasingly sustainable systems of farming involves three nonlinear stages: efficiency, substitution, and redesign (E-S-R) (Hill, 1985). These stages can be sequential, but they are just as likely to occur simultaneously, forwards or backwards, among different practices in concurrent use

(Padel et al., 2020).

Practices that increase the efficiency (E) of a farm usually do not seek to utilize internal, on-farm resources or ecological processes, instead focusing on more judicious use of external inputs (e.g., most applications of precision and digital agriculture technologies). The substitution (S) approach seeks to replace unsustainable inputs or practices with more sustainable or environmentally benign alternatives (e.g., synthetic fertilizers might be replaced with compost). The input substitution approach associated with the conventionalization of organic agriculture involves the use of an NOP-approved input instead of a prohibited one, which is analogous to the more general description of a substitution practice employed by the E-S-R framework. As with efficiency-increasing practices, the implementation of substitution does not necessitate significant changes to the overall cropping system. Redesign (R), in contrast, explicitly involves reshaping an agroecosystem to leverage ecological processes to minimize externalities, enhance resilience, and optimize the provision of ecosystem services. A redesign approach shifts the focus from reactive, curative interventions—even ecological ones—to prioritizing regenerative measures on the farm. Whereas the least sustainable farms are input-intensive in this schematic, the most sustainable redesigned systems are biodiverse and knowledge-intensive.

Informed by our findings, we propose the following generalized relationships: (1) implementing an agroecological practice simply to increase production efficiency is more likely on large-scale organic farms, (2) using an agroecological practice to substitute for a less-sustainable input or practice is no more or less likely on organic farms of a particular size, and (3) using an agroecological practice as part of a system-level redesign approach to optimize ecological processes is more likely on smaller organic farms (Figure 3.6).

In relation to our practice-use diagram, reduced tillage is the only agroecological practice that follows the pattern associated with efficiency (i.e., a positive slope from small to large farms, Figures 3.4, 3.6); compost, crop rotation, cover cropping, and riparian buffers generally follow the pattern of expected use associated with substitution (i.e., marginal or no slope, Figures 3.4, 3.6); and intercropping, insectary plantings, and border plantings follow the pattern of expected use associated with redesign (i.e., a negative slope, Figures 3.4, 3.6). In the efficiency and redesign scenarios it is less likely, but not impossible, for the opposite to occur. Most important in this conceptualization, especially as cropland continues to shift from medium- to large-scale farmers, is the limited probability that large-scale farmers will transition to a system that relies primarily on knowledge- and labor-intensive agroecological practices to redesign their operation. As recent studies have shown, medium-scale farmers can potentially access resources and provide benefits that are distinct from other farm types (Brislen, 2018; Esquivel et al., 2021). Accordingly, the ongoing disappearance of an "agriculture of the middle" is of particular concern (De Master, 2018).

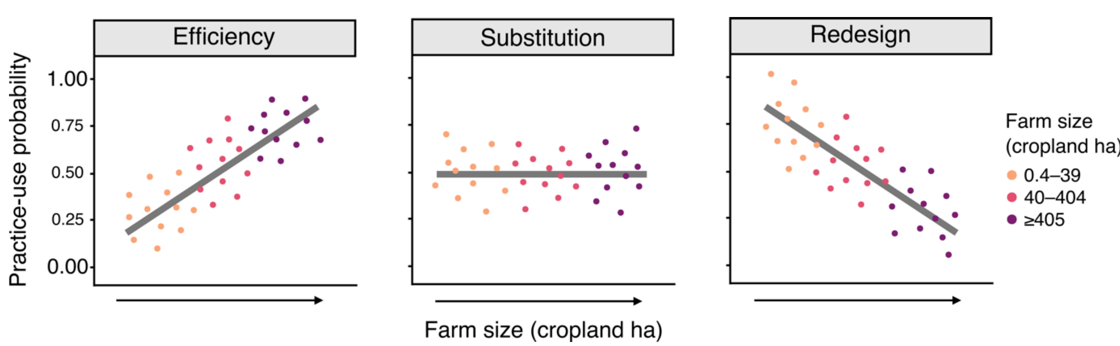

Figure 3.6 | Conceptual diagram illustrating the relationship between farm size and agroecological practice-use. Integrative approaches include using an agroecological practice as an efficiency-increasing tactic, as a substitution for a less-sustainable input, or as part of the systematic redesign of an agroecosystem. Points are for illustrative purposes only.

Conceptualizing the E-S-R framework as it relates to farm size and the probability of practice-use has implications for developing policy that is tailored to farm size. In the policy and scientific discourse about how agriculture should minimize or remedy the socio-ecological ills associated with the dominant food system, two distinct approaches have emerged: incrementalism and transformation (Eyhorn et al., 2019). The former focuses on increasing efficiency and substitution whereas the latter prioritizes redesign. In relation to the E-S-R framework, however, incrementalism and transformation are not mutually exclusive. While greater implementation of agroecological practices can deliver a wide range of social and ecological benefits (Wezel et al., 2014), the use of these practices among farmers is limited, particularly as part of a redesign approach. In light of the relationships between farm size and practice use, we offer public and private sector decision-makers three pathways for guiding transformative change in agriculture:

1. Promote increased use of agroecological practices, especially those involving non-crop vegetation, among large-scale organic farmers through enhanced outreach and education to policy makers, private sector actors, extension educators, and farmers on the multifaceted benefits of comanaging a farm for biodiversity conservation and food safety.
2. Support small and, in particular, medium organic farms by increasing access to "values-based supply chains" and alternative markets, such as regional food hubs, that lie outside the scope of direct competition with large farms.
3. Develop or revise incentive programs to provide progressively greater financial assistance for agroecological practice-use that demonstrates characteristics of efficiency (less support) through redesign (more support).

Just as farm size is a proxy, not a prophecy, conventionalization of the organic sector is not an inevitable trajectory. The degree to which an organic farm might be described as conventionalized exists on a gradient, and the probabilities we have presented are calls to action, not predetermined outcomes. Whether an organic farm has become conventionalized through size or management changes or it has exhibited characteristics of conventionalization since its establishment, targeted, scale-appropriate policy interventions can shift both management and sustainability outcomes.

While this work is focused on organic agriculture, we expect that the farm size and agroecological practice-use relationships we describe within the E-S-R framework exist under all types of farm management. To this end, we recommend that farm size and the way in which agroecological practices are used be positioned more centrally when developing or refining policy and research priorities aimed at generating transformative change in US agriculture.

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CHAPTER 4

CROPLAND CONSOLIDATION, MECHANIZATION, AND A SHRINKING LABOR MARKET: SITUATING THE LABOR-INTENSITY OF AGROECOLOGICAL PRACTICES IN THE U.S.

4.1 ABSTRACT

Agroecology has been promoted as an alternative to industrial agriculture due, in part, to the social and environmental benefits associated with agroecological practices. However, agroecological practices are commonly characterized as more labor-intensive than farm management that relies on fossil-fuel based inputs. The labor-intensity of agroecological practices raises major questions in the United States (US), where the farm labor market is shrinking, political economic pressures have promoted mechanization and consolidation for decades, and labor is often already fruit and vegetable farmers' greatest expense. To understand the degree to which labor requirements present a barrier to agroecological practice-use among fruit and vegetable farmers by farm size (small, 0.4–39 ha; medium, 40–404 ha, and large, ≥405 ha), we conducted a national survey (n = 603) and interviewed farmers in California and New York (n = 49). We show that farmers who did not use agroecological practices perceived a greater labor requirement than farmers who had experience using a given practice. Labor shortages were a greater problem on medium and large farms than on small farms, and increasing mechanization was the main strategy for managing labor-related challenges on large farms, despite already being the most mechanized farm type by size. Our results underscore the need to directly engage with labor-related issues, including political economic lock-ins associated with labor policy and mechanization, to increase the use of agroecological practices in the US.

4.2 INTRODUCTION

The balance between ecosystem services and disservices in agriculture depends primarily on farm management (Power, 2010), with landscape composition and configuration positioned as key, potentially mediating (Rieb and Bennett, 2020), spatial factors. Seeking multifunctionality from farms and agricultural landscapes increases management complexity, however, with interactions among practices capable of producing synergies or trade-offs (Bennett et al., 2009). Landscape simplification (i.e., the combined decrease in compositional and configurational complexity; Meehan et al., 2011) and the continued decline of biodiversity are becoming increasingly urgent concerns around the world (Díaz et al., 2019). In the United States (US), crop species diversity has declined, albeit unevenly across regions and counties, between 1978 and 2012 (Aguilar et al., 2015). In 2017, just two crop species, corn and soybean, comprised 55% of all US cropland (USDA NASS, 2019). Such persistent long-term trends present major sustainability challenges, especially as biodiversity undergirds (agro)ecosystem function, which is in turn critical for the delivery of the ecosystem services upon which humans depend (Wood et al., 2015; Landis, 2017).

In contrast to biological simplification, agricultural diversification can support numerous ecosystem services, such as pest control, pollination, and carbon sequestration, without compromising crop yields (Tamburini et al., 2020). A second-order meta-analysis recently demonstrated that increasing crop diversification—through such agroecological practices as cover cropping, intercropping, and crop rotation—can enhance yields, biodiversity, and the delivery of ecosystem services, although the effects vary by practice (Beillouin et al., 2021). Such findings build on previous work showing that alternative agricultural systems, such as organic farming, exhibit the potential to perform well across sustainability metrics, but that performance is highly context-dependent (Seufert et al., 2012; Ponisio et al., 2015; Seufert and Ramankutty, 2017).

Despite the wide array of potential benefits attributed to highly diversified farms and the use of agroecological practices (Rosa-Schleich et al., 2019; Petersen-Rockney et al., 2021), adoption and consistent use of such practices in the US is limited (Liebert et al., 2022). Instead, agricultural landscapes across the US are dominated by intensive production on industrial farms—farms that are simultaneously decreasing in number while managing an increasing proportion of the total cropland (USDA NASS, 2019, 2020). By substituting or replacing skilled labor, ecological knowledge, and ecological processes with mechanization, capital-intensive technology, and fossil fuel-based inputs, industrial agriculture has pursued high yields while externalizing many ecological and social costs of production (Weis, 2010; Holt-Giménez and Altieri, 2012; Kremen et al., 2012; Vandermeer and Perfecto, 2012; Carlisle et al., 2019b).

In the literature on agroecology, diversification, and related sustainable agriculture approaches, agroecological practices are often described as more labor-intensive than industrial management practices (Johnston et al., 1995; Rosset and Altieri, 1997; Guthman, 2000; Getz et al., 2008; Timmermann and Félix, 2015; Petersen and Silveira, 2017; Carlisle et al., 2019a, 2019b). Yet, this assertion is under-researched, especially empirically, in the US (HLPE, 2019). Agricultural labor is a central factor in historical and political economic analyses of development, class struggle, and agrarian change across many social science and interdisciplinary fields (e.g., see Chayanov, 1966; Marx, 1990 [1867]; Foster, 1999; Lobao and Meyer, 2001; Bernstein, 2010; McMichael, 2013; van der Ploeg, 2013). The intentional choice to rely on manual labor, sometimes explicitly as a form of resistance to both replacement and displacement by capital (e.g., machines and chemicals), has been studied as an essential component of social reproduction, autonomy, emancipation, and food sovereignty (Patel, 2009; Alkon and Mares, 2012; van der Ploeg, 2012, 2021; Edelman et al., 2014; McMichael, 2014; Nelson and Stock, 2018). In contrast, “modern inputs” that aim to replace labor can lead to incorporation into commodity production, consolidated supply chains, insurmountable indebtedness, reduced agency, and a suite of other capitalist logics that are in conflict with the value systems, ways of knowing, and ways of being of many farmers associated with agroecology and the food sovereignty movement (Wittman, 2009; Alonso-Fradejas et al., 2015; La Via Campesina, 2017; Tilzey, 2017). Such descriptions and understandings, however, depend on the context.

Agricultural labor has the potential to help provide meaning and dignity to one’s life (Timmermann and Félix, 2015), but it can also be extractive, exploitative, and unjust under certain conditions (Holmes, 2013; Gray, 2014; Guthman, 2014; Minkoff-Zern, 2014, 2019; Thompson, 2017; Soper, 2020; Weiler et al., 2020). Broader research on the relationship between work conditions and farm size has shown that farmworker treatment by farm size (e.g., small vs. large) or management type (e.g., conventional vs. organic) resists generalization and can defy common public perceptions that valorize small-scale organic farms (Dumont and Baret, 2017). For instance, Harrison and Getz (2015) found that large-scale farms might be able to provide nonwage benefits, such as health insurance, housing, and paid time-off, that small-scale farms cannot afford; however, the authors also found that such benefits accrued disproportionately to white, US-born farmworkers. In a study based in California, Soper (2020) explained the impossible dilemma facing farmworkers whose livelihoods depend on strawberry harvests: short-term economic survival on conventional farms via a wage structure (piece-rate per filled box) favoring larger fruit grown with synthetic inputs, versus long-term occupational health on organic farms due to reduced pesticide exposure. Comparing the working conditions on agroecological, organic, and conventional vegetable farms in Belgium, Dumont and Baret (2017) found that agroecological farms did not consistently provide a better work environment for their farmworkers than other farm types. As the authors note, broader structural factors, such as the socioeconomic and political context in which a farm is embedded, can exert a strong influence on the livelihoods and lived experience of farmworkers.

4.2.1 Conceptual framework: treadmills, lock-ins, path dependency, and inertia

Although the labor-intensity of agroecological practices is commonly acknowledged, recommendations to adopt such practices are rarely situated within region-specific socio-technical trends in agriculture. This, in turn, may be limiting the effectiveness of efforts to increase agroecological practice adoption. Consequently, the concept and theory of an "agricultural treadmill," first described by Cochrane in 1958, is worth briefly revisiting for the synthesis and interpretation of our results.

Originally introduced as a "product price" treadmill whereby farmers adopt new technologies in an effort to increase their income through efficiency gains (Cochrane, 1958; Levins and Cochrane, 1996), discourse on the agricultural treadmill, "early adopters," and "laggards" is well-worn territory among agri-food scholars. In the years since its introduction, many types of so-called treadmills have been proposed. The "pesticide treadmill" is one of the more enduring examples (Nicholls and Altieri, 1997), among many others (e.g., see Obach, 2007; Binimelis et al., 2009; Bakker et al., 2020). Industrial agriculture can be broadly understood by treadmill logic, whereby downward pressure (e.g., a lowering of the prices received due to oversupply) and upward pressure (e.g., increased input costs necessary for production) can force farmers to adopt new technologies or scale up production in an effort to stay in business (Magdoff et al., 2000). As a result of this cyclic process, financial returns are expected to decline per unit of output (government interventions notwithstanding), and farmers are left seeking newer technologies and more land to stay afloat.

