CROP DIVERSIFICATION PRACTICES AS A STRATEGY TO ENHANCE THE RESILIENCE OF FARMS IN THE FACE OF EXTREME WEATHER EVENTS

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CROP DIVERSIFICATION PRACTICES AS A STRATEGY TO ENHANCE THE RESILIENCE OF FARMS IN THE FACE OF EXTREME WEATHER EVENTS

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Due to climate change, farms must be able to withstand increased weather volatility. Crop diversification as a strategy to enhance resilience in the face of extreme weather events is explored in the context of northeastern dairy cropping systems. To address resilience, the farm is understood using a social-ecological systems perspective. In the industrialized setting, the farm as a land use system overlaying other biotic communities is embedded in a socio-technical configuration consisting of individual and institution actors who enforce/reinforce norms, rules, practices, and technologies. Operationalized, resilience is the interaction of ecological, economic, and social elements that produce and restore ecosystem services. Focusing on a farmer's management, the cross-scale feedback mechanisms in the complex system are the criteria of innovation diffusion: relative advantage, compatibility, triability, observability, and complexity. Crop diversification provides farmers with a relative advantage as it increases the adaptability of the farmer through a diversity of practices, and at the field-level, increases the spatial and temporal variance which improves the ability to absorb stress. Thus, the benefits of diversification are derived from increased complexity, which often inhibits diffusion. Compounding this, the socio-technical configuration in which the farmer is embedded shapes their behavior and masks

ecological signals as seen through 25 semi-structured interviews with conventional and organic dairy farmers.

Increasing adoption of crop diversification practices requires creating agronomic knowledge that can be appropriately contextualized, increasing coherence in research findings for easier synthesis, and designing science for application to advance technologies and policies. I worked to this end in two research experiments. Crop diversification strategies were deployed in a multi-site, multi-year forage intercropping experiment, and productivity, weed suppression, forage quality, and yield stability were quantified. Intercropping practices employing interspecific diversity had a greater effect than practices employing intraspecific diversity on yield stability, likely due to an increase in functional and response diversity. I also constructed a framework to design crop mixtures using ecological models and a series of response-surface designs. The framework accounts for the different competitive traits of species so that crop mixtures are more able to deliver multiple ecosystem services. It can be used when recommending seeding rates for mixtures to farmers and may reduce some barriers of adoption.

BIOGRAPHICAL SKETCH

K. Ann Bybee-Finley is an agroecologist with years of experience on how the globalized agrifood system privileges some and unjustly ignores or exploits others. She is particularly interested in strategies to advance the crop diversification in industrialized agriculture in science, practice, and public policy. She was raised in West Virginia but has spent one-third of her life abroad, which has shaped her understanding about the power of the kitchen table and the foundation of humanity around a shared meal. Food insecurity regardless of whether it was in her home state or a developing country has always been her impetus to contribute to the transformation of the agrifood system.

She graduated the top of her class at West Virginia University and earned a B.S. in Biochemistry and a B.A. in International Studies with an emphasis in Development in 2011. Afterwards she worked in the Maize Phytopathology Lab at CIMMYT in Mexico. In 2016, she earned her master's degree in agronomy as Matt Ryan's first graduate student. Her work on annual intercrops in industrialized systems has been published in journals of Crop Science, Weed Science, and Agriculture. She has shared her philosophies for agricultural practices to enhance resilience in USDA visioning sessions and with the National Academy of Sciences.

She has accepted a post-doc position with USDA Agronomic Research Service to network 13 long-term agricultural research sites and conduct nation-wide assessment about the role of crop diversification to enhance the resilience of farms in a changing climate.

To the currently 546,000 people who have died from Covid-19 in the United States of America.

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PREFACE

This dissertation was finished amidst a crisis that has affected the entire world from isolated Amazonian tribes to offshore oil rigs, from farms to metropolises, and everywhere in-between. We have witnessed the response of the world to Covid-19, a tractable problem, something for which global organizations, government agencies, public health infrastructure have existed for decades, if not centuries, to combat. Yet we fail in uniting to overcome it with dire outcomes.

If the global pandemic is bad, the problem that this dissertation attempts to address is worse in an infinite number of ways. Climate change is an unholy beast we have brought upon ourselves. The scales and bounds of an individual alone are too small, too narrow to make concrete, causal linkages. Our world has not organized for the rapid changes that must occur to adapt and mitigate the worst of the consequences.

Advancing the science of crop diversification meant that I needed to learn more about how it would be applied and the ways in which people went about understanding the practices. A science devoid of context is destitute from the start. To do this, I had to leave depth for breadth for which academia is not designed. A combination of science and sociology is akin to holding opposing thoughts in your head. To master this, you must keep pulling back layers until only the pure questions are left—What does it mean to know? And, how do you learn?

The details in this work are for the respective experts. But for those outside the field, fear not! The prescient questions are as follows: What is the structure? What is the function? What is the scale? How do these vary over space and over time?

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CHAPTER 1

A THEORETICAL CONSIDERATION OF FARMS AS SOCIAL-ECOLOGICAL SYSTEMS

1.1 Introduction

Agriculture is the world's largest land-use system and is heavily managed by humans. The United States States has 16.6% of arable land, the highest percentage of any country (World Bank Open Data, 2016). Climate change is affecting agriculture by changing the patterns of temperature, precipitation, pests, and diseases (Smit and Skinner 2002). In particular, extreme weather events are increasing in frequency and causing greater uncertainty in agriculture (Walsh et al. 2014, Wolfe et al. 2018). As such, highly productive monocultures and simplified crop rotations that predominate in the United States are poorly structured to meet these future environmental challenges because they are less able to adsorb or adapt to sudden/extreme weather events (Parry et al. 2004, Rosenzweig and Tubiello 2007).

In this dissertation, I explore a strategy for agriculture to weather environmental change through the frame of "resilience". I explore crop diversification practices as a way to situate the farm as a system within a system, to enhance the resilience of farms in the face of extreme weather events and am interested in the social and institutional conditions under which crop diversification practices are effectively diffused. Drawing from existing lines of inquiry, the central objective of this dissertation is to develop a theoretical framework which simultaneously explains field- and farm-level phenomena regarding adoption of crop diversification practices and the larger social, technical, and institutional structures within which adoption occurs, and further the agroecological scholarship of crop diversification to measure and construct such practices.

How can understanding the farm as a social-ecological system advance the adoption of crop diversification practices that enhance the resilience of a farm to extreme weather events?

Understanding the farm as a social-ecological system considers the fundamental relationship of humans and the environment the illuminates the role of technology and reimagines diffusion criteria as dynamic cross-linkages across elements of a complex system. By turning to this more systemic framing, I can draw important insights into the conditions in which resilience-enhancing strategies are adopted or not. The findings from this dissertation will have implications for the way public policies aimed at enhancing farm resilience are designed and implemented.

1.2 Approach

I use a mixed methods approach that reflects a realist ontology (the world exists beyond our perception of it) and take a critical realist epistemological stance (we can only understand the world from the perspective of humans) (Bhaskar, 2008). Agriculture is both socialy and ecologically complex, leading me to think about agriculture not as a compilation of separate elements operating at different scales and functioning distinctly, but rather in constant and emergent relation to each other. By overlooking these interactions, we risk advancing knowledge decontextualized from the actual forces at play, and thus limited in their capacity to advance effective agricultural transitions in a time of climate change. Thus, a more situational and partial approach to knowledge generation is called for (Leeuwis and Pyburn 2002). This gives way to a systems epistemology, exemplified here through reference to mixed methods, in which the world can be parsed into meaningful subsystems that are nested and dynamic in relation to other systems.

My overall methodological approach combines retroductive logic (an iterative process in which a theory is determined to fit the observations) and deductive logic with hypothesis testing. The former is more commonly found in sociological research while the latter is the dominant framework for biophysical experimentation. These approaches are often seen as incompatible, but I see critical realism as a way to unite these two research forms in generative ways. Combining more normative ways of understanding with the positivist approaches of science is merited with the topic of diversity or diversification because science in practice has barriers. Reliance on purely deductive logic is too timely, too expensive, and the choices too innumerable. To reimagine agricultural systems in face of challenges posed by climate change, it is important to develop new ways to study these systems.

1.3 Theory

Studying agriculture through an social-ecological lens allows me to understand the ways crop diversification practices can be improved and applied to the enhance resilience of farms in the face of extreme weather events. Agroecology's shared theoretical base with social-ecological systems permits such crossover. I connect my field-based research of crop diversification to the adoption of such practices. Here I draw on and extend Rogers' (2003) work on the factors and characteristics crucial for the adoption and diffusion of an innovation. History, subsistence agriculture, and current research show us that crop diversification is a useful strategy to absorb and adapt the effects of extreme weather (Holt-Giménez 2002, Lin 2011), thus increasing diversity may enhance the resilience of a farm. Despite crop diversity being identified as a potential resilience-enhancing mechanism, crop diversification practices in different agricultural sectors have remained limited. While the adoption-diffusion model centralizes the farm as the key engine of change and is valuable to understand the factors explaining how different farms adopt crop diversification practices, such a framework inadequately explains the larger structural dynamics that limit and support the adoption of climate-friendly agricultural innovations like crop diversification practices. Consistent with the retroductive approach, such an observation calls for rethinking the adoption-diffusion model. I show that the adoption-diffusion model remains valuable but must be integrated with a social-ecological systems approach.

Here, I consider the farm as the focal social-ecological system nested within a larger social-ecological system. Social-ecological systems are nested systems characterized by properties, such as resilience, that are emergent rather than given. I show in my research that the farm and its interactions to larger systems and smaller subsystems, promote or prevent adoption of crop diversification practices. The larger system does so by enforcing norms, rules, practices, and technologies. Many aspects of the larger system are supported by narrowly focused science to improve productivity and efficiency. The science of crop diversification remains nascent in regards to its coherence of scholarship, understanding of the multifunctional effects of diversification, and methods to advance the benefits of diversification. I propose that the criteria of an innovation in adoption-diffusion theory describe the feedback mechanisms within and across scales of social-ecological systems. In doing so, I address several gaps in the literature, including the lack of social-ecological system scholarship on industrialized agricultural systems, the extent of human agency in such systems, and new modes of research necessary for increasing crop diversification practices in agriculture.

1.3.1 Resilience theory

Agro-ecosystems are uniquely constructed social-ecological systems designed to produce food, fuel, fodder, and fiber based on fundamental ecological reality. In their study, Peterson et al (2018) illustrated an increasing number of resilience-related publications including in agriculture, showing the prevalence of the concept in the growing dialogue around climate change. Holling (1973) first described resilience as

> "an emergent property of a system that determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of static and dynamic variables, parameters, and still persist."

An emergent property denotes that the whole system is more than the sum its of parts. The term invites engagement with the ecological, social, economic facets which affect agricultural practices in human, land, and human-land dimensions. As I want to engage crop diversification within these complex systems that accompany these dimensions, I use the term resilience operationalized by Tidball and colleagues

(2018) as the interactions between ecology, economics, and social structures that provide and restore ecosystem services, as it uses ecosystem services as a basis for understanding social-ecological functioning.

Many studies on the resilience of agricultural social-ecological systems are focused on developing countries and subsistence farming. Local ecological knowledge is prevalent and people experience tighter ecological feedback loops (Sundkvist et al. 2005, Berkes et al. 2008). As such the social-ecological systems and 'humans in nature' perspectives are more discernable. Subsistence farms are very different social-ecological systems than industrialized farms for many reasons including, widespread mechanization, farm size, availability of synthetic inputs, greater access to globalized markets, and recognition as a specialty group by the government (Rist et al. 2014). In industrialized settings, farms are typically specialized with reduced complexity (Vandermeer et al. 1998). As such, the ecological feedback loops between the land and the farmer are more distant and/or masked (Sundkvist et al. 2005). Yet, superimposing conceptualizations of subsistence agriculture onto industrialized farm systems is a helpful exercise to understand the role that larger institutional structures play. From this, I see that production-oriented ecosystems are able to maintain their function production because of heavy dependence on external inputs, in what Rist et al (2014) calls 'coerced resilience'.

The main idea underlying resilience in agro-ecosystems is that farm practices can build the absorptive and adaptive capacity of the farm, and the farmer can learn and refine these practices. In part, this is driven by self-organization, meaning the components of the system have the ability to reorganize from a lower-level scale or with some autonomy, either ecologically and/or socially. In crops, this understanding reduces to greater temporal and spatial variance at field and farm-scales (Cadotte et al. 2011), while in agricultural management, this means a diversity of practice by the farmer and the ability to learn and apply knowledge which then dictates the amount of crop diversity performed (Colding 2000).

1.3.2 Social-ecological systems

Social-ecological system studies is a field of research that uniquely includes humans and human actions as components of an environment. This field began in the 1970's when ecological studies of large geographical areas (e.g., lakes, watersheds, forests) concluded that human actions indirectly (i.e., upstream) or directly (i.e., management) were affecting the area in question, and thus, could not be excluded. It marks a turning point in biophysical research to a more holistic approach; one that takes a 'human in nature' perspective. Since then social-ecological system scholarship has expanded from an ecological discipline to geography (Crane 2010, Martin 2012), community studies (Ifejika Speranza 2013), urban planning (Ernstson et al. 2010, Tidball et al. 2018), policy analysis (Allison and Hobbs 2004b), political science (Ostrom 2015), globalized systems (Rist et al. 2014), developing countries (Halliday and Glaser 2011), indigenous spaces/communities (Berkes et al. 2008), and continues to grow.

General systems theory (conceptual framework for understanding interacting or interrelating groups) and complexity theory (systems consisting of multiple components) have contributed to the understanding of social-ecological systems

(Bertalanffy 2007). Social-ecological systems are multi-scaled spatially, temporally, and organizationally (Gunderson and Holling 2002). These scales, and the overall system are also dynamic, and have multiple equilibrium states (Holling 1973). As such, social-ecological system are complex systems in that their attributes are non-linear, emergent, and self-organizing (Berkes et al. 2008). These characteristics limit the predictability of a system. To develop understanding of a social-ecological system, components of the system and the linkages to different scales are considered hierarchically (Simon 1977).

1.3.3 Farms as social-ecological systems

Understanding a farm as a social-ecological system means that the biogeophysical properties of the farm are investigated in tandem with the individual and social processes of the farmer. Farms can be understood as land-use systems overlaid on different ecological communities. To advance crop diversification I understand farms at three scalar levels: fields, nested in the farm, and the farm embedded in a socio-technical configuration made up of social and economic systems (Figure 1).), which is embedded in progressively larger social-ecological systems and ultimately in a cosmological system. To operationalize the conceptual framework, I divide the levels into functional subsystems and structurally measurable traits.

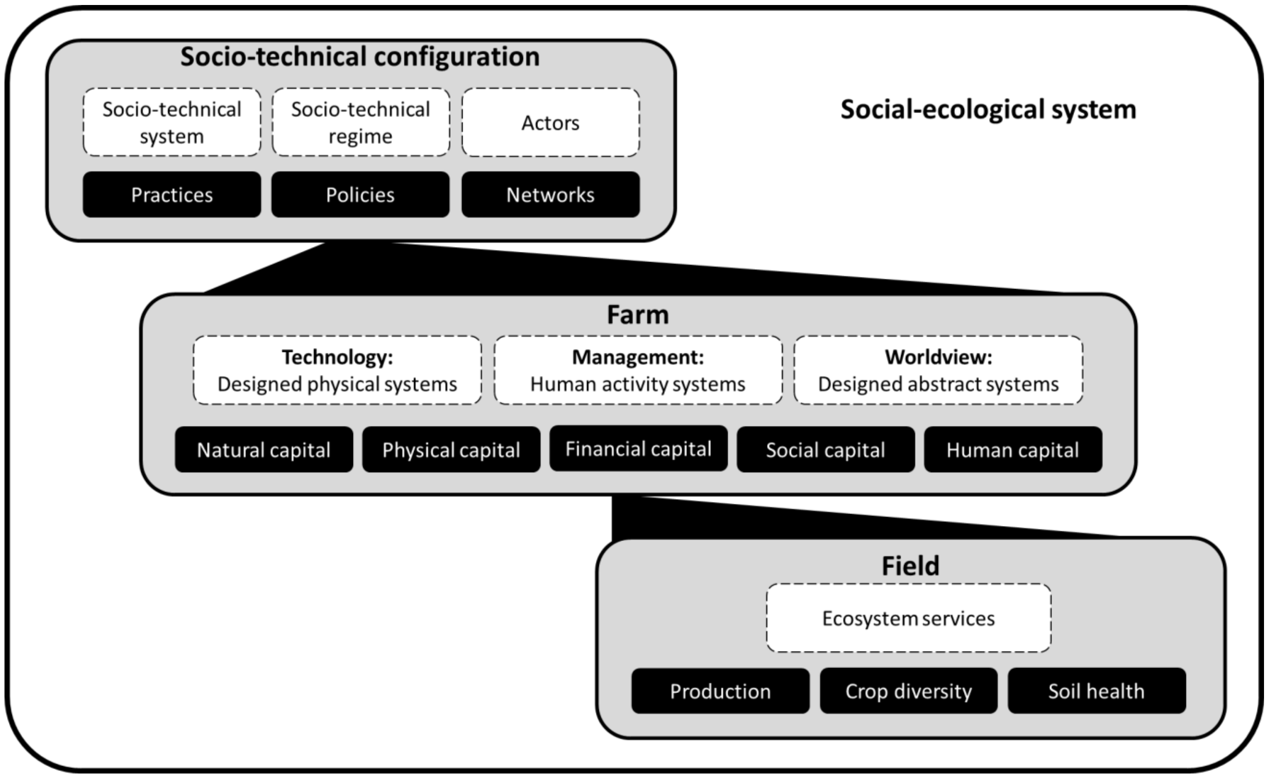

Figure 1. 1. In a social-ecological system, the farm is within a socio-technical configuration and contains fields. The white boxes represent the functional subsystems and have dotted boundaries to denote some degree of permeability with other functional subsystems. The black boxes represent measurable traits of each scale. The functional and structural components on the farm have strong similarities but do not align as they do in the socio-technical configuration.

I examined the social-ecological system at the farm-level because this is where crop diversification practices are managed. At the farm-level, I use a general social-ecological system model developed by Halliday and Glaser (2011) about smallholder farms in Peru. I subdivided the farm into four functional systems:

- **Nature**: humans and the biophysical environment
- **Management**: human activity (social and institutional) systems that mold the biogeophysical and social environments
- **Worldview**: designed abstract systems that encompass values, beliefs, and knowledge systems that guide humans
- **Technology**: designed physical systems implemented by humans as expressions of purposeful activity

These categories serve as heuristics and have permeable boundaries. For instance, crop diversification practices are behaviors implemented by humans, thus within the management subsystem. However, the presence of crop diversity is an expression of purposeful activity, thus part of the technical specification of the farm driven, in part, by the worldview of the farmer. Finally, the crops, production practices, the ways that the crops affect other components of the system represent the nature subsystem. I consider crop diversification practices as technologies as technology has a long history of being understood as the application of science (Barnes 1982). This opens theoretical pathways to understand the science of crop diversification within the social-ecological system.