Lock-ins, path dependency and inertia are complementary concepts to agricultural treadmill theory (Sutherland et al., 2012; IPES-Food, 2016; Leach et al., 2020). In a systematic review on lock-ins and path dependency, Conti et al. (2021) found that 83% of the peer-reviewed studies classified as "agricultural systems research" described the broadscale resistance to agri-food system change through the persistence of dominant technologies, yet none of the scholarship from this research domain sought political economic explanations. Although some depictions of an agricultural treadmill are stepwise and cyclic, we consider the embeddedness of technologies and the influence of political economic factors to operate concurrently as both lock-ins (cause) and path dependencies (effect).

The concept of an agricultural treadmill, influenced by political economy considerations, is useful in relation to the ongoing process of land and power concentration in US agriculture. The exodus of farmers from the sector and gradual increase in mean farm size (as fewer farmers manage increasingly large operations) has been well documented. Over the last three decades, large-scale farms (≥405 ha) in the US have increased the proportion of cropland they manage by nearly 24%; this gain has come almost entirely at the expense of medium-scale farms (40–404 ha), who saw the proportion of cropland they manage decrease by 23% (USDA NASS, 2019; Liebert et al., 2022). The proportion of cropland managed by small-scale farmers (<40 ha), however, has remained essentially unchanged with just a 0.3% decrease over the same timeframe (1987 to 2017). As fewer farmers on large-scale, highly mechanized operations manage an increasing share of the total US cropland, the relative labor-intensiveness of agroecological practices has implications for the feasibility of agroecological transitions (Bruce and Som Castellano, 2017; Carlisle et al., 2019a, 2019b). Although the cultural, socio-technical, and political contexts vary widely, tensions between labor requirements and agroecology also have global resonance (De Schutter, 2012; Navarrete et al., 2015; Coolsaet, 2016; Dumont and Baret, 2017; Bezner Kerr et al., 2019; Akram-Lodhi, 2021). Recent work showing that larger-scale farmers generally use fewer agroecological practices (Pépin et al., 2021; Liebert et al., 2022) further highlights the need for empirically evaluating claims of labor-intensity in relation to socio-technical trends.

The labor-intensity of agroecological practices presents multiple potential issues in the US, where the political economic context has encouraged mechanization and the consolidation of cropland for decades. We use quantitative data from a national survey of fruit and vegetable farmers and qualitative data from interviews with small- to large-scale farmers in California and New York to address several interrelated questions: (1) how does experience with an agroecological practice affect farmers' assessments of labor-intensity; (2) how are labor shortages experienced by farm size; and (3) how do the responses to labor shortages and other labor-related challenges differ by farm size?

4.3 METHODS

To investigate the claims of labor-intensity associated with agroecological practice use, we engaged in a mixed methods approach. We obtained qualitative data from regional interviews with farmers and quantitative data from a national survey of farmers in the US.

4.3.1 Qualitative data: interviews

Between 2017 and 2019, we conducted 49 in-depth, semi-structured interviews with fruit and vegetable farmers in California and New York. Farmer interviewees in our sample produced a wide variety of fruits and vegetables, covering all major categories from roots and tubers to fruit and nut trees. Crop diversity ranged from as few as 2 to more than 50 crops, with some farmers growing hundreds of fruit and vegetable cultivars in a single calendar year. Some of the farmers also produced field crops, such as corn, soybean, and wheat, and some managed livestock in addition to fruits and vegetables.

4.3.1.1 Sample and site description

In California, we interviewed 25 farmers: 13 farmers used either strictly organic or a mixture of both organic and conventional management, and 12 farmers used strictly conventional management. These California farms ranged in size from 0.8 to 40,469 cropland ha, and they were located in Kern, Monterey, San Benito, San Luis Obispo, Santa Clara, Santa Cruz, Solano, Sutter, and Yolo Counties (sometimes spanning more than one county). Although the majority of cropland (>95%) was located in California for the farmer who managed 40,469 ha, it should be noted that this total represents land in several other states across the US as well. In New York, we interviewed 24 farmers: 14 farmers used either strictly organic or a mixture of both organic and conventional management, and 10 farmers used strictly conventional management. These New York farms ranged in size from 1 to 1,093 cropland ha, and they were located in Albany, Cattaraugus, Cayuga, Columbia, Cortland, Delaware, Dutchess, Erie, Genesee, Monroe, Orleans, Oswego, Putnam, Rensselaer, Schoharie, St. Lawrence, Ulster, and Wyoming Counties.

The difference in the upper range of farm sizes between California and New York reflects the substantial differences in the scale of crop production, and degree of industrialization, between the two states. For instance, there was 3.9 million ha of cropland and over 470,000 ha of harvested vegetables in California in 2017 compared with 1.7 million ha of cropland and around 50,000 ha of harvested vegetables in New York (USDA NASS, 2019, 2020). The selection of California and New York as focal areas for this study reflect their importance as fruit and vegetable growing regions in the US, as well as their importance to research team collaborators who have established networks and interest in supporting farmers in the two states.

4.3.1.2 Interview guide and sampling design

Our interview guide was developed through a review of the literature; preliminary, informal farmer interviews; and past field experience of the research team. This interview guide, along with all other pertinent aspects of this study, was approved by the Cornell Institutional Review Board (IRB) for Human Participants (Protocol ID #1612006859).

We used maximum variation purposive sampling to identify and contact potential interviewees in California and New York. This approach allowed us to obtain interviews from farmers spanning multiple axes of characterization, such as simple to diversified agroecosystems and small- to large-scale operations. Our interview guide was used to conduct in-depth, semi-structured interviews with farmers in both states. Unlike the structured questionnaire used for our electronic survey (described below), semi-structured interviews are flexible enough to foster some of the common conventions of natural conversation. In this way, semi-structured interviews are intended to bring interviewees into a dialogue so that they can direct it in ways that better communicate their experiences and perceptions. We continued to interview farmers until new information on the motivations and deterrents to agroecological practice use—a broader research project focus—no longer emerged, indicating that saturation (or redundancy) had been reached. Interviews were conducted in multiple phases to facilitate an iterative process whereby emergent topics and themes could be integrated into the interview guide, serving as foci in subsequent interviews. This staggered approach also allowed the interview findings to inform the development and refinement of the survey questionnaire, which in turn affected how we conducted the interviews. In this way, we followed a “concurrent mixed methods” approach (Creswell, 2009).

4.3.1.3 Interview analyses

The farmer interviews lasted between 1 and 6 hours, with a mean duration of 2.5 hours. Interviews were audio recorded with permission and transcribed verbatim in all cases but one. During the interview with the farmer who did not agree to be recorded, field notes of the responses were documented in real-time by the interviewer. Designed to yield more granular, yet complementary, data to our national survey, these interviews covered a broad range of topics, including, but not limited to, agroecological practices and on-farm decision-making, labor and mechanization, economics and marketing, wildlife conservation, information and knowledge networks, policy, and climate change. The transcribed interviews were analyzed in ATLAS.ti (version 22). Using an iterative approach, the transcriptions were coded with key factors related to agroecological practice use, labor, knowledge, and related topics, as well as emergent themes. Illustrative quotes have been selected to represent the common or typical response for a given topic, unless otherwise noted. Interviewee attribution has been anonymized in accordance with the IRB-approved protocol.

4.3.2 Quantitative data: survey

A national survey of fruit and vegetable farmers was designed and distributed to complement and enhance the findings from the regional farmer interviews. As noted, the interviews helped inform the development of the survey tool by indirectly providing guidance on whether certain topics demanded more or less attention, how questions should be phrased, the response options that should be provided, and the inclusion of new, emergent topics that were not included in initial drafts of the questionnaire. After a series of revisions based on the insight gained from farmer interviews, the questionnaire was pilot tested by a diverse group of farmers from across the US. Feedback from these farmers was incorporated into a final version of the questionnaire.

4.3.2.1 Sampling approach

The questionnaire was created with the Qualtrics online survey platform and was accessible with a computer, tablet, or smartphone. We predominantly used maximum variation sampling, which is a sub-type of purposive sampling, as it was important for our research objectives to collect responses from fruit and vegetable farmers who managed simplified to diversified and small- to large-scale operations. Sampling bias was minimized through a diverse, purposeful survey outreach approach. This strategy, which also helped ensure that we obtained a sufficient sample of respondents across the diversification and size spectrums, included a wide array of tactics aimed at reaching farmers electronically. For example, some of these efforts, as described by Liebert et al. (2022), included posting survey invitations on farmer listservs; sharing invitations through various social media platforms, on farming-focused websites, and in electronic agricultural newsletters; promoting the survey through trade magazine interviews; contacting farmers directly with email addresses obtained from extension educators, grower associations, non-governmental organizations, and public databases; and through referral (snowball) sampling.

Survey responses were collected between February and November 2018.

Outreach and advertisement were intermittent, rather than regular or continuous, during this extended period of time. The questionnaire could be completed, once started, within a two-week timeframe.

4.3.2.2 Data preparation

A total of 1,264 responses were collected from fruit and vegetable farmers throughout the US. Data preparation, such as cleaning, was conducted using R version 4.1.1 (R Core Team, 2021), making extension use of the ‘tidyverse’ package (Wickham et al., 2019). All exclusion criteria were pre-established. For the statistical analyses of the quantitative data in this study, we required respondents to satisfy the following criteria: (1) farm in the US, (2) manage farms at least 0.4 ha in size (to align with most USDA Census thresholds), (3) grow some fruits or vegetables (not necessarily exclusively), and (4) indicate whether they use or do not use at least one of the eight agroecological practices of interest (compost/manure, intercropping, insectary plantings, reduced tillage, diverse crop rotation, cover cropping, border plantings, riparian buffers). After excluding responses according to these four criteria, 603 farmer respondents from 44 states were retained for the statistical analyses.

Based on the amount of cropland under production, the 603 responses were then organized into one of three farm size categories: 0.4–39, 40–404, or ≥405 ha. This size-based categorization process was also used by Liebert et al. (2022). Each of the categories presented here is a combination of several size groups used in the USDA 2017 Census of Agriculture. Combining farm size groups with consistently decreasing or increasing 30-year trends avoided obscuring the overall long-term trend of cropland consolidation in the US.

4.3.2.3 Data analysis

All data analyses and visualizations were also completed in R version 4.1.1 (R Core Team, 2021). Working exclusively with categorical variables, our analyses of $I \times J$ contingency table data tested the null hypothesis that there was no association between the two variables in question, unless specified otherwise. In most cases, farm size (0.4–39, 40–404, or ≥405 ha) was the categorical "row" variable. The "column" variable was either a single response categorical variable (SRCV) or a multiple response categorical variable (MRCV), which determined the statistical technique used to analyze the resulting contingency table. In addition to the statistical tests that were performed on counts (n), the survey data were also visualized as proportions of farmer respondents (%), by farm size where possible (Wickham et al., 2019).

For survey questions that restricted farmers to selecting a single, discrete response (i.e., an SRCV), a contingency table of counts was created to assess the occurrence of low cell counts ($n < 5$). As none of the contingency tables had <80% of cells with counts <5 (McHugh, 2013), we were able to use chi-squared tests to assess independence (i.e., test the null hypothesis). Given an $I \times J$ contingency table, the test statistic (χ^2) follows a chi-squared distribution with degrees of freedom (df) equal to $(I-1)(J-1)$ (Agresti, 2013). A significant p-value ($p < 0.05$) for the chi-squared tests indicates that there is an association between the two categorical variables. To investigate which specific values and relationships were most strongly influencing this broadly significant association, adjusted Pearson residuals were calculated and extracted from the given contingency table (R Core Team, 2021). As the adjusted Pearson residual follows a standard normal distribution, $N(0,1)$, *post hoc* tests were conducted to assess whether an observed value was significantly different ($\alpha = 0.05$) than expected for a given combination of factors (Agresti, 2019). The Bonferroni correction was used to account for inferential issues related to the multiple comparisons problem. For an adjusted alpha, α_{Bon}, the specified alpha level (α) was divided by number of tests (m); following this, the absolute value of the adjusted residual was compared to the new, corresponding critical value: $N(0,1)_{1-\alpha_{Bon}/2}$ (Bilder and Loughin, 2015).

For survey questions that allowed farmers to "select all [response options] that apply" (i.e., an MRCV), the assumption that observations are independent is violated (Bilder and Loughin, 2015). Consequently, chi-squared (or Fisher's exact) tests could not be used. Instead, an extension of the chi-squared test was used to test for multiple marginal independence (MMI) between one SRCV and one MRCV (Bilder and Loughin, 2015), with a Bonferroni correction and the significance level, α, set to 0.05 ('*MRCV*' package: Koziol and Bilder, 2014). The Bonferroni-corrected *p*-value, $\tilde{p}$, for the overall MMI test is presented in the Results and Discussion for each analysis for brevity, but a bootstrap approximation (with *B* = 10,000 "resamples") and Rao-Scott correction was also performed for each MMI test. In all cases, the three tests of independence were in agreement. An analogous technique to the adjusted Pearson residual-based *post hoc* test was not possible for the contingency tables comprised of one SRCV and one MRCV.

4.4 RESULTS AND DISCUSSION

In addition to 49 interviews with fruit and vegetable farmers in California (*n* = 25) and New York (*n* = 24), our mixed methods approach includes the survey responses of 603 fruit and vegetable farmers from 44 US states. Although grouping farmers into a binary of conventional and organic management types can be a useful framing for some research objectives, numerous studies have shown that the performance of these systems is context-specific and that evaluating a dichotomy can obscure the heterogeneity and important differences within each broad management approach

(Seufert et al., 2012; Seufert and Ramankutty, 2017; Liebert et al., 2022). Here, we characterize farms on a spectrum of biological diversification: simplified farms use few agroecological practices whereas diversified farms use many.

4.4.1 Experience, perception, and farmer assessments of labor-intensity

In analyzing whether labor requirements are evaluated differently among those who do and do not use a given agroecological practice, we are not suggesting that agroecological practices require minimal labor or less labor than alternatives. Instead, we are interested in the potential implications of such a comparison in relation to broader labor market dynamics and trends in cropland consolidation, which might lend useful insights on how to improve adoption and sustained use of agroecological practices. As many of the farmers we interviewed explained, labor can be one of the most important factors driving management decisions and the use of agroecological practices. This issue emerged in a conversation with a small-scale, highly diversified farmer from New York:

> **JL:** In terms of using fewer [agroecological] practices, is it usually being driven by an agronomic reason? Or economic? Is it —
>
> **NY Farmer 19:** It's usually, I think, labor. Cutting down labor has been a large part of it.