To ensure a complete conceptual framework, I also divide the farm into quantifiable subsystems of natural, physical, financial, social, and human capital. Quantifying capital is a well-established strategy in agricultural development when attempting to operationalize sustainability (Bossel 1999, Saunders et al. 2007). For this dissertation, I engage with specific aspects of the social-ecological system, namely describing the ways in which the social and ecological components of farms are intertwined with the extent of adoption of diversification practices and information sources with which farmers engage.

The field-scale is nested within the farm-scale and it is here where crop diversification occurs. At this level, I am interested in the functional subsystem of ecosystem services, although it could have others. Here, ecosystem services are not simply benefits from an ecosystem, rather, they are an interaction of social-ecological systems on ecosystems (Niemelä et al. 2011). As such, the type and amount of ecosystem services depend on the farm management and the biogeophysical space of the farm. Examples of measurable traits include the productivity, the level of crop diversity, and soil health, but many other indicators exist. In this dissertation, I assess productivity, weed suppression, forage quality, and changes to soil organic matter. Other work from the experiments described in this dissertation assessed other soil characteristics, soil microbial communities, and legacy effects of different levels of crop diversification (Menalled et al. 2020).

In social-ecological systems, the focal scale is commonly embedded in landscapes or regions, as seen in Olsson et al. (2004, 2006), Anderies et al. (2006), Halliday and Glaser (2011), and Martín-López et al. (2017). However, I believe place-based divisions limit my ability to understand the adoption of crop diversification practices in an industrialized context where the socio-technical aspects supersede specific geographic areas (Sundkvist et al. 2005b, Foley 2005, Rosenzweig and Tubiello 2007, Campbell 2009, Darnhofer et al. 2010). Place-based infrastructure, like processing plants, does create a spatial dimension that can instigate changes in farmer behavior (Lewis et al. 2011). With this reasoning, I wholly contend that adoption is more likely to occur in the presence of secure market opportunities, an outcome of spatial and institutional dimensions (Herrera and Dimitri 2019). As my case study is focused on a single region, I account for the spatial component and can focus on the socio-technical configuration affecting adoption.

In industrialized production systems that are reliant on external inputs to exist, the farm-scale is embedded in a socio-technical configuration. The social-ecological system's literature has so far overlooked the importance of technology in advancing behavior. In this next section, I show their similar theoretical backgrounds and argue for their overlay.

1.3.4 Socio-technical configurations

Many agricultural scientists who engage with social-ecological system themes have highlighted avenues for policy and/or community engagement to create more favorable contexts for the greater diffusion of practices that would enhance the resilience of agriculture (Anderies 2005, Foley et al. 2005, Lin 2011). While useful for drawing attention to structural elements, these suggestions do not delve into scholarship on social systems or a social system's co-evolution with technologies or practices. As technology develops from humans and humans are a part of nature, then logically socio-technical configurations are a part of social-ecological systems.

For my work, I use socio-technical configurations as conceptualized by Geels (2004) because I am interested in the socio-technical perspective with special attention to crop diversification practices. Geels (2004) builds from the seamless web approach and integrates aspects of sociology of technology and institutional theory. He describes a configuration with three components: the systems (resources, material aspects), the actors involved in maintaining and changing the system, and the rules and institutions which guide actor's perceptions and activities. Socio-technical configurations parse out the large-scale structural dynamics in order to understand societal transitions to more sustainable configurations. By conceptualizing socio-technical configurations as the level superseding the farm in social-ecological systems, the pathways to discussing diversification practices at the societal level and the farm-level are open.

A socio-technical perspective means that the technical elements of agricultural production are studied in tight relation to social elements (Berkhout et al. 2004). The socio-technical configuration provides a framework for examining the dynamics between social, cognitive, information, and hardware systems. Socio-technical theory developed in organizational science and was first introduced by Trist and Bamforth (1951) in their study about the change in the community at the workplace as the coal mining industry began to use more advanced technology. Later, Hughes (1986) using the term, large technical systems, described a 'seamless web' and discussed the co-evolution of social and technical systems with regard to electrification of a city. Motivated by failures in Dutch environmental policy in late 20th century, the socio-technical perspective was applied to examine system-level transformations to understand policy levers for change (van der Brugge and van Raak 2007). The body of research in the socio-technical perspective came to be known as transition management, just as research in the social-ecological systems perspective came to be known as adaptive management.

Both systems perspectives have roots in complex systems theory but developed in different disciplines. Studies in social-ecological system focused mainly on natural resource management of ecological systems and rarely considered the dynamics of technological change in any detail (Smith and Stirling 2010). Studies in socio-technical perspective focused more on social systems and the human element of natural resource management (van der Brugge and van Raak 2007). Both social-ecological systems and socio-technical configurations are complex in that they exhibit non-linear, unpredictable behavior with interacting and emergent properties. According to Foxon et al. (2009), both consider change to be evolutionary and path-dependent. They both apply an epistemology of iterative, learning-based approaches with a wide range of stakeholders for institutional changes that would allow for greater opportunities to learn (van der Brugge and van Raak 2007). Methodologically, arguments in social-ecological systems and transition management are often built on case studies. For example in transition management, authors discuss main interactions that they identified to be barriers or useful for transition points for Netherland's waste disposal systems (Kemp et al. 1998), electric cars (Hoogma et al. 2005), and organic food in the UK (Smith 2006).

Differences exist between the two perspectives regarding the extent of human agency and the desired outcome. Smith and Stirling (2010) found that adaptive management of social-ecological system often pursued resilience in desirable states and transformation less frequently. In contrast much work on transition management is directed to radical regime change from some existing state, giving it a longer temporal component, a more forward-looking approach generally does not have a spatial context (Smith and Stirling 2010). Socio-technical systems and transition management are centered on human-control driving change in social and economic systems and rarely have a direct emphasis on diversity (Foxon et al. 2009). By nesting socio-technical into the social-ecological, I address some of these shortcomings.

Socio-technical configurations as complex systems are embedded in a landscape of exogenous variables and dynamics that exist outside the boundaries of inspection, and socio-technical configurations contain nascent spaces known as niches (Kemp et al. 1998). The regime of a configuration describes the incumbent rule-making dynamic that shapes and is driven by mainstream concepts (Geels and Kemp 2007). Niches develop when the regime creates a space for an alternative to take shape (Schot and Geels 2008). According to Kemp et al. (1998), niches:

> "demonstrate the viability of a new technology and provide means for further development, niches help build a constituency behind a new technology and set in motion interactive learning processes and institutional adaptions in management, organization, and the institutional context that are all-important for the wider diffusion and development of the new technology."

Hoogma et al (2005) describes a niche as a discrete application domain where actors are willing to invest in improvements of new technology. For this dissertation, the socio-technical niche is understood as one that views farming with an ecological lens.

Crop diversification practices have co-evolved with technology. Although, it might be more appropriate to state that the simplification of agroecosystems is a result of the co-evolution of agriculture and technology (Meynard et al. 2017). For example, farmers that graze their cows have pasture, but if animals are not grazing then the farm does need to have pastures. Diversification practices are determined by the seeds, equipment, labor, and other inputs available to the farmer, i.e. the forms of capital in Figure 1, but they are also promoted or demoted by the structural elements of the agrifood system.

1.4 Adaption of the adoption-diffusion model

Adoption-diffusion of innovations theory provides reasoning about factors affecting the adoption process, including personality types and socioeconomic factors of the adopter, the role communication and social networks, as well as attributes of the innovation (Rogers 2003). The theory has two major assumptions. The first is that the innovation is beneficial for the farmer. The second is that farmers act as individuals influenced by their network. As such, the theory does not adequately acknowledge the system in which the farmer is embedded. In my understanding of industrial farms as social-ecological systems, the socio-technical configuration influences farmer behavior and affects the structure and the function of the farm. Thus, I expand on adoption-diffusion theory by adapting it to a complex system. I propose that the criteria for diffusion (relative advantage, compatibility, trialability, observability, and complexity of an innovation) describe the feedback mechanisms of the farm in a way that connects the three levels of the social-ecological system (Figure 2).