In our survey, farmers were asked to indicate the labor requirement (i.e., intensity) of eight agroecological practices from 1–5 (with 1 indicating "very low" and 5 indicating "very high"), even if they did not use a given practice. Overall, farmers who did not use a given practice *perceived* that the practice was more labor intensive than the labor requirements reported by farmers who had *experience* using the practice

(Figure 4.1). Farm size did not have an effect ($p > 0.05$) on the labor requirement responses for all agroecological practices except insectary plantings ($p = 0.001$; data not shown). With farm sizes pooled together, use and disuse of a given agroecological practice affected farmers' responses to questions about the labor intensity for compost/manure ($p = 0.001$), intercropping ($p = 0.0002$), insectary plantings ($p = 0.002$), cover cropping ($p = 0.02$), and border plantings ($p = 0.0004$), but not for reduced tillage ($p = 0.5$), diverse crop rotation ($p = 0.4$), and riparian buffers ($p = 0.1$).

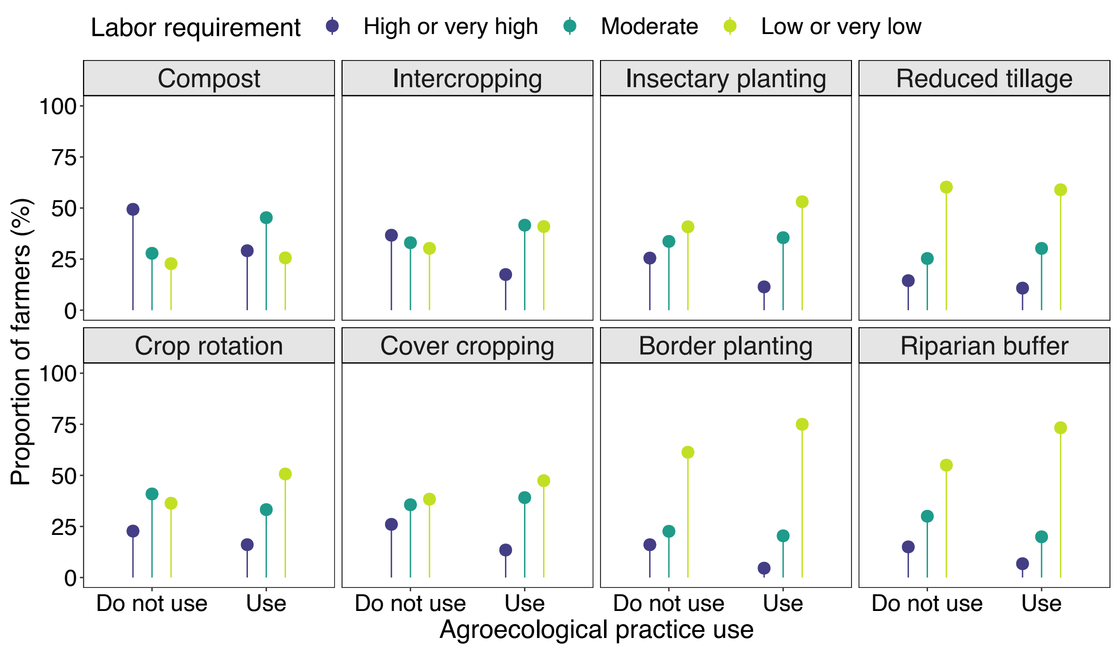

Figure 4.1 | The effect of experience with a given agroecological practice on evaluations of labor intensity. For each agroecological practice, survey respondents are grouped by practice experience: those who do not use a practice and those who do. Within these groups, the perceived (do not use) or experienced (use) labor requirement (high or very high, moderate, low or very low) is shown as a proportion of farmers (%) for each practice.

Farmers' perceptions of whether a given practice had a "high" or "very high" labor requirement differed based on whether they used the practice or not. A greater proportion of farmers who did not use a given practice indicated that the labor requirement of that practice was "high" or "very high" compared to farmers who used the practice (Figure 4.1), with differences ranging from 4% for reduced tillage (15 to 11%, disuse to use) to 20% for compost use (49 to 29%, disuse to use). Conversely, for seven of the eight practices, more farmers who used a given practice indicated that the labor requirement was “low” or “very low” compared to those who did not use the practice, with differences ranging from 3% for compost use (26 to 23%, use to disuse) to 18% for riparian buffers (73 to 55%, use to disuse). Reduced tillage was an exception, marginally, with 1% more farmers who did not use the practice, compared to those who did use it, indicating that the labor requirement was “low” or “very low.”

4.4.2 Labor shortages

Labor shortages have been a persistent, though spatially uneven and temporally irregular, feature of US agriculture. In fiscal years 2017–2018, the US Department of Labor’s National Agricultural Workers Survey (NAWS) found that of all the interviewed farmworkers involved in crop production, 64% were born in Mexico, 32% were born in the US or Puerto Rico, 3% were born in Central America, and the remainder were born in other regions around the world (USDOL ETA, 2021). The findings from NAWS also revealed that 63% of farmworkers were authorized to work in the US (USDOL ETA, 2021). Recently, however, two key trends have emerged: the number of farmworkers from Mexico is decreasing, and the rate of undocumented immigration from Mexico has slowed such that it is now lower than the rate at which undocumented immigrants are returning to Mexico (Zahniser et al., 2018). Together, these trends—born of multiple factors, such as increasing rural education and a growth in both agricultural and non-agricultural employment in Mexico—are strong indicators of a tightening labor market (Zahniser et al., 2018).

Among the farmers we surveyed, a chi-squared test indicated that there was a relationship between farm size (0.4–39, 40–404, or ≥405 ha) and the severity, or absence, of a labor shortage (crisis, major problem, minor problem, no shortage; $\chi^2 = 30.02$, $df = 6$, $p < 0.0001$). Small-scale farmers were less likely (18%, $n = 63$) and large-scale farmers more likely (42%, $n = 21$) than expected to indicate that the labor shortage was a major problem (Figure 4.2). Conversely, small-scale farmers were more likely (45%, $n = 160$) and large-scale farmers less likely (18%, $n = 9$) than expected to indicate that they were not experiencing a labor shortage at all.

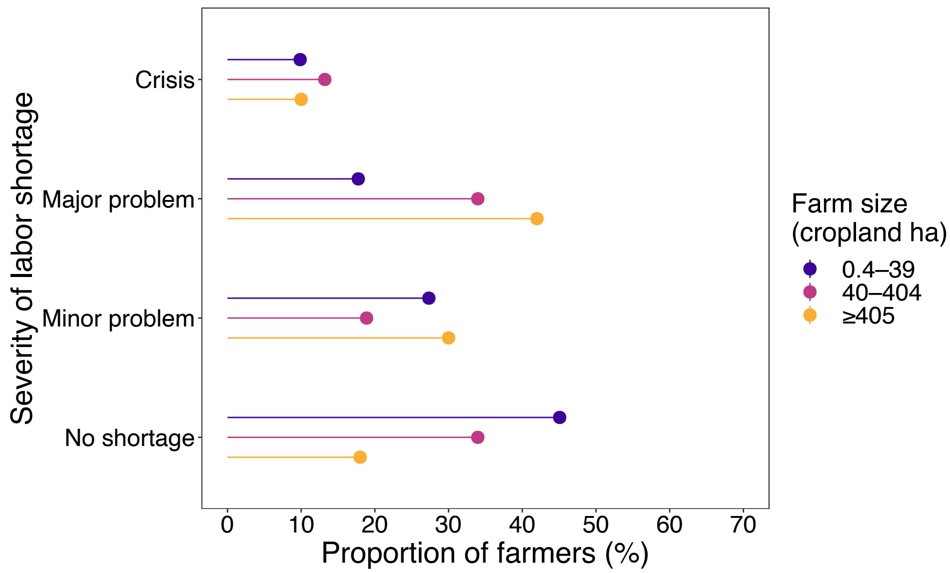

Figure 4.2 | The relationship between farm size (0.4–39, 40–404, or ≥405 ha) and the severity of a farm labor shortage, if present (crisis, major problem, minor problem, or no shortage).

In correspondence with the shrinking farm labor market, labor frequently emerged in our interviews as a complex, multifaceted challenge. All farmers with hired workers designated labor as the greatest expense on their farm, with estimates ranging from 30 to 60% of total costs. Although paying farmworkers was the single largest expense, many farmers also expressed how difficult it was to get enough workers to complete daily tasks. Beyond tilling unharvested crops into the soil or leaving them to rot, a shortage of workers can also translate to farmers spending a significant amount of time training new workers. Notably, some of the older farmers explained that in addition to a labor shortage, there was a shortage of a certain “kind” of farmworker—one that is, as various farmers put it, “capable,” “hardworking,” “skilled,” and “qualified.” This characterization of farmworkers as “unskilled” or “unqualified” plays into racial and class dynamics that have long been used to justify poor wages, unsafe working conditions, and limited labor rights for farmworkers (Hagan et al., 2015; Klocker et al., 2020). Such descriptions also diminish the knowledge, skill, and abilities required for farm work by implying that farmworkers are interchangeable or even disposable (Hernández Romero, 2012).

Taking advantage of the increased vulnerability of undocumented farmworkers has been described in ethnographic research and interviews with farmworkers throughout the US (Holmes, 2013; Snipes et al., 2017; Thompson, 2017). In our interviews, the exploitative nature of farmer-farmworker relationships occasionally emerged, particularly in relation to workers’ status. For example, the conflict between farmers’ support for stricter immigration policies (Montenegro de Wit et al., 2021) and the effect it was having on a reliable source of “cheap” and exploitable labor was apparent as some farmers grappled with this contradiction during the interviews. Describing what they understood as differences between US-born and migrant or foreign-born farmworkers, as well as those with different documentation (i.e., work authorization) status, CA Farmer 10 noted:

> For them, they don’t have the desperation—the need that a lot of the migrant workers used to have… Having said that though, definitely a part of the problem has been immigration enforcement, because the difference between a guy with papers and a guy with no papers is that at the end of the day, the guy with papers, if he doesn't like the job and

> doesn't like where he's at can say, 'Okay, I'm going to go find another job.' And the guy without papers, if something happens, something goes wrong, he can't say anything.

In contrast, some farmers expressed gratitude for the farmworkers laboring on their farm, which often involved descriptions of kinship. In a sentiment about farmworkers shared by farmers of all sizes, CA Farmer 15 explained:

> I want them to be happy. I don't want them to come in and feel that they're not worth what they are, or that they're not wanted, or feel uncomfortable… I feel like they're my family.

Although we make no assessment of the authenticity of the various claims the farmers in our study made about the farmworkers they employed, it should be emphasized that other researchers have interrogated similar claims of family-like relationships and found them to obscure class differences and, in some instances, facilitate farmworker exploitation (Gray, 2014; Harrison and Getz, 2015; Reid-Musson, 2017).

Some farmers were also keenly aware of how broader economic changes domestically and abroad could have severe ramifications for their ability to hire enough workers. A robust US economy and strong growth in the residential and commercial construction industry was commonly cited by participants as a sector that was drawing away workers due to the lure of higher wages, more time off, and greater benefits. Farmers also noted that a strong Mexican economy tended to reduce the availability of farmworkers in the US, playing an important role in the shrinking farm labor market (Zahniser et al., 2018). Just as the availability of "cheap" labor can disincentivize research into labor-saving technologies, a reduced availability of farm labor is likely to spur investments in such technologies and increase mechanization (Zahniser et al., 2018). Insensitive to farmworker exploitation or experience, myopic research and development priorities can directly contribute to lock-ins and path dependency in the industrial agri-food system (Conti et al., 2021).

4.4.3 Mechanizing farm work

A chi-squared test of our sample showed that there was an association between farm size (0.4–39, 40–404, or ≥405 ha) and the proportion of mechanization (0–25, 26–50, 51–75, or 76–100%) on a farm ($\chi^2 = 122.81$, $df = 6$, $p < 0.0001$). Overall, small-scale farmers managed less-mechanized operations than medium- and large-scale farmers (Figure 4.3). Over 50% of small-scale farmers ($n = 186$) indicated that 0–25% of the work on their farms was mechanized, compared with 22% ($n = 24$) of medium-scale farmers and 4% ($n = 2$) of large-scale farmers. These counts (n) were higher than expected for small-scale farmers and lower than expected for both medium- and large-scale farmers based on the adjusted Pearson residuals with a Bonferroni correction. Conversely, just 6% of small-scale farmers ($n = 22$, lower than expected) managed operations that were 76–100% mechanized, whereas 30% ($n = 32$, higher than expected) of medium-scale and 50% ($n = 25$, higher than expected) of large-scale farmers described their farms as such.

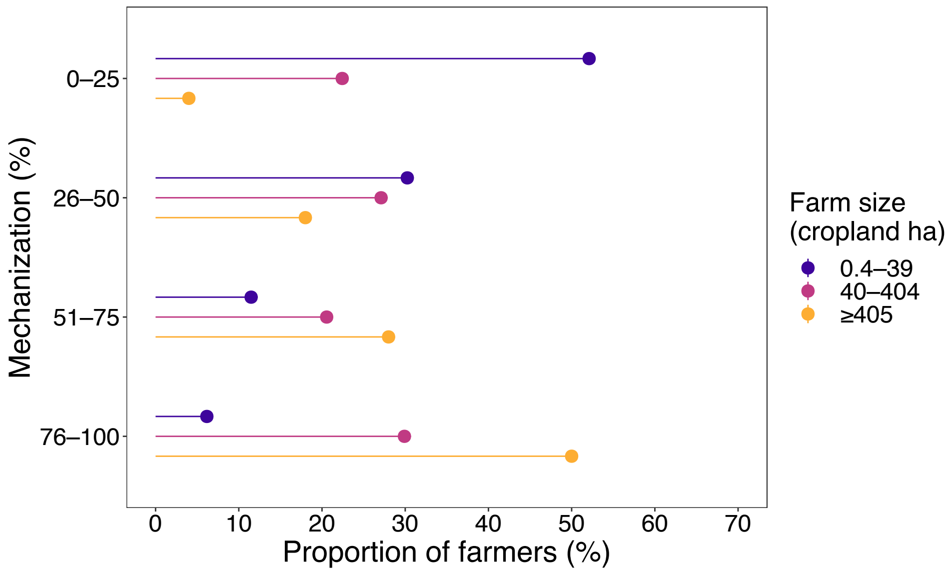

Figure 4.3 | The relationship between farm size (0.4–39, 40–404, or ≥405 ha) and the proportion of farm work that is currently mechanized (0–25, 26–50, 51–75, or 76–100%).