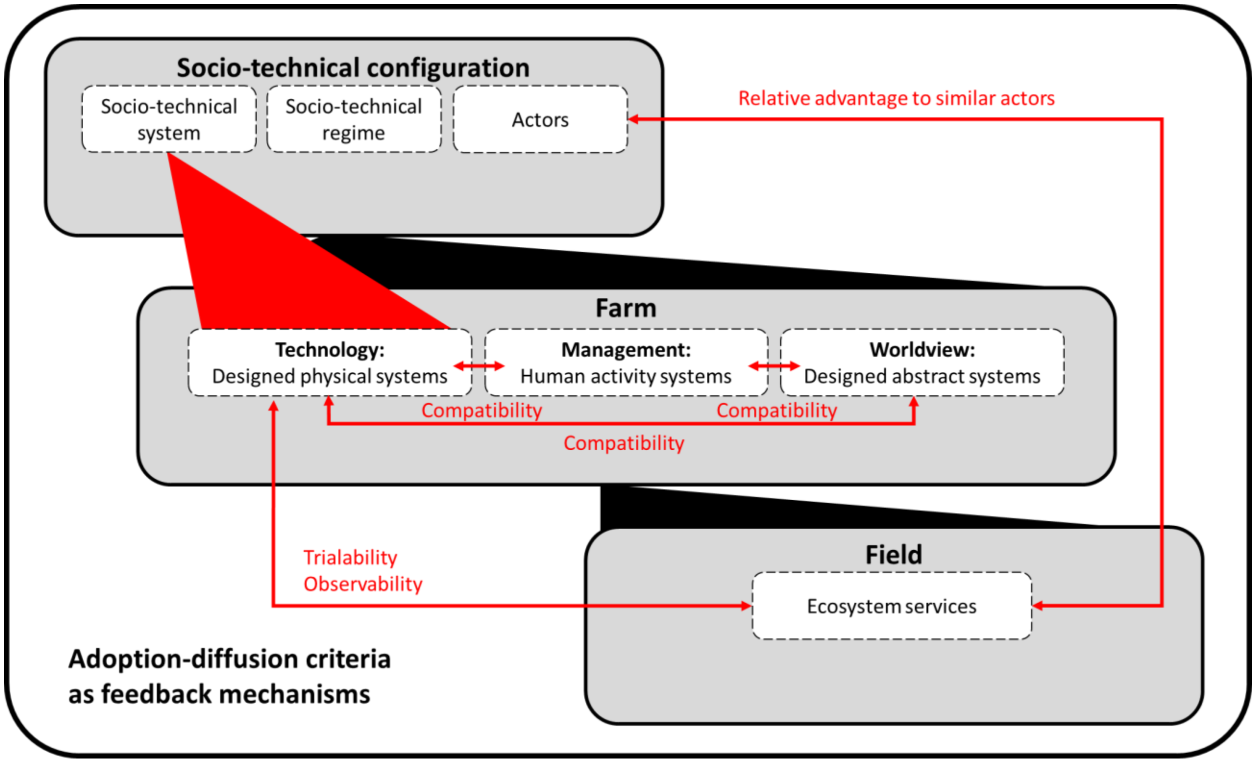

Figure 1. 2. Criteria of an innovation as diffusion feedback mechanisms in the social-ecological system of farms. A socio-technical practice is expressed in the technology subsystem of the farm.

Feedback mechanisms provide a dynamic understanding of the diffusion process. Feedback mechanisms are essential in adaptive cycles so that self-organization can occur in response to signals (Yli-Pelkonen and Niemelä 2005, Webb et al. 2017). The industrialized agrifood system masks feedback from ecological signals of the farm with external inputs (Sundkvist et al. 2005) and distance (Campbell 2009). Situating the diffusion criteria as responsive factors to systemic influences connects the farmer to the more structural-side of the agrifood system and enhances our understanding of farms as social-ecological systems. Moreover, understanding adoption-diffusion of crop diversification practices as components of the social-ecological system, provides a framework for adoption strategies for farmers specific to their embeddedness in the socio-technical configurations.

I am particularly interested in the relative advantage crop diversification offers in the face of extreme weather (Figure 2). For example, diversification practices could have greater yield stability (Bybee-Finley et al. 2016) or lower weed biomass (Picasso et al. 2008). Furthermore, the relative advantage could "cultivate the potential for a virtuous cycle" (Tidball et al. 2018) where the benefits seen from diversification on-farm could instigate changes to socio-technical configuration (e.g. reforms to agri-environmental policy). Compatibility of diversification practices is necessary in regards to the biophysical elements and resources of the farm, its management, and the farmer's worldview. Compatibility must also occur between the socio-technical configuration and the farm. Observations of ecological signals resulting from crop diversification practices serve as the feedback mechanism that occurs between the farm and the field. Trialability of a diversification practices represents another feedback mechanism between the farm and the field in regards to refining management or design of diversification practice. The boon and the bane of crop diversification practices is the final criterion Rogers identified, the complexity of the innovation. Diversification results is an increase in complexity at the field- and the farm-scale. The complexity allows for ecological signals to resound and for farmers to adaptively manage their land.

Now that industrialized farms have been conceptualized as social-ecological systems with biophysical elements at the field-scale, fields nested within the farms-scale, the fields are managed by people who hold certain worldviews, and the farms are embedded in socio-technical configurations that enforce beliefs by rules and norms, promote practices and technologies, and privilege certain knowledge, we turn to the ways crop diversification practices enhance resilience.

1.5 Crop diversification practices

Crop diversity is an indicator of resilience as it describes both the amount of ecological diversity and the variety and flexibility in management of the farm (Colding 2000, Walker et al. 2006). Diversification practices can enhance the resilience of a farm in the face of extreme weather events by providing spatial and temporal variance on the field and farm. A diversity of crops means greater genetic variation and the ability to perform under a variety of conditions.

Mechanistically this is because of functional and response diversity. Functional diversity represents the structure~function relationship and is the ability of different species to perform different functions because of plant physiology and phenology (Elmqvist et al. 2003) (biodiversity-productivity relationships). Functional diversity provides the ability of species to acquire resources differently (niche differentiation, sometimes called, resource partitioning) or the process of facilitation, the ability of one species to improve the environmental conditions for another species (Flombaum et al. 2014). Functionally diverse communities have been shown to enhance ecosystem processes (Cardinale et al. 2007, 2011) and be more productive than the most productive species in the community (Tilman et al. 2001, Iverson et al. 2014). Response diversity refers to the variability of responses within a functional group to environmental change (Elmqvist et al. 2003) (biodiversity-stability relationships). In this regard, agroecosystems with a redundancy of species that perform the same function are more stable because loss of one species does not result in the loss of that function (Walker et al. 1999). Stability of the agroecosystem (e.g., yield stability) is also increased because species can differentially respond to variable conditions and perturbations (Díaz and Cabido 2001). For these reasons, diverse fields and farms are better prepared for an extreme weather event because of a greater ability to absorb stress or adapt to the growing condition due to the variety within and across fields.

On the farmer side, management of crop diversity depends on the application of ecological knowledge and the ability to adapt in response to ecological signals (Olsson et al. 2004). The diversity of practices generally means the farmer uses various technologies at different times distributing labor requirements more evenly throughout the season (Hoagland et al. 2010). The ability to access multiple markets further reduces risks, although with the extent of specialization in industrialized farms this tactic currently has limitations.

1.6 Dissertation overview

Crop diversity affects functioning in agroecosystems (Szumigalski and Van Acker 2006; Smith et al. 2008; Smith et al. 2014) yet fundamental questions regarding the number of species or functional/response traits necessary and the spatial/temporal scales at which diversity effects are most apparent remains unanswered (Cardinale et al. 2011). Since the effects of diversification very much depend upon context, e.g. place, weather, and management (Low et al. 2002), establishing precise causal linkages is difficult, if not impossible. I once again ask, how can understanding the farm as a social-ecological system advance the adoption of crop diversification practices that enhance the resilience of a farm to extreme weather events? For the dissertation, I frame my work on forage cropping systems of dairy farmers in the Northeast. Dairy farms are typically specialized fitting the mode of industrialized farms, but perform a range of crop diversification practices, including annual and perennial crop production for animal feed.

In Chapter 2, I work to understand the social-ecological systems using interviews with conventional and organic dairy farmers in western NY. Using a network to illustrate one aspect of the socio-technical configuration, and one where I would situate myself as an agroecologist, I link crop diversification practices with information sources to understand how farmers make sense of their farm management for each farm type. This chapter provided real-world context for my other chapters.

In Chapter 3, I review scientific progress about intercropping, planting multiple species together at the same time in the same place, in industrial agricultural landscapes because it provides the highest resolution of complexity—spatial and temporal variance within a field. It is an essential component of subsistence cropping systems, but in industrialized crop production intercropping is underutilized (Vandermeer et al. 1998, Foley et al. 2005, Lin 2011). Here, I detail the main ecological mechanisms and benefits of intercropping and discuss multiple facets of research, practice, and institutional barriers.

In Chapter 4, I report my findings from a multi-year, multi-site research experiment that measured the effects of different levels of diversification of forage crops across the Northeast. The purpose of the experiment was to better understand the benefits and trade-offs diversity. The focus of the chapter was quantifying the absorptive elements of resilience operationalized in a holistic manner. Here, I compared forage crop yield, yield stability, weed biomass, forage quality, and seed costs for the diversity treatments.

Intercropping as a diversification practice to enhance resilience can be more effective if the resulting mixture can provision more ecosystem services. The relative advantage of a mixture is increased if the cost benefit ratio can be improved with more precise recommendations. In Chapter 5, I detail a framework about constructing crop mixtures to enhance the delivery of multiple ecosystem services by leveraging the seeding rates of each species. I draw from existing ecological theory to quantify crop competition amongst different species. By reducing the competition amongst species proxied through species evenness, I premise that more multi-functional mixtures can be generated.

Using multiple modes of thinking, this dissertation explores the strategy of crop diversification practice to enhance resilience of farms in a nested manner starting with wider, normative understanding of the context in which diversification would occur and homing in on scientific approaches to generate empirical evidence and further adoption. In finality, the epilogue connects across scales and offers concluding remarks about these approaches to advance adoption of crop diversification practices.

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CHAPTER 2

SOCIAL-ECOLOGICAL NETWORKS AND RESILIENCE: REFLECTIONS FROM DAIRY FARMERS IN WESTERN NEW YORK

2.1 Abstract

Agricultural systems vulnerable to losing their functionality must be able to adapt if they are to remain viable. I assess crop diversification as a strategy to enhance farm resilience using network analysis and quantitative mixed methods for elucidating the linkages between information sources and farm management in the multi-scaled complex system. Based on 25 interviews, conventional farmers prioritized annual diversification practices and had greater engagement with information sources, whereas organic farmers prioritized perennial diversification practices and had less engagement with information sources. Organic farms required information more focused on ecological management, whereas, conventional farms required greater precision about annual crop diversification practices. Considering a farmer's production practices, the way they learn, and their coordination with the socio-technical configurations can advance crop diversification strategies appropriate for different types of farms. Organic-certified farms had more land in perennial production and greater complexity in their crop rotations suggesting regulations focused on crop diversity is useful for enhancing social-ecological systems resilience in the face of extreme weather.