After estimating the proportion of farm work that is currently mechanized on their operations, farmers were asked if they would increase the mechanization on their farm if possible (i.e., assuming they could purchase new equipment or otherwise afford to do so). A relationship was observed between farm size and both an interest in increasing mechanization ($\chi^2 = 27.09$, $df = 6$, $p = 0.0001$) and the reasons for that interest (MMI: $\tilde{p} < 0.0001$). Approximately 44% of small-scale farmers indicated that they would "definitely" want to increase the amount of mechanization on their operation if possible, compared to 62% of medium-scale farmers and 68% of large-scale farmers (Figure 4.4A). Combining the response options of "probably not" and "definitely not," 27, 13, and 2% of small-, medium-, and large-scale farmers, respectively, indicated a disinterest in increasing the mechanization on their operations.

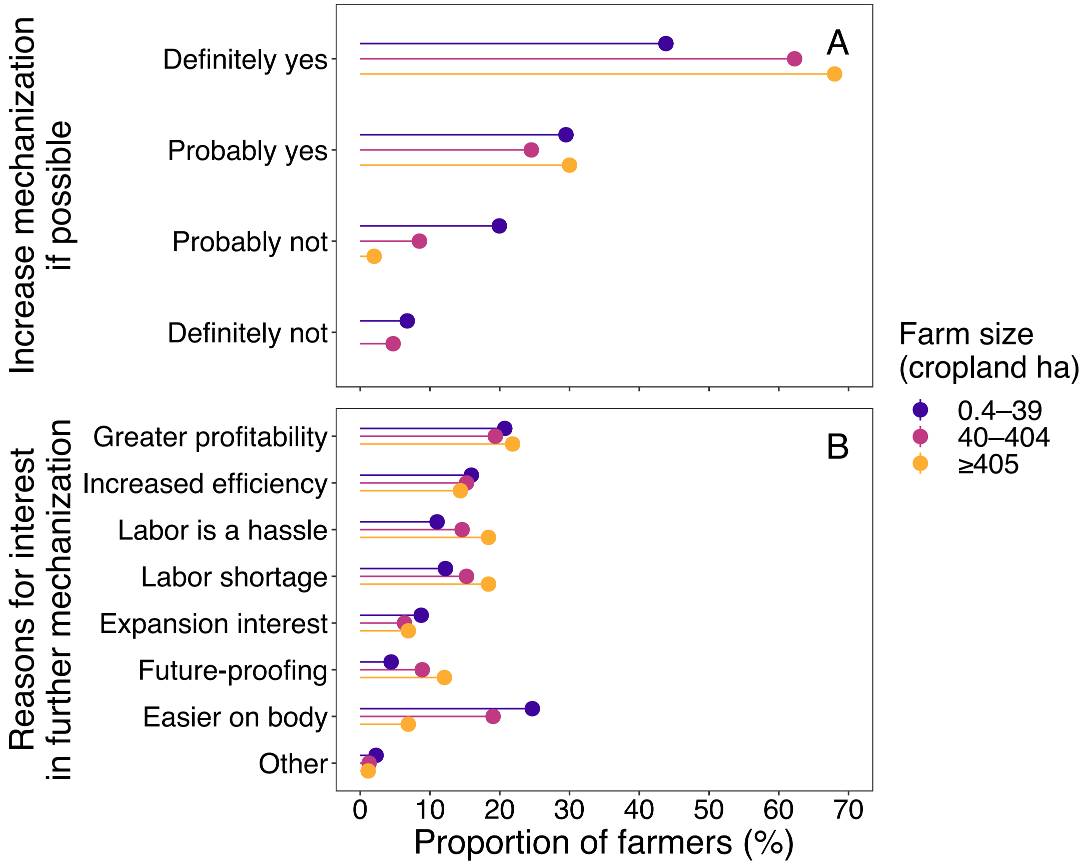

Figure 4.4 | The relationship between farm size (0.4–39, 40–404, or ≥405 ha) and (A) the desire to increase mechanization, assuming there are no economic or other barriers to doing so; and (B) the reasons explaining why farmers were interested in further mechanization (i.e., among those who indicated "definitely yes" or "probably yes" as their desire to increase mechanization).

Based on Bonferroni-adjusted *p*-values, there were associations between farm size and the following reasons for desiring greater mechanization: labor is a hassle or burden ($p = 0.0008$), labor shortage ($p = 0.007$), highly mechanized farms are the future of agriculture ($p < 0.0001$), and such management would be easier on their body than manual labor ($p < 0.0001$). For large-scale farmers, the burden of managing labor, finding enough labor, and "future-proofing" their operation more frequently underlaid an interest in increasing mechanization, whereas small-scale farmers pointed to the physical relief that mechanization can afford compared to manual labor (Figure

4.4B). Among the farmers who indicated disinterest in greater mechanization (i.e., "probably not" or "definitely not"), no association was observed between farm size and the reasons for disinterest (MMI: $\tilde{p} = 0.2$; data not shown). It is worth noting, however, that over 19% ($n = 63$) of small-scale farmers indicated that they were not interested in greater mechanization because they thought such a change would prevent them from farming the way they want to, which includes a substantial amount of manual labor.

4.4.4 Managing labor challenges: minimum wage, cheap food, and the urban-rural divide

Overall, 55% of small-, 66% of medium-, and 82% of large-scale farmers reported experiencing a labor shortage that was at least a "minor problem" for their operation (Figure 4.2). The approaches farmers took to managing this labor shortage varied by farm size (MMI: $\tilde{p} < 0.0001$). In particular, farm size exhibited a relationship with the following management approaches: increasing mechanization ($\tilde{p} = 0.0001$) and hiring H-2A temporary agricultural workers ($\tilde{p} < 0.0001$). Proportionally, less small-scale farmers (12%, $n = 60$; and 5%, $n = 9$) than large-scale farmers (22%, $n = 28$; and 11%, $n = 14$) indicated that they would manage the labor shortage through greater mechanization or hiring H-2A workers, respectively (Figure 4.5A).

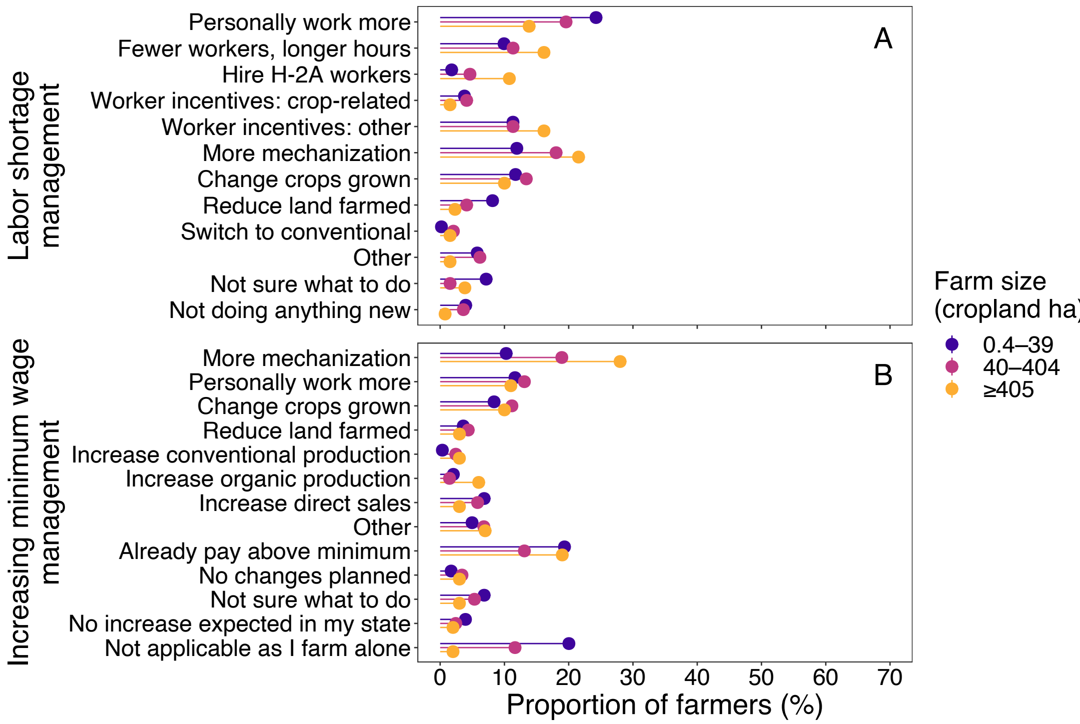

Figure 4.5 | The relationship between farm size (0.4–39, 40–404, or ≥405 ha) and (A) management changes in response to a labor shortage and (B) management changes in response to a mandated increase in the minimum wage.

In addition to a lack of workers, mandated increases to the minimum wage in some states were also driving farmers to look towards various compensatory strategies (Figure 4.5B), which also differed by farm size (MMI: $\tilde{p} < 0.0001$). Greater mechanization was again associated with farm size ($\tilde{p} < 0.0001$), along with switching to conventional management (for organic-only or mixed operations) to reduce labor needs ($\tilde{p} = 0.03$). Among small-scale farmers, 10% ($n = 60$) indicated an interest in greater mechanization, compared to 28% ($n = 28$) of large-scale farmers. Although there was an association between farm size and switching to conventional production, the number of farmers who selected that strategy was fewer than 5 for both small- and large-scale farmers.

In California, a diversified large-scale farmer described how scheduled changes to farmworker overtime policy (i.e., that stipulate an overtime rate of pay based on hours worked per day or week), the scheduled increase in minimum wage, and the labor shortage might collectively affect their operation:

> **JL:** What are your thoughts on the overtime policy change that's coming, and the minimum wage increase in California?
>
> **CA Farmer 23:** We're factoring. We're factoring it into our business every day as far as it's probably going to change some of our crops that we grow in the future. Of course, some labor-intensive crops, we probably won't be able to grow.
>
> **JL:** Which labor-intensive crops might you have to drop?
>
> **CA Farmer 23:** Carrots are probably one of them, but we're probably going to tackle that by mechanizing. That would be one that's very labor intensive. Some of the other ones, like green beans, bell peppers, zucchini, cucumbers—those are all labor intensive.
>
> **JL:** Will you hire more people so that fewer employees work overtime?
>
> **CA Farmer 23:** Well, you can in theory, but you literally cannot hire enough people right now. We're short of labor every day, all year. Every morning we need to decide what we're not going to harvest that day because we don't have enough labor.
>
> **JL:** Does that mean produce gets disced?
>
> **CA Farmer 23:** [Nods silently]

During our interviews, some farmers became the most animated when discussing labor in relation to changes to the minimum wage. For these farmers, public expectations of social (and environmental) justice were incommensurate with an unchanged expectation for cheap food. As CA Farmer 17 clarified:

> Talking about labor, I would never want to say that people who are working don’t deserve the money. They deserve the money. They deserve more than they're getting paid. Everybody works incredibly hard. We're just not getting paid enough for the produce.

In the Central Coast of California, a highly diversified medium-scale farmer who already paid his workers above the minimum wage lamented that the scheduled minimum wage increases were too slow and too far in the future. He noted that a mandated increase might make his customers more accepting of the prices he charged, which partially reflect his organic certification, but he was also worried about affordability. The price premium this farmer receives, however, is likely due to an array of customer perceptions about organic agriculture, from personal health benefits and superior taste to greater environmental stewardship and higher animal welfare standards (Hughner et al., 2007). Notably, customer motivations for buying organic food do not typically include an improvement of farmworker livelihoods, working conditions, or treatment. Accordingly, the absence of clearly defined social dimensions in the US National Organic Program guidelines have also been widely critiqued (DeLind, 2000; Guthman, 2004; Darnhofer et al., 2010; Jaffee and Howard, 2010; Seufert and Ramankutty, 2017). Whether or not a farmer could obtain a price premium for their produce, the farmers we interviewed described their ability to absorb higher labor expenses as constrained, in part, by persistent public expectations for low-cost food. Large-scale farmers who sold wholesale, rather than directly to customers, articulated having even fewer options given the power asymmetry in place during price negotiations with buyers. A relatively simplified large-scale farmer in New York put it plainly during the interview:

JL: And with the increase in minimum wage on the horizon, do you see that as being…

NY Farmer 12: Oh, it's a huge problem!

JL: What will you do? Do you have any plans in place?

NY Farmer 12: We can't afford it, you know what I mean? We try to raise our prices a little bit, but we're not really price makers—we're price takers.

Some of the themes that emerged in our interviews can also be understood as part of the so-called rural-urban divide, which has been studied in the US for decades (Bealer et al., 1965). Although many of the farmers we interviewed expressed varying degrees of discontent towards an urban population who they claimed does not understand "what it takes to farm," researchers have described the rural-urban boundaries as more fluid than such simple dichotomies imply (Lichter and Ziliak, 2017; Shellabarger et al., 2019). Rather than reify perceptions of cultural and ideological rifts, our intention is to highlight how some farmers described feeling powerless to market forces outside of their control. In New York, for example, a moderately diversified small-scale farmer grew increasingly exasperated when discussing the challenges associated with an increasing minimum wage:

NY Farmer 21: Labor is an issue for everybody. And it's an issue for me because the increasing costs, this rising minimum wage is a burden on all small businesses like myself. It's being forced on us. The price of corn, the price of cucumbers—they have not risen appreciably in the last five years, while my labor bill is up 40%.

> **JL:** So the increase in minimum wage is a big deal.
>
> **NY Farmer 21:** It's a huge deal… And people don't realize—I run a legitimate business. These guys are on the books. So not only does the wage go up, all the supporting costs to have an employee also go up. Medicare goes up, social security—my share goes up. Workers' Compensation is based on payroll; unemployment. These days, field workers go and get unemployment, and my unemployment [insurance payment] goes up.
>
> **JL:** It sounds like it can add up pretty quickly.
>
> **NY Farmer 21:** So, for a small business, this increase in minimum wage is… it's too fast. It's artificial. Another case of government overregulation run amok.

Similar to NY Farmer 21, other farmers that we interviewed conveyed frustration with broader sociopolitical changes, such as those associated with proposed increases to the minimum wage, that seemed out of step with their lived experiences.

4.4.5 Labor, mechanization, and agroecology: synthesizing agricultural treadmill implications by farm size

4.4.5.1 Large-scale farmers

The large-scale farmers we surveyed and interviewed appear to be exhibiting characteristics described by treadmill theorists. Compared with small- and medium-scale farmers, the large-scale farmers in our study expressed more interest in greater mechanization (Figure 4.4A), despite already managing farms with the highest degree of mechanization (Figure 4.3). More large-scale farmers also indicated that further mechanization was their management strategy for dealing with a labor shortage or an increase in the minimum wage (Figure 4.5).

Agroecology scholarship that is centered on large-scale farms is uncommon, but several research foci for supporting a shift among large-scale farmers toward agroecological management have been recently articulated (Tittonell et al., 2020). Notably, however, Tittonell et al. (2020) point out that the labor requirements of agroecology-based transitions to a more sustainable agri-food system might be prohibitive, especially given the high cost of labor. This potential barrier might be a concern for larger farms in general, but the labor requirements of agroecological practices become more problematic in the US context where the long-term trend has been towards fewer farmers and farmworkers directly involved in agriculture, especially among increasingly large farms.

Although increasing crop diversity, which can be achieved through the use of agroecological practices, has been shown to provide jobs and improve rural livelihoods (Garibaldi and Pérez-Méndez, 2019), this rural development strategy would require significant social, economic, and political support to redirect the current large farm-oriented trajectory in the US. As such, questions about the labor-intensity of agroecological practices need to directly tackle the challenges in overcoming long-standing socio-technical trends, particularly among larger-scale farmers who are more highly mechanized, seek even greater mechanization, and who use fewer agroecological practices than small-scale farmers (Liebert et al., 2022).

4.4.5.2 Medium-scale farmers

Medium-scale farmers occupy a distinct position in the agri-food system due to the diversity of markets they can serve; however, the potential to sell through both direct and wholesale markets has been described as both a benefit and a barrier. Some research has suggested that this market flexibility can, in part, confer greater agency, which can facilitate the use of agroecological practices (Esquivel et al., 2021). In contrast, medium-sized farms have also been described as too large and commoditized to sell produce via direct market channels and too small to compete with the large-scale farmers in wholesale markets (Kirchenmann et al., 2008). This latter account in particular has been associated with scholarship on the disappearing “agriculture of the middle” (De Master, 2018). As large farms continue to consolidate cropland at the expense of medium-scale farmers and pursue an even greater degree of mechanization (to reduce labor costs), medium-scale farmers might be facing an increasingly precarious position, at least in terms of traditional wholesale markets. Although some medium-scale farmers are relatively well-capitalized, competition in a highly concentrated commodity market tends to favor economies of scale.

As other researchers have emphasized, slowing the trend of a “disappearing middle” will likely involve a market-based intervention, among other factors. “Values-based supply chains” (VBSCs), for example, have received significant attention from agri-food scholars. VBSCs are regionally focused, short supply chains that aim to ensure economic stability for farmers while embedding social and environmental values in a local food system (Feenstra and Hardesty, 2016). Selling produce directly to retail, food hubs, and institutions, such as hospitals and schools, are the most common examples of intermediated market channels in the US, which can also be described as part of VBSCs in some instances (Dimitri and Gardner, 2019). Among the medium-scale farmers in our survey, 7% sold directly to retail, <1% to food hubs, and <1% to institutions, which underscores the need to further develop, support, and protect intermediated market channels and other alternative supply chain models, such as VBSCs (Stevenson et al., 2011; Feenstra and Hardesty, 2016; Brislen, 2018; De Master, 2018; Dimitri and Gardner, 2019).

4.4.5.3 Small-scale farmers

Some small-scale farmers do not appear to be as affected by the same forces pushing and pulling medium- and large-scale farmers into the agricultural treadmill. There are a few possible explanations here. Small-scale farmers typically sell their produce through direct markets (e.g., farm gate, community-supported agriculture programs, or farmers' markets), which return higher prices per unit than wholesale. If production costs are relatively low, such as with family labor or volunteer workers, direct market channels might help shield small-scale farmers from some of the forces that draw farmers into the agricultural treadmill. Also, it is important to note that across all farms in the US, <25% of farm household income is derived from on-farm production, indicating that >75% is earned off-farm (Burchfield et al., 2022). This divergence is even more pronounced by farm size, with smaller-scale farmers earning substantially less household income on-farm (<5% in some cases) compared to larger-scale farmers, the average of which earn nearly 79% of household income from on-farm activities (Schnepf and Rosch, 2021; Burchfield et al., 2022). Deriving an income from both on- and off-farm work—a combination known as pluriactivity—has been a feature of farming lifestyles in the US and globally. Although pluriactivity can be understood more narrowly as an economic "household survival strategy" (Ward, 1993), some agroecologists have described it as an integral practice used by farmers to pursue greater autonomy (van der Ploeg, 2012; Meek, 2014). From an agroecological perspective, a diversified approach to income generation can be complementary, or even synergistic, with on-farm biological diversification (van der Ploeg, 2012; Nelson and Stock, 2018). Still, contextual factors are important; as some of the farmers we interviewed explained, they would not choose to work off-farm if they could earn a living exclusively through farming.

4.4.6 Conclusion

Contextualized by the long-term trend of cropland consolidation among large-scale farmers, US fruit and vegetable farmers face a complicated array of labor-related challenges: a tightening farm labor market and competition with other sectors for workers, a rising minimum wage, and crop prices that have failed to keep pace with escalating operational expenses. As our results have shown, there is a need for researchers to engage with the social, cultural, and political barriers to, and consequences of, agroecological practice recommendations. Barriers to agroecological practice use are typically multidimensional, spanning individual (social-psychological values, attitudes, and behaviors) and structural obstacles and deterrents. Although farmers who have experience using agroecological practices reported lower labor requirements than the expectations of those who don't use agroecological practices, labor is still the greatest "input cost" or expense for most farmers with hired workers. Consequently, labor conditions should be included more explicitly in efforts to understand and overcome practice-use barriers. These conditions, in relation to our findings from the survey and interviews, raise several questions:

1. In what ways can researchers, extension educators, and other practitioners support alternative models of knowledge-sharing, such as farmer-to-farmer networks (Kansanga et al., 2021), to address the discordance between perceived and experienced labor intensity associated with agroecological practices?
2. Under what conditions are agroecological practices amenable to mechanization without diminishing the delivery of social, environmental, and economic benefits?

3. How can academics and policymakers at all levels of government work more closely together to address infrastructural rigidities, which is one of the most overlooked industrial agriculture lock-ins (Conti et al., 2021), to better support transitions to agroecology?
4. To what extent does the use of agroecological practices, especially many practices used together in complex management systems, depend on off-farm income, farmer self-exploitation (Galt, 2013), and farmworker exploitation?
5. How can policy tools, like a universal basic income (Gundersen, 2021), price parity initiatives (Graddy-Lovelace and Naylor, 2021), or a rights-based approach to food (Anderson, 2013; Riches, 2020), be further explored in the US context to bridge producers' (farmer and farmworker) concerns about the pursuit of dignified livelihoods with eaters' need for equitable access to food?

The recalcitrance of agri-food systems to transformative change is well-established (Kloppenburg et al., 1996; Buttel, 2004; Holt Giménez and Shattuck, 2011; Sutherland et al., 2012; Anderson, 2019; Conti et al., 2021), and our findings underscore the importance of moving beyond compartmentalized scholarship and decontextualized technical solutions. The social-ecological crises confronting society have prompted increasingly urgent calls for inter- and transdisciplinary scholarship (Díaz et al., 2019; Barrett et al., 2020; Webb et al., 2020). Yet too often, agricultural research is designed to pursue narrow goals that can strengthen and reinforce the very lock-ins, path dependency, and inertia that are inhibiting transformative change (Conti et al., 2021). As Ferguson et al. (2019) explain, scaling agroecology involves "relationships, processes, policy, power, and practice that nurture social organization, learning, and adaptation." In the US, there is a tension among numerous trends, including cropland consolidation, a tightening labor market, rising demands for a living wage, and rapid technology development. To realize the full potential of agroecology as a driver of agri-food system change, it will be crucial to bring labor requirements, production lock-ins, and both farmer and farmworker justice into focus.

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EPILOGUE

In the Prologue, I described the numerous challenges facing agroecology research in the US, as well as opportunities for scaling it out. In the chapters that followed, I shared some of my contributions to the development of US-based agroecology, which spanned numerous farming systems (dairy, grain, and fruit and vegetable) and spatial scales (local, regional, and national). My approach was drawn from a range of disciplines—from agronomy, animal science, and weed ecology to rural sociology and political economy—and I used both quantitative and qualitative analytical methods. Broadly organized around the extended efficiency-substitution-redesign framework of multi-level agri-food system transformation (Hill, 1985; Hill and MacRae, 1996; Gliessman, 2015; Wezel et al., 2020), my research was primarily focused on agroecosystem redesign (level III). According to the analytical framework, this level has the potential to help transform agricultural systems through fundamentally changing the ecological structure of a farm, and it serves as an essential step towards transformative change in the food system.

Findings and contributions

In Chapter 1, I compared the yield and quality (i.e., nutritive value) of four cultivars per winter cereal species—barley, cereal rye, and triticale—grown as forage and harvested at eight crop growth stages. I found that while barley cultivars maintain higher relative forage quality (RFQ) across growth stages than cereal rye and triticale, yield was considerably lower. For farmers seeking the earliest harvest timing, cereal rye exhibited a more optimal trade-off between yield and quality, compared with barley and triticale. Yet, it can be challenging to harvest winter cereal forages at a pre-determined growth stage given the many time-sensitive tasks on a dairy farm, and weather conditions can also delay harvest or cause rapid changes to crop maturity. Consequently, a longer harvest window to obtain high quality forage might be more desirable to some farmers than basing species and cultivar selection primarily on early maturity. For these farmers, triticale might be the preferred choice as it generally exhibited greater RFQ than cereal rye at later growth stages, and yields were substantially higher than barley. Building on previous winter cereal forage research in the Northeast and other comparable regions (Jemison et al., 2012; Ketterings et al., 2015; Landry et al., 2019; Lyons et al., 2019), I found that winter cereals can provide high quality forage when feed inventories are typically low, or when feed shortages elsewhere place a greater strain on feed inventories. Winter cereal forages can provide ecosystem services that are similar to those delivered by overwintering cover crops, and they can decrease the environmental and economic costs associated with importing feed.

In Chapter 2, I analyzed the effect of cover crop termination timing and soybean planting date, along with winter cereal cover crop species and cultivar selection, on cover crop growth stage, cover crop biomass, weed biomass, soybean density, soybean yield, and cover crop reseeding. At the earliest date, cereal rye reached more advanced growth stages, on average, than barley or triticale. In contrast, barley matured more rapidly than cereal rye and triticale between later rolling dates. Although there were differences among barley, cereal rye, and triticale, I observed several benefits associated with terminating all three species before anthesis, such as sufficient weed suppression and higher soybean yields. Overall, the results from Chapter 2 suggest that cereal rye is not the only viable species for cover crop-based no-till planted organic soybean production—triticale performed as well, or better, than cereal rye across numerous metrics. Given the moderate trade-offs between yield and quality that were observed for triticale when compared to cereal rye and barley in

Chapter 1, triticale should receive greater consideration from researchers, extension educators, and farmers in the Northeast as a locally adapted, high-performing, multifunctional winter cereal cover crop.

In Chapter 3, I used the results from a national survey to characterize the use of eight agroecological practices among organic fruit and vegetable farmers, predict the use of each practice by farm size, and assess potential indicators of conventionalization among organic farmers in the US. Overall, small- and medium-scale farmers in our sample used over five of the eight practices on average, which was more than the average number reported by large-scale farmers. Intercropping, insectary plantings, and border plantings were at least 1.4-times more likely to be used on small farms than on large farms. Compared with medium farms, reduced tillage was less likely and riparian buffers were more likely to be used on small farms. Features attributed to conventionalization, including low crop diversity, high mechanization, wholesale marketing, and non-local markets, were all generally associated with larger farms in the survey. These findings provide new insights on the heterogeneity of agroecological practice use on organic farms by farm size, as well as new evidence that conventionalization is occurring in the US organic sector. Farm size is a useful proxy for understanding practice use and conventionalization, but it does not predetermine social and environmental sustainability outcomes, nor does it necessarily prevent or promote agroecosystem redesign and the pursuit of agri-food system transformation. Instead, interventions that aim to redirect trajectories toward transformative change should be more attendant to barriers that are unique to a given farm size, or more precisely, the farm features that a size represents.

In Chapter 4, I focused on the claim that agroecological practices are more labor-intensive than industrial management practices. The intention of this work was not to cast doubt on these assertions, but instead to consider what a higher labor requirement might entail for farmers facing a tightening farm labor market, scheduled increases to the minimum wage, a persistent public expectation for cheap food, and long-term cropland consolidation. I used a mixed-methods approach that integrated quantitative survey data (national) and qualitative interview data (California and New York), which provided both a coarse and granular lens for analyses. I assessed whether a farmer's experience using (or not using) an agroecological practice affected their evaluation of labor-intensity; if small-, medium-, and large-scale farmers experienced labor shortages differently; and how farm size might be associated with the strategies that farmers use to manage labor shortages, an increasing minimum wage, and other labor-related challenges. The results showed that farmers who did not use agroecological practices perceived a greater labor requirement than farmers who had experience using a given practice; medium- and large-scale farmers experienced labor shortages as a greater problem than small-scale farmers; and the most commonly reported strategy among large-scale farmers for managing a labor shortage and increase in minimum wage was to increase mechanization, despite already operating the most highly mechanized farms across all sizes. These results underscore the need for more collaborative work, particularly with social movement actors and policymakers, to overcome the complex array of socio-technical and political economic labor challenges in the US and increase the use of agroecological practices.

Limitations, lessons, and future research directions

Reflecting on the four experiments that compose my dissertation, it is important to acknowledge limitations, distill (potentially) generalizable lessons that emerged from this process, and briefly describe how further research on the chapter topics might be informed by these reflections. For the research station-based experiments in Chapters 1 and 2, the findings represent the field conditions of a farm transitioning to organic production. These are unique conditions that are typically distinct from the soil quality and weed seedbank composition of an organic farmer who is not currently transitioning cropland. At the research stations where this work took place, previous crop management had likely drawn down the weed seedbank due to the effectiveness of routine synthetic herbicide applications over many years. Weed seedbanks in fields under organic (non-chemical) weed management usually exhibit greater density (i.e., they are "larger") and species richness than fields under conventional (chemical-based) weed management (Ryan et al., 2010; Graziani et al., 2012). As weed suppression is often a key ecosystem service of interest when assessing such agroecological practices as reduced tillage, cover cropping, and diverse crop rotations, the legacy effects (Cordeau et al., 2022) of past conventional management, particularly for Chapter 2, limit the interpretation of my findings for organic farmers.