2.2 Introduction

Climate models forecast an increased frequency of extreme precipitation events and short- and medium-term droughts in the northeastern United States (Wolfe et al. 2018). The Northeast contains the largest concentration of dairy farms in the country (Boynton and Novakovic 2014) and such events affect their ability to produce on-farm feed for their animals and instigate importing feed (Dalton et al. 2008, Sweet et al. 2017). Crop diversification practices are an important agricultural innovation that enhance the resilience of dairy farms in the face of extreme weather events. To understand the adoption of such practices, it is useful to examine the social and institutional structures in which the farm is embedded (Buttel et al. 1990).

Sociological studies of adoption are valuable for understanding how and why farmers adopt new practices, but they are also incomplete in a number of ways. Most studies fall under the umbrella of adoption-diffusion theory. Adoption-diffusion theory shifts focus from the farmer towards broader systemic factors that determine farmer decision-making. While useful in highlighting the embeddedness of a farm in economic and social institutions, these studies do not adequately engage the farmer or specifics of the farm ecology (Buttel et al. 1990, Smith 2006b, Simin and Janković 2014, Lamine 2015). Furthermore, crop diversification practices are often generalized under conservation agriculture, sustainable agriculture, or best management practices (Prokopy et al. 2019), but a more specific examination of crop diversification practices can help explain their diffusion or lack thereof. Combining social-ecological systems theory, which posits humans are a part of nature, with a socio-technical perspective, which focuses on farm-level dynamics with the larger social and institutional structures, can help integrate analysis at the level of the individual farm by examining the techniques and information used on the farm. Drawing on these theories, I ask how socio-technical configurations facilitate the adoption of crop diversification practices, and how, through these facilitations, the socio-technical configuration affects the socio-ecological system of farms.

I argue that adoption of crop diversification practices differs on farms that are part of different socio-technical configurations. Smith (2006) argues that farms operate under a socio-technical configuration, i.e. they follow certain rules and methods of practice, and are more likely to connect with actors who also engage that configuration. Following this definition of a socio-technical configuration, I use a binary classification of dairy farming in western New York - conventional and organic. Conventional farms have a greater reliance on external inputs and tend to prioritize productivity over other ecosystem services (Foley 2005). As a result of the productivity emphasis, conventional farms typically comprise large fields of monocultures and simplified rotations (Rist et al. 2014). Organic agriculture is bounded by a formal certification process, but there is a general emphasis on localized knowledge and practices that enhance ecological processes rather than fossil fuel-derived inputs (Heckman 2006, Rist et al. 2014). Organic farms are typically smaller than conventional competitors, involve more complex crop-rotations, and more actively engage ecological signals.

To characterize the differences in the socio-technical configurations of organic and conventional farmers, I use social-network analysis. Networks are useful to illustrate the interactions across scales of complex system (Janssen et al. 2006, Bodin and Crona 2009). For each configuration, I build a social-ecological system network. The network links farmer informational sources to the extent of their crop diversification practices. The characteristics and compositions of these networks helps identify adoption pathways or leverage points. While it may be intuitive to understand that organic and conventional farming systems exhibit differences in their adoption of crop diversification practices, the combined use of a social-ecological and a socio-technical approach provides a more precise understanding of how the two modes of farming differ in their ability to adaptively manage the land and what aspects of management enhance what kind of resilience.

2.2.1 Farms as social-ecological and socio-technical systems

Humans manage ecosystems to produce food, fuel, fiber, and fodder. A social-ecological perspective means that humans are within and not outside of such ecosystems. Social-ecological systems is a field of research that has its roots in ecology and draws from complex systems theory (Colding and Barthel 2019). Social-ecological systems are multi-scaled spatially, temporally, and organizationally (Gunderson and Holling 2002) and exhibit non-linear, emergent, and self-organizing attributes (Berkes et al. 2008). In the social-ecological systems sense, farms are land use systems overlaid on existing soil, plant, and other biotic communities within abiotic settings. Farmers can adaptively manage their land by responding to the feedback (ecological signals) of such communities.

However, a 'humans in nature' perspective inadequately characterizes New York dairy landscape, which is dominated by industrialized farms. The industry is highly specialized, relies heavily on external inputs, and is integrated into globalized supply chains. Together, these characteristics mask the ecological signals of the farm (Rist et al. 2014), and underscore a need to engage not only the ecological factors, but also technological factors in understanding farming systems. Thus, I integrate in a socio-technical perspective to studies of socio-ecological systems (see first chapter, for details). In the socio-technical sense, the technical elements—tools and practices—are tightly related to social elements (Berkhout et al. 2004). Institutions and infrastructure are a part of the social-ecological system of the industrial farms, i.e. the farm is embedded in a system that shapes the decision-making of the individual farmer.

Geels (2004) provides a framework to characterize a socio-technical system. Geels identifies three components: the *systems* (resources, practices), the *actors* involved in maintaining and changing the system, and the *rules and institutions* which guide an actor's perceptions and activities. The framing brings the technical aspects of the farm into continuity with the institutional aspects, providing a framework to examine the dynamics between social, cognitive, informational, and hardware systems (Berkhout et al. 2004).

2.2.2 Resilience in the face of extreme weather

Predictions about climate change show that farms are vulnerable to losing their functionality (Allison and Hobbs 2004a, Ingram et al. 2008, El Chami et al. 2020). For this reason, scholarship framed around resilience in agriculture have resonated in recent years (Peterson et al. 2018). Holling (1973) defined resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.” Characteristics of resilience include robustness, transformability, and adaptability of the system (Holling 2001). Robustness is the ability to withstand perturbations. Transformability relates to the ability of the social-ecological system to self-organize, i.e. the level of connectedness of the farmer to a network of external forces (Milestad and Darnhofer 2003, Olsson et al. 2006). Adaptability is the ability of the system to learn and respond to appropriate signals (Holling 2001).

In the context of agriculture, the principal relationship is between the ecosystem’s ability to provide for humans and the humans’ ability to adaptively manage the ecosystem. The key challenge is to identify the practices or activities that confer resilience, i.e. strengthen farmer ability to adaptively manage their farm ecosystems. Thus, the type and amount of ecosystem services depend on the structures described above, farm management and the land itself. Reorganizing socio-technical configurations to better support ecosystem services, particularly those beyond production, is essential for continued agricultural production in a changing climate.

To manage ecosystems, a farmer must be able to learn. To understand a farmer’s ability to learn (and adapt) depends to a large extent on the sources information they encounter in the socio-technical configurations. Farmers seek out information and are also provided information through sources such as their friends, extension agents, bureaucrats of the United States Department of Agriculture (USDA), and agricultural service providers. Understanding the relations around information can provide insights into how farmers learn, what they learn, how farmers are able to or not able to use this information o adaptively manage their farm. Diversity of knowledge sources can contribute to learning that supports adaptive management of the ecosystem (Berkes et al. 2008), but high degrees of connection with external sources can also limit a farmer's ability to apply this information.

Networks of information provide a structure to the systemic elements of learning. The network is a dynamic entity that creates and reinforces norms, rules, practices, and technologies (Borgatti and Cross 2003, Prokopy et al. 2008). Networks can generate ecological knowledge through social memory, legitimize management practices, and provide opportunities for financial and political support (Hahn et al. 2008). Depending on the nature of the knowledge network and the influences of the socio-technical system, information can be shared and spread or dismissed and forgotten. The network decides what crop diversification practices are valued, what modes of learning or ideas are legitimate, and provides a supportive space, i.e. communities of practice (Bouttes et al. 2018).

2.2.3 Crop diversity as a strategy for resilience

Crop diversification is a strategy to enhance the resilience of a farm in the face of extreme weather events (Isbell et al. 2011, Peterson et al. 2018, Bowles et al. 2020, Tamburini et al. 2020). Diversification practices do so by increasing the spatial and temporal variance of crops on a farm landscape that increases the likelihood of crops responding favorably to given growing conditions. Benefits conferred through increased variance (i.e., the portfolio effect) occur because of functional and response diversity. Functional diversity expressed through plant physiology and phenology results in the ability of species to perform different functions (Elmqvist et al. 2003). Plants with differing traits can acquire different resources (i.e., resource partitioning) and facilitate the access to resources that would be otherwise unavailable (Vandermeer 1989; Duchene et al. 2017; Bybee-Finley and Ryan 2018). Response diversity is expressed when species that perform the same function have divergent responses to a particular stress (Elmqvist et al. 2003, Elsalahy et al. 2020). This multitude of responses provides the crop the opportunity for continued production under stress. Finally, greater variance within a farm instigates a diversity of practice, that is a variety of avenues to manage ecosystem services and a greater adaptive capacity (Colding 2000). A diversity of crops requires different equipment and agronomic management throughout the growing season. Spreading labor demands more evenly can reduce bottlenecks during peak times, result in higher quality crop management, and use available labor resources more thoroughly (Hoagland et al. 2010).

2.2.4 Connecting crop diversification practices to information sources

To understand how socio-technical configurations promote, demote, or ignore particular crop diversification practices, it is useful to look specifically at sources and channels that farmers in these configurations rely on for information about these practices. Using the classification of conventional and organic, this paper links information sources to adoption of crop diversification and explores how the two socio-technical configurations affect social-ecological systems of farms. This approach simplifies the three scales of the social-ecological system (field, farm, and socio-technical configuration) into one network between sources and practices with ties representing the farmer behavior.