Notably, access and availability of organic research facilities is a nationwide barrier for university researchers. Research station experiments serve an important role for testing novel practices, but more on-farm research (Drinkwater, 2002) and greater collaboration with a broad diversity of farmers will be critical for increasing the adoption of agroecological practices (Warner, 2006, 2008; Laforge and Levkoe, 2021). As the democratization of knowledge is part of the core ethos in agroecology (Martínez-Torres and Rosset, 2014; Pimbert, 2017; Global Alliance for the Future of Food, 2021), limitations on research stations in the Global North invite scholars to learn from and adapt participatory models of knowledge co-production, such as through farmer-to-farmer knowledge sharing, participatory on-farm research, and other popular forms of agroecological education that are well-established in the Global South (Altieri and Toledo, 2011; Mier y Terán Giménez Cacho et al., 2018; Rivera-Ferre et al., 2021).

On-farm data were collected at the same time as research station data for

Chapter 1. If the farmer collaborators were selected based on the similarity of their soil and crop management, however, these data could have strengthened the findings from the research station experiments. The highly variable use of soil amendments among the farmers I collaborated with reflects the heterogeneity of farm management, but it served as a confounding effect when trying to include these data in Chapter 1. For example, applications of manure or nitrogen fertilizer in the spring can have a substantial effect on crude protein and overall quality in winter cereal forages (Lyons et al., 2018), and nitrogen availability is also known to affect crop phenology (Mirschel et al., 2005). These farmer collaborators all grew different winter cereal species and cultivars as well. With a lot more data, such variability could be addressed through more complex models; for the small number of farmers relative to the number of categorical fixed effect levels, rank deficiency was an unavoidable statistical limitation in pursuit of the original research objectives. Still, working with extension educators in New York was a deeply enriching experience. These data were analyzed and presented at a range of farmer-, extension educator-, and crop consultant-oriented conferences, and they were made available online.

Replicating the Chapter 2 experiment in Maryland during the first year would have provided replication in both time and space, which can facilitate more robust statistical analyses and interpretations than either form of replication alone. A mediation (path) analysis, which is a specific type of structural equation modeling, emerged as an intriguing statistical technique for parsing out the individual and combined effects of the different factors contributing to weed suppression in the cover crop-based no-till planted soybean experiment. Although my work included too many factors (12 nested cover crop species-cultivar combinations by 4 roll-plant dates) for such a mechanistic analytical approach, further research could untangle the relative contribution to weed suppression of individual and combined tactics, such as the effects of cover crop mulch and soybean canopy shading, through specific research design decisions. This statistical method also lends itself to a wide range of data visualization techniques (e.g., see Figure E.1), which is advantageous for communicating research findings to different audiences. A related, yet broadly applicable, recommendation is to generate random data to test statistical techniques of interest (i.e., in R or other statistical software) before implementing a research design, which could streamline data analysis and help refine research objectives and hypotheses.

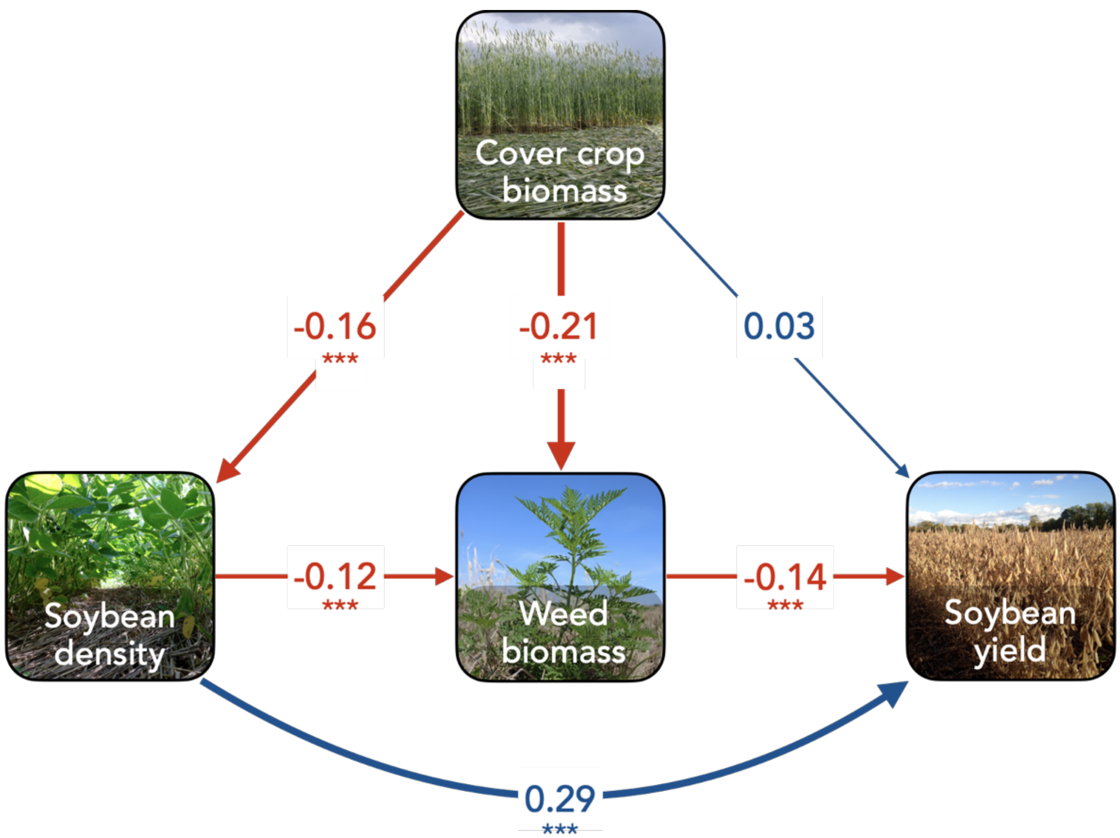

Figure E.1 | Mediation analysis diagram showing the direct relationships among cover crop biomass, soybean density, weed biomass, and soybean yield. All information, such as the standardized estimates for each direct path (numerical values), indications of statistical significance (asterisks), and effect strength (line width), are presented for illustrative purposes only.

Data limitations are common in survey-based research. For Chapters 3 and 4, a lack of data from conventional farmers and large-scale organic farmers restricted the types of analytical approaches I could apply. I took specific actions to minimize the occurrence of unbalanced data across the numerous categorical levels, but the difficulty I encountered obtaining responses from some types of farmers forced me to adjust the original objectives for this research project. The emergent analyses, however, were considerably more interdisciplinary and mixed-methods-focused than initially planned, which ended up strengthening the chapters. Still, more data across all categories of interest (i.e., combinations of farm size, management type, and cropping system) would have permitted the use of more granular predictive models with farm size as a continuous variable. Balanced data would have also allowed me to characterize my findings more clearly as a spectrum of input-dependency and diversification, from biologically simple farms that depend on external inputs to biologically complex farms that depend on the maintenance of on-farm agrobiodiversity, ecological processes, and ecosystem services (Kremen et al., 2012; Tittonell, 2014; Kremen, 2020). Obtaining more data from all sizes of conventional farmers would have allowed me to present a stronger, more distinct counterfactual to the claims made about the benefits of diversification and agroecological practice use. Although I was able to point to the literature in some instances, a single study with an embedded counterfactual can create a strong narrative through empirical evidence.

The scope of the survey tool and interview guide used in Chapters 3 and 4 were designed to be wide-ranging, covering environmental and production issues (such as agronomic challenges, wildlife conservation, and climate change) to socioeconomic issues (such as labor shortages, financial concerns, knowledge networks, and policy). The breadth of the quantitative and qualitative data was beneficial for broadly exploring the complicated nature of motivations and barriers to agroecological practice use, but it also limited the depth of the analyses for a given topic. For example, having such an extensive list of core topics to cover during my interviews meant that I had to forgo follow-up questions in some instances out of respect for a farmer's time. Insights on certain topics were undoubtedly missed due to this time constraint. However, the scope of the work I conducted in Chapters 3 and 4 has provided the opportunity to think carefully about current knowledge gaps and better understand the types of research questions that excite and motivate me. To this last point, interviewing farmworkers and a greater number of BIPOC farmers would have provided a much needed, and often overlooked, perspective in my research.

Conclusion

For some scholars, agroecology is a contemporary way to describe the (natural) science of agroecosystems and the farming practices that rely on these ecological principles. My interest in emphasizing the social component of agroecology in both the Prologue and Epilogue is twofold. First, agroecology is generally understood as an *inseparable* integration of science, praxis, and social movement (Wezel et al., 2009; Méndez et al., 2013). This is how hundreds of millions of peasant and other small-holder farmers around the world understand and practice agroecology (La Via Campesina, 2017). Without explicitly acknowledging this, agricultural research runs the risk of obscuring or reproducing problematic power imbalances within the dominant agri-food system. Second, it is precisely due to the social movement associated with agroecology that there is the degree of global support for agroecology among scholars, practitioners, farmers, activists, NGOs, and intergovernmental agencies. This movement is also a primary reason that many of the most powerful actors in the industrial agri-food system, particularly in the private sector and in government, view agroecology as a threat (e.g., see Canfield et al., 2021; Gliessman and Montenegro de Wit, 2021). Social movement actors have been at the forefront of opposing the privatization and commodification of knowledge (through economic or legal means), “land grabbing” and other forms of land consolidation, and the exploitation of farmers, farmworkers, and the environment.

It is important to reiterate that agroecology is epistemologically pluralistic (Martínez-Torres and Rosset, 2014). My intention of highlighting the importance of the agroecology movement is not to exclude or diminish the work of those who support agroecology by exclusively advancing the science or practice. After all, this is primarily what I have tried to do with the research presented here. Instead, my goal is to encourage—in my own work and in academia more broadly—more interdisciplinary scholarship, more participatory and action-based research, and more collaboration with farmers and social movement actors.

Despite the magnitude of the social-ecological crises facing society, there are opportunities to act boldly, but the window for action is narrow. Agroecology has the potential to meaningfully contribute to agri-food system transformation, but it will require considerably more support both inside and outside of academia. Still, the solidarity, compassion, and leadership demonstrated by farmers and farmworkers in the agroecology movement gives me hope that the struggle for a more just and sustainable food system can prevail.

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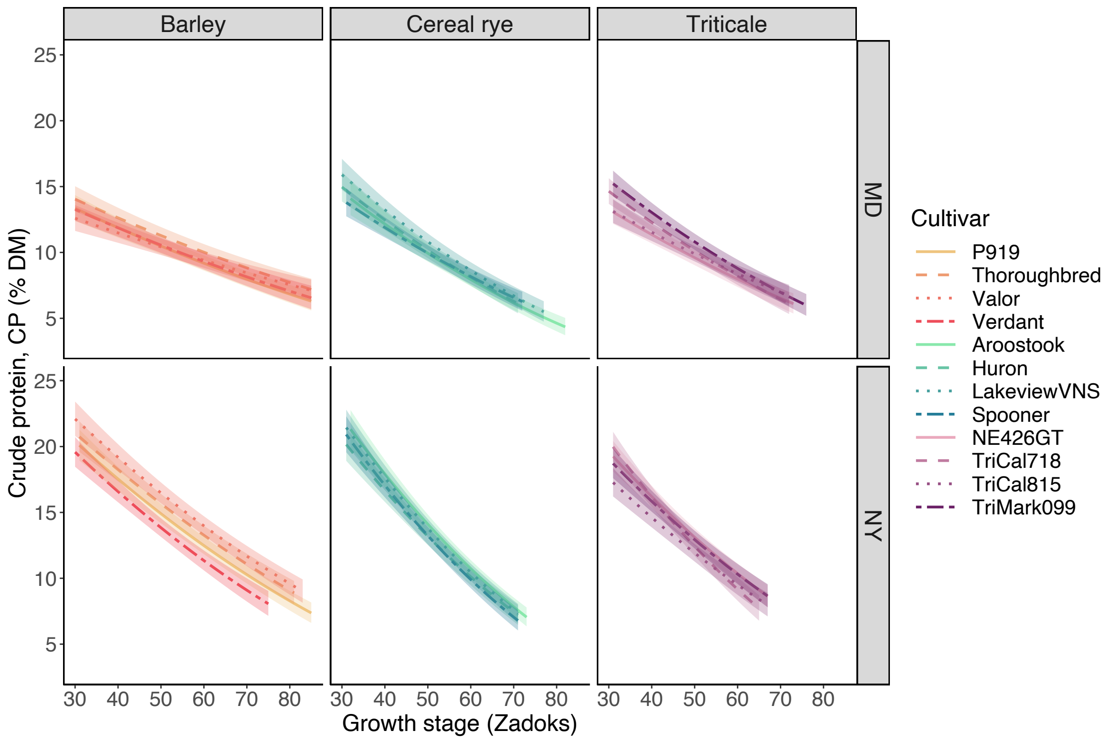
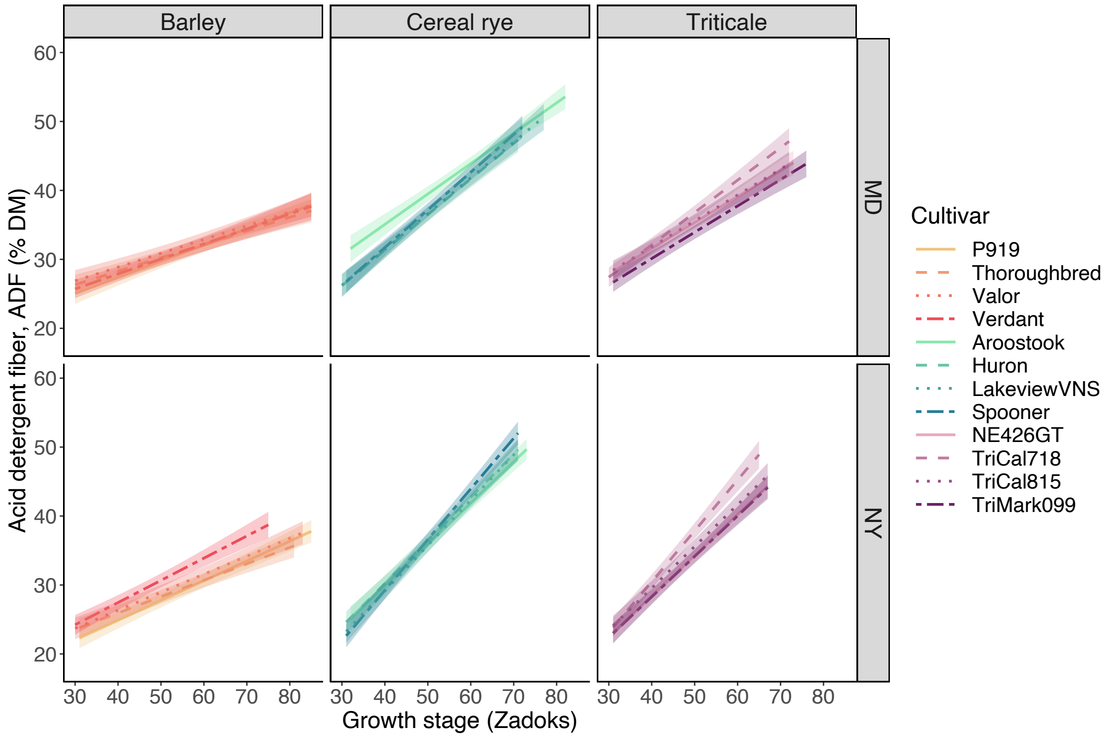
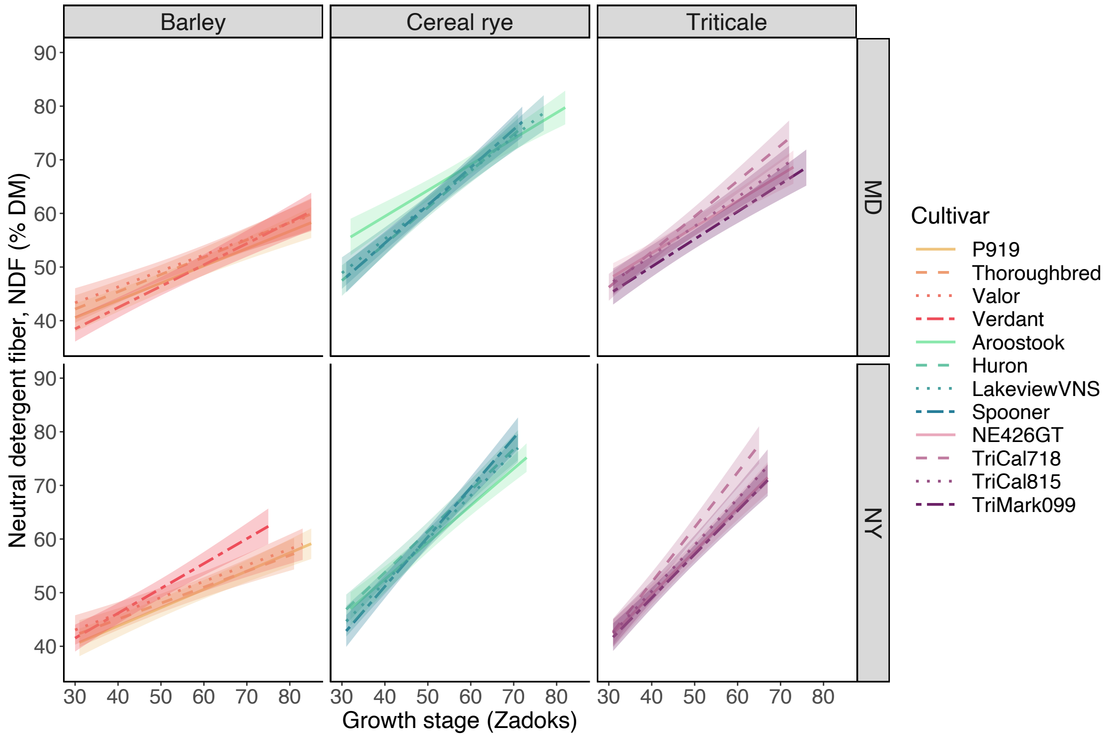
APPENDIX A: SUPPLEMENTARY MATERIALS FOR CHAPTER 1



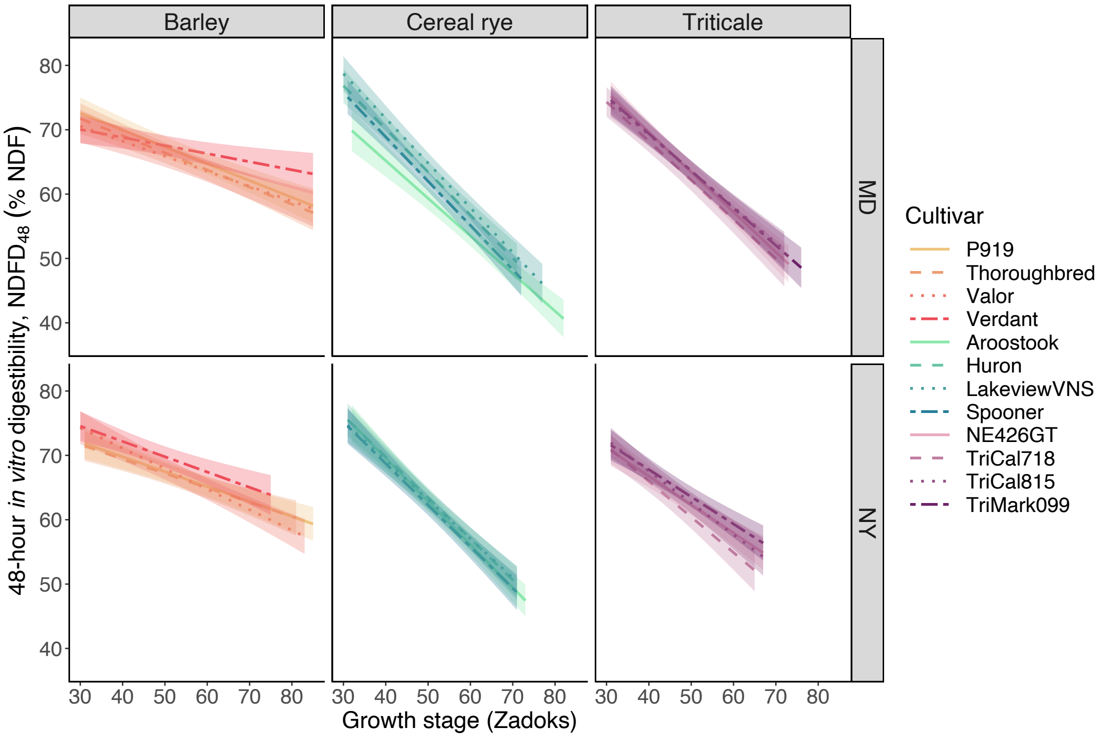
Supplementary Figure A1 | The effect of winter cereal cultivar (four per species), growth stage (Zadoks), and site (MD and NY) on crude protein (CP, % dry matter, DM). CP has been back-transformed from a square root transformation. The shaded "ribbon" accompanying each cultivar slope (line) represents a 95% confidence interval. Analysis of variance and coefficients of determination for this linear mixed-effects model are presented in Supplementary Table A1.



Supplementary Figure A2 | The effect of winter cereal cultivar (four per species), growth stage (Zadoks), and site (MD and NY) on acid detergent fiber (ADF, % dry matter, DM). The shaded "ribbon" accompanying each cultivar slope (line) represents a 95% confidence interval. Analysis of variance and coefficients of determination for this linear mixed-effects model are presented in Supplementary Table A1.



Supplementary Figure A3 | The effect of winter cereal cultivar (four per species), growth stage (Zadoks), and site (MD and NY) on neutral detergent fiber (NDF, % dry matter, DM). The shaded "ribbon" accompanying each cultivar slope (line) represents a 95% confidence interval. Analysis of variance and coefficients of determination for this linear mixed-effects model are presented in Supplementary Table A1.



Supplementary Figure A4 | The effect of winter cereal cultivar (four per species), growth stage (Zadoks), and site (MD and NY) on 48-hour *in vitro* digestibility ($NDFD_{48}$, % neutral detergent fiber, NDF). The shaded "ribbon" accompanying each cultivar slope (line) represents a 95% confidence interval. Analysis of variance and coefficients of determination for this linear mixed-effects model are presented in Supplementary Table A1.

Supplementary Table A1 | Analysis of variance for crude protein (CP, % dry matter, DM), acid detergent fiber (ADF, % DM), neutral detergent fiber (NDF, % DM), and 48-hour *in vitro* digestibility ($NDFD_{48}$, % NDF) as affected by winter cereal cultivar (all 12), growth stage (Zadoks), and site (MD and NY).

Predictors	CP*	ADF	NDF	$NDFD_{48}$
	p-value			
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001
Growth stage	<0.0001	<0.0001	<0.0001	<0.0001
Site	<0.0001	<0.0001	<0.0001	0.2046
Cultivar × Growth stage	<0.0001	<0.0001	<0.0001	<0.0001
Growth stage × Site	<0.0001	<0.0001	<0.0001	0.1007
Cultivar × Site	0.0391	0.0116	0.0001	0.0032
Cultivar × Growth stage × Site	0.6362	0.0002	<0.0001	0.0621
Coefficient of determination				
Marginal	0.875	0.897	0.845	0.778
Conditional	0.880	0.898	0.848	0.780

* Crude protein (CP, % DM) was square root transformed to address heteroscedasticity.

Supplementary Table A2 | Logistic models described by a sigmoid function for phenological development of barley, cereal rye, and triticale cultivars in MD and NY.

Barley						Cereal rye						Triticale					
		MD		NY				MD		NY				MD		NY	
Cultivar	Parameters*	Estimate	*p*-value	Estimate	*p*-value	Cultivar	Parameters	Estimate	*p*-value	Estimate	*p*-value	Cultivar	Parameters	Estimate	*p*-value	Estimate	*p*-value
P-919	$\o_1$	28.9	<0.0001	28.8	<0.0001	Aroostook	$\o_1$	95.6	<0.0001	-11.5	0.8334	NE426GT	$\o_1$	30.2	<0.0001	30.2	<0.0001
	$\o_2$	86.2	<0.0001	89.9	<0.0001		$\o_2$	–[†]	–	75.9	<0.0001		$\o_2$	74.6	<0.0001	66.9	<0.0001
	$\o_3$	125.2	<0.0001	139.4	<0.0001		$\o_3$	114.8	<0.0001	122.0	<0.0001		$\o_3$	127.1	<0.0001	138.2	<0.0001
	$\o_4$	4.7	<0.0001	5.5	<0.0001		$\o_4$	17.6	0.0001	10.5	0.0363		$\o_4$	5.1	<0.0001	4.5	<0.0001
Thoroughbred	$\o_1$	29.1	<0.0001	30.1	<0.0001	Huron	$\o_1$	30.0	<0.0001	28.5	<0.0001	TriCal 718	$\o_1$	28.5	<0.0001	30.2	<0.0001
	$\o_2$	87.5	<0.0001	87.3	<0.0001		$\o_2$	72.8	<0.0001	72.2	<0.0001		$\o_2$	76.1	<0.0001	76.9	<0.0001
	$\o_3$	126.2	<0.0001	141.5	<0.0001		$\o_3$	125.8	<0.0001	136.8	<0.0001		$\o_3$	128.8	<0.0001	146.5	<0.0001
	$\o_4$	5.1	<0.0001	5.1	<0.0001		$\o_4$	5.8	<0.0001	5.6	<0.0001		$\o_4$	6.3	<0.0001	7.0	<0.0001
Valor	$\o_1$	26.7	<0.0001	30.0	<0.0001	Lakeview VNS	$\o_1$	30.5	<0.0001	26.5	<0.0001	TriCal 815	$\o_1$	30.9	<0.0001	30.6	<0.0001
	$\o_2$	88.2	<0.0001	86.0	<0.0001		$\o_2$	74.5	<0.0001	70.4	<0.0001		$\o_2$	73.0	<0.0001	68.5	<0.0001
	$\o_3$	125.1	<0.0001	140.2	<0.0001		$\o_3$	123.7	<0.0001	133.8	<0.0001		$\o_3$	127.3	<0.0001	140.4	<0.0001
	$\o_4$	5.5	<0.0001	4.6	<0.0001		$\o_4$	5.7	<0.0001	5.3	<0.0001		$\o_4$	4.4	<0.0001	4.9	<0.0001
Verdant	$\o_1$	26.8	<0.0001	32.1	<0.0001	Spooner	$\o_1$	33.3	<0.0001	26.7	<0.0001	TriMark 099	$\o_1$	29.3	<0.0001	30.7	<0.0001
	$\o_2$	112.0	<0.0001	79.0	<0.0001		$\o_2$	70.3	<0.0001	68.7	<0.0001		$\o_2$	78.7	<0.0001	66.9	<0.0001
	$\o_3$	135.1	<0.0001	144.4	<0.0001		$\o_3$	123.6	<0.0001	133.5	<0.0001		$\o_3$	128.6	<0.0001	139.0	<0.0001
	$\o_4$	8.2	0.0011	4.2	<0.0001		$\o_4$	4.0	<0.0001	5.6	<0.0001		$\o_4$	5.9	<0.0001	4.4	<0.0001

[*] The logistic models are described by sigmoid functions with four parameters: $\o_1$ is the horizontal asymptote as x approaches ∞, $\o_2$ is the horizontal asymptote as x approaches –∞, $\o_3$ is the x value at the inflection point, and $\o_4$ is a scale parameter on the x-axis.

[†] Unlike all other cultivars, the phenological development of Aroostook in MD was best described by a three-parameter logistic model whereby $\o_1$ is the horizontal asymptote as x approaches ∞ and 0 is the horizontal asymptote as x approaches -∞ (as $\o_3 > 0$). The $\o_3$ parameter is the x value at which the response is $\o_1 / 2$ (i.e., the inflection point of the curve), and the scale parameter $\o_4$ representing the distance on the x-axis between the inflection point and the point where the response is $\o_1 / (1 + e^{-1}) \approx 0.73\o_1$ (Pinherio and Bates, 2000).

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APPENDIX B: SUPPLEMENTARY MATERIALS FOR CHAPTER 2

Supplementary Table B1 | Estimated marginal means for all significant interactions detected in the analyses of variance presented in Table 2.3. Means comparisons and a Tukey's HSD test have been conducted to identify differences ($p < 0.05$) among the cultivars within each roll-plant date.