To deepen understanding of the ties of this simplified network, I examine how trust, familiarity, and perception of a diversification practice affect farmer decision-making. Trust is both a cognitive and a social element, standing in relation to perceived risk and risk management (Arbuckle et al. 2015). Dietz (2007) has argued that when people make decisions under uncertain conditions with imperfect knowledge, they seek guidance from trusted sources. Similarly, Skaalsveen et al. (2020) show that farmers manage ecosystem services with the support of information from both external sources and from interpersonal relations (advice). The farmer's understanding and engagement with information sources and diversification practices is mediating how the socio-technical configuration affects the socio-ecological system of farm.

2.2.5 Description of case study

Dairy farming is the largest agricultural sector in the northeastern United States, but has undergone significant declines over the past several decades due to the rise in competition from other states that can produce milk with lower marginal costs (Winsten et al. 2010). Small- and medium-size farms caught between increasing production costs and falling purchase prices have sought organic certification that provides a price premium (Guptill 2009). New York is the largest producer of organic milk in the northeastern United States with 607 farms producing more than 175.4

million kg of milk in 2017 (USDA National Agricultural Statistics Service 2017). Between 2014 and 2018, the number of certified organic farms producing dairy has since doubled to 672 (Organic Integrity Database 2018). Organic certification requires several production practices, including at least 30% of the dairy feed to come from grazing for at least 120 days of a year (Northeast Organic Farming Association of Vermont 2014). As organic-certified dairies have regulatory standards that affect crop production practices, I analyzed the conventional and organic-certified dairies separately.

The general goal of crop production on dairy farms is to produce a high quantity of high-quality feed for cows. I made a list of crop diversification practices associated with forage crop production for dairies in this region. These practices increase the spatial and temporal variance at the field- and farm-scale, allowing farmers a greater ability to adapt to growing conditions because of the divergent responses of the crops.

Crop diversification practices for perennial crop production include integrating pasture, intercropping perennials, and planting grass waterways. Pasture is grazed land that generally contains a multitude of species from a range of plant families and is maintained for multiple years, without reseeding (Barnes et al. 2003). Grazing management is a complex endeavor of both livestock and land management (Sanderson et al. 2004). Land in pasture can also be mowed to make hay. In New York, it is common that hay consists of perennial species harvested multiple times throughout the year and stored as winter feed (Fick and Cox 1995). Intercropping perennials is the growing of multiple species of perennial crops in the same space at the same time, either in strips or in a mixture (Vandermeer 1989). Alfalfa (*Medicago sativa* L.) can be seeded in pure stands or in mixtures, commonly with clovers and cool season grasses (Cherney et al. 2017). Grass waterways are areas with vegetation near flows of surface water. They can be on field borders, e.g. areas alongside a creek, or in the middle of fields in areas where runoff from precipitation events is channeled (NRCS 2014).

Crop diversification practices for annual production include cover cropping, double cropping, and intercropping annuals. Cover crops are crops that are seeded and not harvested or grazed with the intention of improving the soil. In New York, most commonly, cover cropping involves the planting of winter annual cereals such as cereal rye (*Secale cereale* L.) following the harvest of corn silage (Long et al. 2013). Double cropping is the harvest of two annual crops within a year, i.e. the harvest of a winter annual in spring and subsequent harvest of a summer annual in fall (Ketterings et al. 2015b). The most common practice of intercropping annuals is in cover crop mixtures, but mixtures of summer annuals for forage is also possible (Bybee-Finley et al. 2016).

This paper advances a social-ecological system-level analysis of two configurations of dairy farms, focused at the level of the farmer. Farmers interact with lower scales of system through management and with the higher scales by sourcing information. I report on networks characteristics to describe the structure and mixed methods including direct quotes to describe how farmers make land management decisions. The relationships of the network are measured with indicators of trust with regard to information sources and familiarity and perception with regard to crop diversification practices. The analysis includes the following sub-questions:

1. What is the extent of adoption of crop diversification practices by farmer type?
2. What information sources do farmers engage with regarding land management practices?
3. What are the connections between information and crop diversification by farmer type?
4. Who do farmers turn to for advice regarding land management practices?
5. How does trust of information sources factor into these relationships?
6. What is the familiarity and perception of farmers to crop diversification practices?
7. How do farmer types differ in their knowledge synthesis?

2.3 Methods

The case study was conducted in contiguous counties of western New York dairy region in the United States (Table 1), identified by Boynton and Novakovic (2014) as an area with sustaining growth in milk production and high production in general. In this region, the topography varied with land becoming flatter to the west. Topography likely affected production practices of farmers since some practices are more well-suited to certain landscapes (i.e. marginal lands) (Fick and Cox 1995). The total sample contained a range of production practices for both conventional and organic farms building a breadth of understanding of farms as social-ecological systems.

Table 2. 1. A breakdown of the number of farms, organic farms, and concentrated animal feeding operations (CAFOs), as well as milk marketed and milk per farm by county in the Western milk production region of NY.

County	No. of farms[1]	No. of organic farms[2]	No. of CAFOs[3]	Total milk marketed	Milk marketed per farm
				(thousand kg)	(thousand kg)
Cayuga	92	11	14	42492	462
Genessee	68	13	11	28560	420
Livingston	62	6	10	26091	421
Onondaga	71	15	11	23041	324
Ontario	102	8	8	22314	219
Seneca	103	28	8	6693	65
Wayne	48	0	1	8701	181
Wyoming	143	18	20	45690	319
Yates	255	38	1	10199	40

[1] The number of farms and milk marketed are from the 2016 Annual Summary of the NY State Dairy Statistics (Trodden and McCue 2016).
[2] The number of organic farms is from the Organic Integrity Database (2018).
[3] The number of CAFOs is from a 2013 Environmental Protection Agency report obtained by a Freedom of Information Act and shared on the National Resource Defense Council website that has since been removed (Am et al. 2013, Miller 2019). An undated map of New York State is the best record of CAFOs by county I could find (Department of Environmental Conservation n.d.).

2.3.1 Sampling

Farmers were initially sampled using a heterogenous snowball sampling, however, this sampling approach proved challenging given that sharing of farmers' information is considered inappropriate by many farmers and extension agents. Instead, I randomly sampled 13 organic farmers from the National Organic Integrity Database (contacting 30 farmers by telephone of which, 43%, responded). For conventional farmers, I utilized my own Cornell network (Pro-Dairy, professors, students from NY dairy farms) to connect with conventional farmers, and some of these farmers did provide me with contact information about other farmers. As such, sampling included a combination of random and snowball sampling. This methodological approach led to a dataset that spanned a range of farm types and sizes, which highlights the range of dairy farmers in western, NY.

I interviewed 25 farmers. Twelve were conventional dairies out of a population in western NY of 807 farms (NY State Dairy Statistics, 2016). Thirteen were certified organic dairies out of a population of 137 in western NY (Organic Integrity Database, 2018). Of the thirteen organic farmers, three had grass-fed operations (meaning no annual crop production), six were Plain people (Amish or Mennonite), two used robotic milkers, and two were classified as concentrated animal feeding operations (CAFOs), which is defined as farms having 300 or more cows (Ashline 2018). Of the twelve conventional farms, nine were CAFO, one contained acreage that was certified organic but not used for the dairy operation, and none had grass-fed operations, were Plain, nor used robotic milkers.

Across both farm types the average farm was 567 hectares with a herd size of 575 milking cows producing 29 kg of milk per cow per day. For the conventional farms, the average farm size was 971 hectares with 1090 milking cows producing 39 kg of milk per cow per day. For organic farms, the average farm size was 162 hectares with 100 milking cows producing 21 kg of milk per cow per day. According to the New York State Dairy Statistics (2019), the average herd size of interviewed farmers tended to be larger the average farmer found in the western region. Data about organic crop or milk production by county was not readily available for comparison. The differences between herd sizes of the interview sample and the western region indicates some sampling bias, likely due to the size of the conventional farms. Conventional farmers most accessible to me tended to be from larger operations than the average conventional NY farms. However, I understand this sample adequately captures the diversity of the dairy industry in western NY.

2.3.2 Approach

Semi-structured interviews were conducted in-person at the farm with the primary decision-makers for crop production. The preliminary draft of questions was based on issues raised in the literature regarding adoption of sustainable/alternative technologies by farmers, of which I focused on diversification practices, the influence of social networks of farmers, and production practices of dairy farmers. These questions were reviewed by professors across a range of disciplines specializing in New York dairies. The interview guide and outreach materials were approved for exemption by the Institutional Review Board (IRB) Office (#1807008135) in the summer of 2018. Five pilot interviews followed, and the questions and delivery were refined for a smoother, more coherent flow. The interview instrument can be found in Appendix A.

Interviews were conducted in the summer of 2019 after spring planting, and the fall of 2019 after the harvest, i.e. less busy time for farmers. Most often interviews were conducted with an individual, but occasionally it was a father-son, husband-wife, or a farmer-crop manager pair. Farmers were interviewed using mixed methods, comprising of questions that had closed responses with answer options and others that were free response. Interviews ranged between one to two hours and had main components: general information about the farm, the cropping practices performed, and a survey-like portion involving position-generator questions about what information sources farmers access for information. The first two sections were about understanding the farms operations and cropping practices. The third section was about the sources of information with which the farmer engages. Interviews were audio recorded and detailed notes were taken immediately following the interview (Weiss 1995, Creswell 2013). All interviews were transcribed by the 3Play Media (Boston, MA) service.