			Cover crop growth stage			Soybean yield	Cover crop reseeding
			Site-year			Site-year	Site-year
Date	Species[*]	Cultivar	NY 2014	NY 2015	MD 2015	NY 2014	MD 2015
			Zadoks			Mg ha^{-1}	Cover (%)
Early	Barley	Verdant	37 c[†]	37 g	32 d	2.85	23 bcd
		Valor	56 ab	43 def	33 d	2.49	34 abc
		P-919	59 a	48 cd	33 d	2.43	35 abc
		McGregor[§]	46 bc	41 efg	33 d	2.58	36 ab
	Cereal rye	Huron	59 a	46 cde	35 cd	3.15	5 d
		Spooner	59 a	54 ab	38 bc	2.86	25 abc
		Aroostook	59 a	58 a	57 a	2.75	43 a
		Lakeview VNS	59 a	51 bc	39 b	3.03	5 d
	Triticale	TriCal 815	50 ab	39 fg	33 d	2.76	18 bcd
		TriCal 718	46 bc	37 g	33 d	2.93	30 abc
		NE426GT	54 ab	40 fg	34 d	2.93	20 bcd
		TriMark 099	55 ab	40 fg	33 d	2.72	16 cd
Early-mid	Barley	Verdant	40 f	41 d	49 ef	3.06	19 abc
		Valor	59 bcd	58 ab	61 ab	2.41	29 ab
		P-919	70 a	63 a	63 a	2.57	33 a
		McGregor[§]	48 ef	55 bc	61 ab	2.95	28 ab
	Cereal rye	Huron	65 abc	57 ab	55 cd	2.90	1 c
		Spooner	59 abcde	59 ab	58 bc	2.53	10 bc
		Aroostook	68 ab	59 ab	61 ab	2.88	25 ab
		Lakeview VNS	62 abc	58 ab	58 bc	2.75	0 c
	Triticale	TriCal 815	57 cde	51 c	50 ef	2.74	15 abc
		TriCal 718	50 def	45 d	48 f	2.88	26 ab
		NE426GT	59 bcd	55 bc	52 de	2.66	15 abc
		TriMark 099	59 bcd	55 bc	50 ef	2.72	11 bc
Mid-late	Barley	Verdant	46 c	71 b	68 bcd	2.91	23 abcd
		Valor	65 ab	82 a	70 abc	2.41	31 ab
		P-919	69 ab	83 a	74 a	2.32	38 a
		McGregor[§]	67 ab	80 a	72 ab	2.62	15 bcde
	Cereal rye	Huron	69 a	69 bcd	63 efg	3.02	0 e
		Spooner	69 a	67 bcde	66 def	2.43	3 de
		Aroostook	67 ab	71 b	70 bc	2.66	26 abc
		Lakeview VNS	66 ab	70 bc	67 cde	2.54	0 e
	Triticale	TriCal 815	62 ab	62 ef	63 fg	2.87	10 cde
		TriCal 718	59 b	59 f	59 g	2.37	18 bcde
		NE426GT	67 ab	63 def	64 ef	2.69	3 e
		TriMark 099	67 ab	65 cde	63 efg	2.81	9 cde
Late	Barley	Verdant	53 c	80 ab	84 ab	2.58 ab	24 bcde
		Valor	85 a	84 a	86 a	1.91 b	35 abc
		P-919	85 a	85 a	86 a	2.03 ab	48 a
		McGregor[§]	83 a	81 ab	85 a	1.98 ab	16 cdef
	Cereal rye	Huron	71 b	71 d	70 c	2.21 ab	2 f
		Spooner	71 b	73 cd	71 c	2.14 ab	10 def
		Aroostook	71 b	77 bc	81 b	1.99 ab	40 ab
		Lakeview VNS	71 b	73 cd	74 c	1.97 ab	2 f
	Triticale	TriCal 815	69 b	71 d	72 c	2.49 ab	3 f
		TriCal 718	69 b	68 d	71 c	2.17 ab	25 bcd
		NE426GT	69 b	70 d	72 c	2.01 ab	1 f
		TriMark 099	69 b	68 d	74 c	2.69 a	5 ef

[*] Cultivars are organized by species to provide additional insight for interpretation of the results, but note that species was not included in these linear mixed-effects models.

[†] Different lowercase letters within the same site-year (table column) for an interaction across Cultivars within a given Date indicate differences ($p < 0.05$) among the estimated marginal means based on a Tukey's HSD test. No letters indicate no significant differences.

[§] In 2015, 'McGregor' barley seed was not available. It was replaced with another barley cultivar, 'Thoroughbred,' in both NY and MD.

APPENDIX C: SUPPLEMENTARY MATERIALS FOR CHAPTER 3

Supplementary Table C1 | Comparison of the demographic characteristics of our survey respondents and respondents from the USDA 2017 Census of Agriculture. Demographics include gender identity, age, farming experience, and race.

Demographic	Percent of total (%)*	
	Survey	2017 Census†
Female	39	37
Male	58	63
Other	3	—‡
Age, <35	17	18
Age, 35 to 54	34	36
Age, ≥55	48	46
Farming experience, ≤5 years	21	18
Farming experience, 6 to 10 years	22	17
Farming experience, ≥11 years	57	65
Hispanic or Latinx	2.7	4.5
Native American or Alaska Native	0.0	0.5
Asian	1.6	1.7
Black or African American	0.9	0.7
Native Hawaiian or other Pacific Islander	0.0	0.2
White	92	96
Other	5.9	—
More than one race reported	2.6	0.9

* Percentages might not add up to 100 due to rounding.

† Data from the 2017 Census of Agriculture: Characteristics of All Farms and Farms with Organic Sales report[1].

‡ An em dash (—) indicates that this demographic variable was not an option in the survey.

Supplementary Table C2 | Pairwise comparisons of the predicted probability (estimated marginal means) that a farmer uses a particular agroecological practice by farm size (cropland ha), within each practice.

Practice	Contrast by farm size*	Odds ratio	Standard error	*z*-ratio	*p*-value†
Compost	small / medium	1.8	0.52	1.97	0.1190
	small / large	2.4	1.04	1.96	0.1217
	medium / large	1.3	0.64	0.59	0.8240
Intercropping	small / medium	2.3	0.61	3.19	0.0041
	small / large	2.7	1.07	2.44	0.0390
	medium / large	1.1	0.51	0.31	0.9490
Insectary planting	small / medium	2.7	0.71	3.71	0.0006
	small / large	9.5	4.13	5.17	<0.0001
	medium / large	3.5	1.67	2.68	0.0202
Reduced tillage	small / medium	0.5	0.15	-2.31	0.0547
	small / large	0.5	0.23	-1.54	0.2711
	medium / large	0.9	0.50	-0.13	0.9913
Crop rotation	small / medium	0.8	0.41	-0.38	0.9227
	small / large	1.1	0.74	0.13	0.9911
	medium / large	1.3	1.03	0.35	0.9353
Cover cropping	small / medium	1.1	0.33	0.17	0.9835
	small / large	1.8	0.78	1.30	0.3976
	medium / large	1.7	0.84	1.04	0.5550
Border planting	small / medium	0.7	0.19	-1.32	0.3857
	small / large	2.7	1.18	2.31	0.0539
	medium / large	3.8	1.83	2.82	0.0132
Riparian buffer	small / medium	3.1	1.21	2.99	0.0079
	small / large	2.1	1.47	1.06	0.5378
	medium / large	0.7	0.48	-0.56	0.8406

* Farm size (cropland ha): small (0.4–39 ha), medium (40–404 ha), and large (≥405 ha).

† Tests are performed on the log scale, and the Tukey Method was used for the *p*-value adjustment.

Supplementary Table C3 | Pairwise comparisons of the predicted probability (estimated marginal means) that a farmer uses a particular agroecological practice by practice, within each farm size (cropland ha).

	Small (0.4–39 ha)				Medium (40–404 ha)				Large (≥405 ha)			
Contrast by practice	**Odds ratio**	**Standard error**	***z*-ratio**	***p*-value†**	**Odds ratio**	**Standard error**	***z*-ratio**	***p*-value**	**Odds ratio**	**Standard error**	***z*-ratio**	***p*-value**
Compost / Intercropping	2.0	0.38	3.78	0.0039	2.6	0.85	3.05	0.0473	2.3	1.20	1.57	0.7668
Compost / Insectary planting	1.5	0.28	2.08	0.4256	2.2	0.71	2.55	0.1749	6.0	3.28	3.25	0.0255
Compost / Reduced tillage	2.6	0.48	5.19	<0.0001	0.7	0.26	-0.86	0.9896	0.5	0.31	-1.11	0.9560
Compost / Crop rotation	0.5	0.12	-2.85	0.0836	0.2	0.12	-2.91	0.0703	0.2	0.17	-1.98	0.4942
Compost / Cover cropping	1.1	0.21	0.29	1.0000	0.6	0.22	-1.31	0.8960	0.8	0.44	-0.42	0.9999
Compost / Border planting	4.9	0.90	8.79	<0.0001	2.0	0.63	2.12	0.4015	5.7	3.13	3.16	0.0341
Compost / Riparian buffer	0.4	0.11	-3.46	0.0125	0.7	0.25	-1.08	0.9619	0.3	0.25	-1.45	0.8326
Intercropping / Insectary planting	0.7	0.13	-1.74	0.6591	0.8	0.26	-0.54	0.9994	2.6	1.38	1.83	0.5963
Intercropping / Reduced tillage	1.3	0.22	1.48	0.8189	0.3	0.09	-3.84	0.0031	0.2	0.13	-2.60	0.1560
Intercropping / Crop rotation	0.2	0.06	-6.03	<0.0001	0.1	0.04	-4.96	<0.0001	0.1	0.07	-3.16	0.0335
Intercropping / Cover cropping	0.5	0.10	-3.50	0.0109	0.2	0.08	-4.22	0.0007	0.3	0.18	-2.00	0.4835
Intercropping / Border planting	2.4	0.40	5.39	<0.0001	0.7	0.23	-0.96	0.9794	2.5	1.31	1.74	0.6630
Intercropping / Riparian buffer	0.2	0.05	-6.18	<0.0001	0.3	0.09	-3.85	0.0030	0.1	0.11	-2.61	0.1515
Insectary planting / Reduced tillage	1.7	0.30	3.21	0.0293	0.3	0.11	-3.36	0.0180	0.1	0.05	-4.12	0.0010
Insectary planting / Crop rotation	0.3	0.08	-4.63	0.0001	0.1	0.05	-4.63	0.0001	0.0	0.03	-4.38	0.0003
Insectary planting / Cover cropping	0.7	0.14	-1.79	0.6247	0.3	0.10	-3.75	0.0044	0.1	0.07	-3.65	0.0065
Insectary planting / Border planting	3.3	0.57	7.01	<0.0001	0.9	0.27	-0.43	0.9999	1.0	0.52	-0.09	1.0000
Insectary planting / Riparian buffer	0.3	0.07	-4.99	<0.0001	0.3	0.11	-3.40	0.0155	0.1	0.04	-3.84	0.0031
Reduced tillage / Crop rotation	0.2	0.04	-7.17	<0.0001	0.3	0.16	-2.29	0.3010	0.4	0.34	-1.06	0.9651
Reduced tillage / Cover cropping	0.4	0.07	-4.92	<0.0001	0.8	0.31	-0.46	0.9998	1.5	0.90	0.71	0.9968
Reduced tillage / Border planting	1.9	0.31	3.97	0.0018	2.7	0.88	2.94	0.0655	10.9	6.44	4.03	0.0014
Reduced tillage / Riparian buffer	0.1	0.04	-7.14	<0.0001	0.9	0.34	-0.27	1.0000	0.6	0.50	-0.56	0.9993
Crop rotation / Cover cropping	2.1	0.51	3.10	0.0402	2.7	1.37	1.93	0.5285	3.4	2.53	1.66	0.7107
Crop rotation / Border planting	9.8	2.24	10.05	<0.0001	8.4	4.12	4.35	0.0004	24.6	18.25	4.31	0.0004
Crop rotation / Riparian buffer	0.8	0.24	-0.90	0.9859	2.9	1.50	2.02	0.4668	1.5	1.31	0.42	0.9999
Cover cropping / Border planting	4.7	0.84	8.55	<0.0001	3.1	1.07	3.34	0.0188	7.2	3.98	3.55	0.0092
Cover cropping / Riparian buffer	0.4	0.10	-3.69	0.0056	1.1	0.41	0.17	1.0000	0.4	0.32	-1.14	0.9481
Border planting / Riparian buffer	0.1	0.02	-9.57	<0.0001	0.3	0.12	-3.02	0.0523	0.1	0.05	-3.77	0.0041

† Tests are performed on the log odds ratio scale, and the Tukey Method was used for the *p*-value adjustment.

Supplementary Table C4 | Contingency tables of responses, reported as counts (*n*) by farm size (cropland ha), to six survey questions associated with conventionalization. A two-sided Fisher's exact test was also conducted for each contingency table, as applicable.

Farm size (cropland ha)	Crop diversity (number of crops in rotation)			
	1–2	3–9	10–29	≥30
Small (0.4–39 ha)	10	87	137	109
Medium (40–404 ha)	3	46	14	23
Large (≥405 ha)	2	20	10	0
Fisher's exact test: $p < 0.0001$				

Farm size (cropland ha)	Mechanization (mechanization (%) as a proportion of farm work)			
	0–25	26–50	51–75	76–100
Small (0.4–39 ha)	181	100	34	21
Medium (40–404 ha)	21	29	19	26
Large (≥405 ha)	1	5	10	15
Fisher's exact test: $p < 0.0001$				

Farm size (cropland ha)	Market channel (wholesale (%) as a proportion of total sales)			
	0–25	26–50	51–75	76–100
Small (0.4–39 ha)	247	20	7	42
Medium (40–404 ha)	28	11	5	48
Large (≥405 ha)	21	1	1	27
Fisher's exact test: $p < 0.0001$				

Farm size (cropland ha)	Distribution (distance from farm (km) to final point of sale)			
	<16.1	16.1–161	>161	Unknown*
Small (0.4–39 ha)	96	191	41	11
Medium (40–404 ha)	9	37	44	3
Large (≥405 ha)	0	11	18	2
Fisher's exact test: $p < 0.0001$				

Farm size (cropland ha)	Competition (most difficult farm types to compete against)			
	Large conv.†	Large organic	Sm.-med. organic	Sm.-med. conv.
Small (0.4–39 ha)	137	211	57	81
Medium (40–404 ha)	38	50	12	13
Large (≥405 ha)	19	11	2	5
Fisher's exact test: *NA*‡				

Farm size (cropland ha)	Scaling up (interest in increasing farm size if possible)			
	Definitely yes	Probably yes	Probably no	Definitely no
Small (0.4–39 ha)	104	101	100	88
Medium (40–404 ha)	29	33	30	17
Large (≥405 ha)	21	11	6	1
Fisher's exact test: $p = 0.002$				

* "Unknown" indicates that the farmer respondent did not know where the crops they grew were sold, not that data were missing.

† Abbreviations: conv. = conventional; Sm. = small; and med. = medium.

‡ Farmers were able to "select all that apply," which prevented the use of Fisher's exact test.

REFERENCES FOR APPENDIX C

USDA NASS (2019). *2017 Census of Agriculture - Characteristics of All Farms and Farms with Organic Sales*. Available online: https://www.nass.usda.gov/Publications/AgCensus/2017 (accessed May 03, 2021).