2.3.3 Assessment of networks

For this chapter, mostly closed response questions are reported (farm size, use of information source, trust of information source, trust and frequency of advice, familiarity and perception of crop diversification practice). Questions regarding advice sources were open-ended. I coded for occupation of the advice source and selected quotes that expressed the general sentiment of the farmers who were interviewed. Questions about extent of adoption were determined based on ratios of the total farmed land. Quotes highlighting farmers' thoughts on systemic factors of production or understanding the farm as a system were included to illustrate how farmers position themselves within the socio-technical configuration. Statistical analyses were performed in R version 3.6.1 (R Core Team, 2019). Network visualizations were performed with the 'igraph' package (Csardi and Nepusz 2006).

To assess the information networks, farmers were asked to indicate whether they used an information source from a list of sources and report their level of trust for each source (1-5, where 1 = strongly distrust and 5 = strongly trust). To illustrate farmer-information source relationship using networks, information sources were categorized based on shared characteristics of information focus. The Community category included family, friends, neighbors, and church; this category mostly consisted of farmers. The Growing Feed category included agronomists, nutritionists, grazing groups, and employees. Their roles are focused on producing quality feed for dairy cows. The Cow Care category included veterinarians and milk cooperatives. While these are very different roles, both are focused on the health of the cow particularly regarding milk production (e.g., somatic cell counts). Finance category included banks, financial consultants, Natural Resource Conservation Service (NRCS), and Soil and Water Conservation Districts (SWCD). While often understood as conservation programs that provide technical advice, the NRCS and SWCD both offer voluntary cost-share programs that offset the economic burden of conservation practices. Banks offer access to financial capital. The Input category included fertilizer, pesticide, and seed salespeople. The Land Grant category included Cornell, county extension services, Cornell Cooperative Extension, and professors (i.e. Cornell professors with extension positions). These represent those who are fulfilling the mission of land grant universities to the region.

Farmers were also asked to name five people who they turn to for advice when considering a change in their land management practices and their occupation, level of trust (1-5, where 1 = strongly distrust and 5 = strongly trust), and frequency of communication (1-5 where 1 = Never (less than yearly) to 5= Daily). Information sources represent generalizable entities where farmers may seek information. Advice sources are specific people that farmers name. The same categories for information sources were applied to advice sources but an additional category, Big Data, was added for the farmer who sought advice on how to manage large amounts of data. Extent of adoption was measured by five categories (none, tried and quit, little (~1/3 farmed land), around half (~1/3 to ~2/3 farmed land), and more than half (more than 2/3 farmed land)) and reported in three categories (no adoption, less than half of farmed land, and around half or more of farmed land). To understand farmer's cognition about the practices, I measured their familiarity (1-5, where 1 = not at all and 5 = a great deal) and perception (positive, neutral, or negative) of crop diversification practices. Greater familiarity and positive perception indicate a higher likelihood of adoption of a practice (Rogers 2003).

For information sources, descriptive statistics (e.g., mean, range, standard deviation of ties) were used to summarize each farm type. The number of sources represents the density of one aspect of a farmer's knowledge network, while range and standard deviation of sources indicate diversity within farm types (Borgatti et al. 2013). Engagement with multiple sources of information may not mean that the information about land management practices are more varied (Stedman et al. 2012). It does indicate that farmers draw from a more expansive learning environment and perhaps have a greater capacity (e.g., time, willingness) to engage. Mean and standard deviation were reported for trust and frequency of communication for each farm type. Lower deviations indicate greater similarities within farm type (Scott 2017). High levels of trust and more frequent conversation indicate a stronger tie between the farmer and those they seek advice or information from.

Following the methods of Díaz-José et al. (2015), two-mode networks were created to describe the farmers' information sources and adopted crop diversification practices for each farm type. First, a two-mode network was constructed between the farmers ($N = \{n1, n2, \ldots ng\}$) and the information sources ($M = \{m1, m2, \ldots mg\}$) by farm type. The matrix of the two-mode network is represented by A=$\{a_{ik}\}$ and connects the farmer with an information source. The element A takes the value 1, if farmer *i* engages with the information source *k*, and 0 otherwise.

$$a_{ik} = \begin{cases} 1 \text{ if farmer } i \text{ engage with information source } k \\ 0 \text{ otherwise} \end{cases}$$

Second, a two-mode network was created between the farmers ($N = \{n1, n2, \ldots ng\}$) and crop diversification practices (P = {p*1, p2, . . .pg*}) by farm type. The element A takes the value 1, if farmer *i* had adopted practice *p* on around half or more of their farmed land, and 0 otherwise.

$$a_{ip} = \begin{cases} 1 \text{ if farmer } i \text{ engage with practice } p \\ 0 \text{ otherwise} \end{cases}$$

While this method results in a loss of resolution about the extent of adoption, it is useful for drawing distinctions between farm types.

To connect information to crop diversification practices, the practice adoption matrix (a_{ip}) was transposed (T) and multiplied with the information matrix (a_{ip}) to generate element X (Eq. 1). Network X is a two-mode, social-ecological network of information categories and crop diversification practices. The values in the network represent the extent of engagement with an information category and adoption of a crop diversification practice across all farmers by type.

$$X_{kp} = a_{ik} \times (a_{ip})^T \qquad \text{(Eq. 1)}$$

2.4 Results

2.4.1 Adoption of crop diversification practices

Apart from the grass-fed dairies that only had pasture, farmers in the interviews often performed multiple crop diversification practices. Regardless of type, all farmers grew perennials on around half of their land (Figure 1). This was the most frequently used diversification practice. In contrast, intercropping annuals was the least frequently used diversification practice. Farmers who intercropped annuals mostly did it in their cover crops. However, both types of farmers discussed intercropping perennials as a risk management strategy to mitigate weather and pest conditions. With regards to intercropping, a conventional farmer spoke of risk reduction of field variability as a justification for intercropping.

> It [intercropping] also spreads out the risk a little bit, where if you have a wetter spot, the grass might do a little better. Drier spot, the alfalfa

> might do a little better. So it kind of spreads out your risk on field variability.
> —Conventional farmer, July 24, 2019

In contrast, the organic farmer went beyond risk reduction and spoke about using a more precautionary approach and dealing with potential unknowns.

> Oh, jeez, that [pure stands] would be a disaster. We've got to have a little insurance that if something gets eaten, there's some-- if the weevil ate the alfalfa, at least we've got something left to harvest…
> —Organic farmer, July 24, 2019

Conventional farmers had greater extent of adoption of annual diversification practices, simply because they had more crop production in annuals. About half of the conventional farmers had a small amount (one-third of farmed land or less) of pasture that was used for heifers or dry stock, especially if space in the barn was limited (Figure 1). All conventional farms performed some amount of cover cropping (Figure 1). Many expressed a preference to cover crop all their land that was planted in corn, but this was not always possible often due to timing and labor constraints. All conventional farmers had grass waterways, likely due to higher extent of annual production.

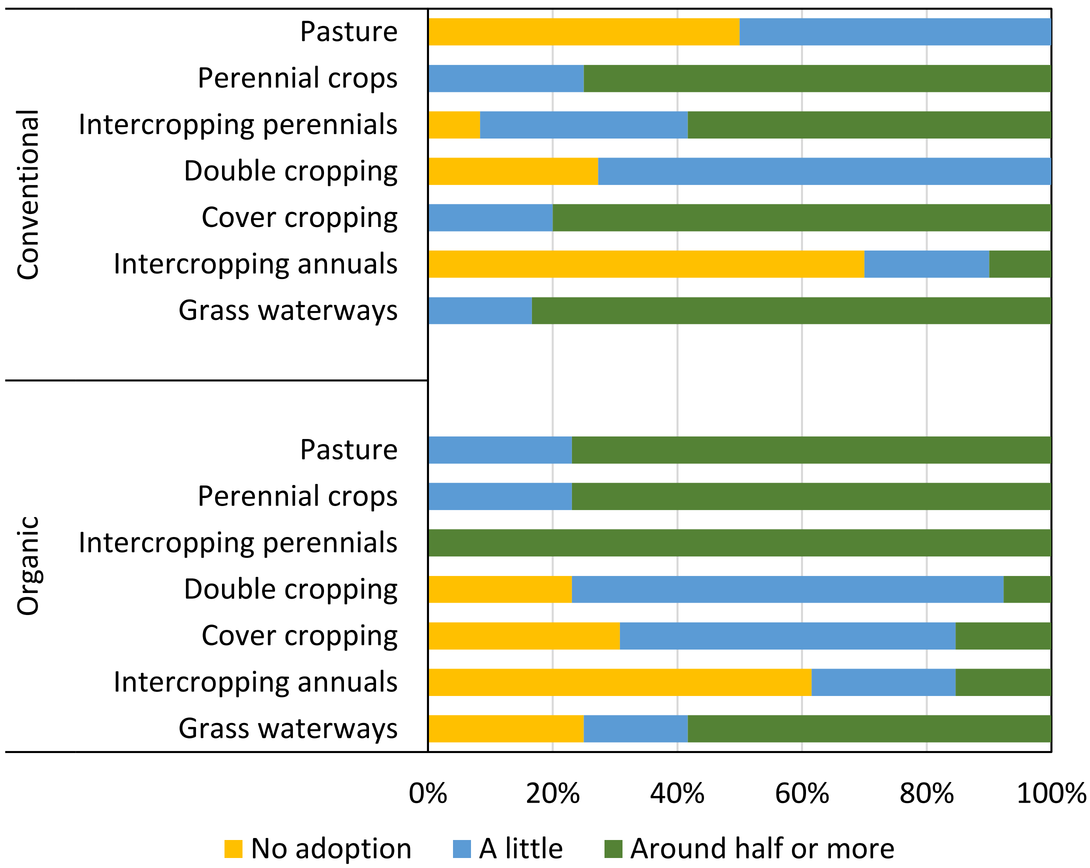

Figure 2. 1. Extent of adoption of crop diversification practices by conventional and organic farmers was measured by five categories (none, tried and quit, little (~1/3 farmed land), around half (~1/3 to ~2/3 farmed land), and more than half (more than 2/3 farmed land)) and reported in three categories (no adoption, a little of farmed land, and around half or more of farmed land. The lack of adoption seen in organic farmers is partially due to the three grass-fed organic farms that did not grow annuals or need grass waterways because land was in perennial production.

Organic farmers adopted annual crop diversification practices to a lesser extent than conventional farmers. This is because more of the organic farmers' land was in pasture. More than half of the organic farmers had around half or more of their land in pasture. In addition to pasture, organic farmers tended to intercrop their perennials more frequently than conventional farmers (Figure 1). All organic farms, apart from the grass-fed dairies, double-cropped a small amount of their land (Figure 1). Organic farmers spoke more often about managing diversity to the land. An example of this is the description by one farmer as to how he plants his hay fields.

> If I put three kinds [of alfalfa] in there… Some alfalfa does better in heat. Some does better in wet…The mix might be doing well in the hot of the summer. If we get a dry year, at least something will grow. And they may not all be in the same mix in the same field…A field that's more bottomland will get more grass that can handle wet, although it's really not an issue on this farm because we have gravel [soil]. I have to watch drought tolerance oftener [more often], although I do have some shady areas that they're just going to get a different mix.
> —Organic farmer, November 11, 2019

2.4.2 Information sources

Information sources represent one social aspect of the social-ecological network and help understand how supportive the socio-technical configuration is for learning and self-organization. Conventional farmers sought information from more sources than organic farmers (Table 2). Conventional farmers had on average three more ties to information sources than organic farmers, but organic farmers had a greater variance in the number of ties. The most frequent sources for both farm types were those found in the Community and Growing Feed categories (Table 3). Conventional farmers more likely turned to specialized knowledge sources such as agronomists who recommend crops, rotations, fertility, and pest management, and nutritionists who recommend the cow diets based on quantity and quality of feed. Having a diversity of sources also requires the farmer to sift through recommendations, knowing that each information was provided through a particular lens.

> I… sometimes, for certain things, I know what they're going to say, and I don't want to hear it….if they were to pick all the varieties of crops that you grow because of one reason, because of how they feed, and no other reasons, that's not a good balance necessarily.
> —Conventional farmer, July 24, 2019

The most common source of information organic farmers cited were family members because knowledge about integrated crop-livestock management was passed down through the family (Table 3). Organic farmers listed Grazing groups as the most important source of information in the Growing Feed category. A grazing group is a community of graziers who share their experiences often through facilitated participatory exercises like pasture walks where they discuss management practices.

> I learned by going to pasture walks…That's going to different farmers and seeing what they're doing. And then you take what you like, and you leave what you don't like. What works for me, won't work for the neighbor. Because he manages different. But something that works good for him, might not work for me.
> —Organic farmer, August 8, 2019

Here, the farmer views other farms as a complete system and is able to see the integrated nature between the biophysical and farm management.

Table 2. 2. Mean, standard deviation (SD), minimum, and maximum number of information sources by farm type.

Farm type	Mean	SD	Min	Max
Conventional	8.1	1.58	6	11
Organic	5.5	2.67	1	10

Table 2. 3. Counts of information sources farmers engage with when seeking to change to a land management practice by farm type. NRCS is the Natural Resource Conservation Service and SWCD is the Soil and Water Conservation District. For information trust for information sources that farmers used see Appendix A.

Category	Position	Conventional		Organic	
		--------------*Counts (%)*--------------			
Growing Feed	Agronomist	11	(92)	6	(46)
	Grazing group	0	(0)	8	(62)
	Nutritionist	11	(92)	6	(46)
Community	Church	1	(8)	4	(31)
	Family	6	(50)	10	(77)
	Friend	7	(58)	8	(62)
	Neighbor	8	(67)	6	(46)
Cow Care	Milk cooperative	0	(0)	3	(23)
	Veterinarian	6	(50)	4	(31)
Land Grant	Cornell	9	(75)	5	(38)
	Extension	7	(58)	1	(8)
Finance	Bank	6	(50)	2	(15)
	NRCS	7	(58)	2	(15)
	SWCD	7	(58)	4	(31)
Input	Input salespeople	6	(50)	1	(8)

2.4.3 Linking information sources with crop diversification practices

The network analysis used to connect the diversification practices with the information sources used for each farm type illustrated how some practices had greater connections to particular information sources (Figure 2). For conventional farmers (Figure 2a), the most adopted crop diversification practices were planting grass waterways, cover cropping, and planting perennials and were most linked to Growing Feed, Finance, and Land Grant. These information categories represent formal systems representing external expertise, traditional outreach, and funding support. The practice of intercropping perennials was adopted at a lower rate than planting perennials and had a fewer number of ties to information categories. Yet, most conventional farmers intercropped at least some of their perennials.

For organic farmers (Figure 2b), Community and Growing Feed information categories were more strongly connected to crop diversification practices. The most widely adopted practices were intercropping perennials, having pasture, and planting perennials. Intercropping perennials had links to all information categories with the strongest tie to Community. Using pasture was the second most common practice and had the greatest number of ties with the Growing Feed category followed by Community. It is likely that those in the grazing group are also members of the community, especially within the Plain Sect farmers. Among organic farmers, double-cropping, cover cropping, and intercropping annuals had lower rates of adoption compared to other crop diversification practices due to the overall lower extent of annual crop production.

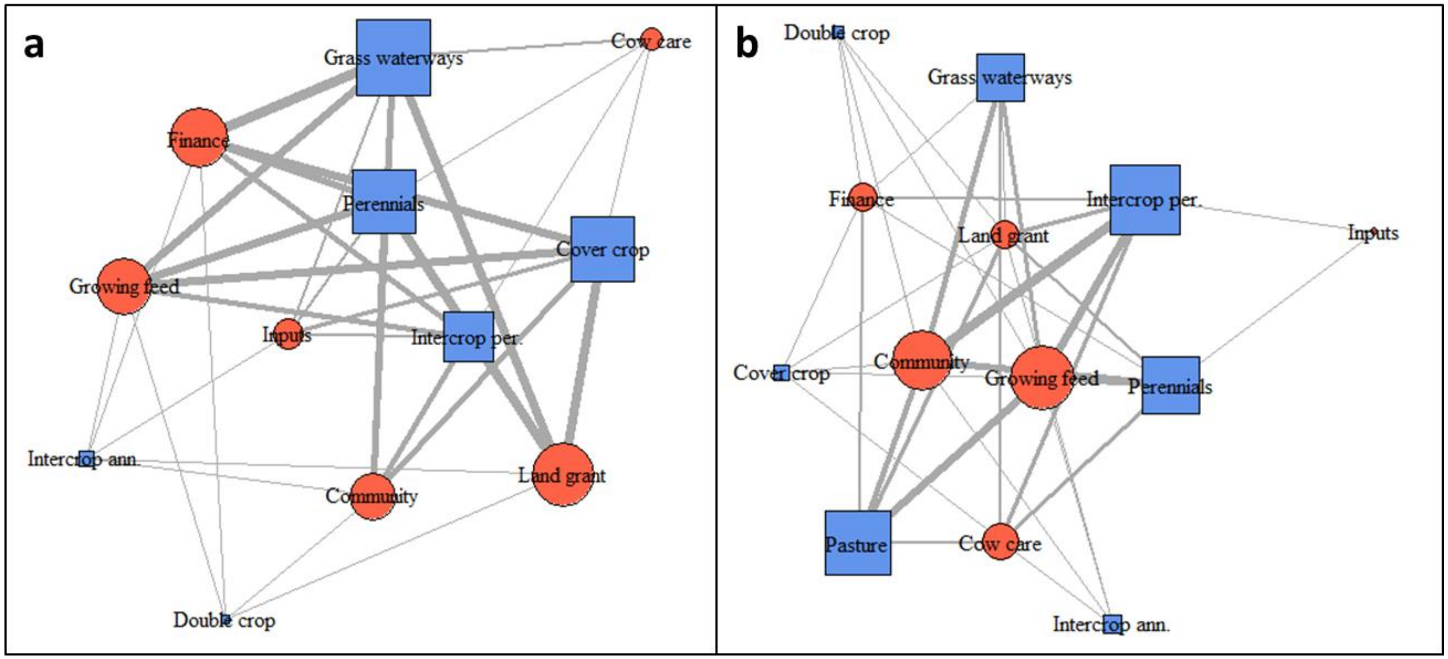

Figure 2. 2. Bipartite networks for a) conventional and b) organic farmers connecting crop diversification practices (blue squares) to information categories (red circles). The size of these shapes is the average of the number of times each information source was used and whether the practices were performed on half or more acres of the land, respectively. The lines connecting information sources to practices illustrate the relationship of the information sources and the practices. Thicker line width reflects greater frequency between use of an information category and performance of a crop diversification practice.

2.4.4 Farmer perceptions

To further advance an understanding of the social-ecological network, I examined how farmers perceive different practices and how they trust different information sources. The farmer mediates information they receive and relates the information to their land and farm resources (described as capital in the first chapter). The mediation and application of information represents the farmer's ability to learn and adapt (Darnhofer et al. 2010, Bouttes et al. 2018).

Trust was examined for all information sources. Both types of farmers tended to trust the sources of information they had self-selected (Table 1A). As such, agronomists and nutritionists had high levels of trust from conventional farmers whereas family, friends, and grazing groups had high levels of trust from organic farmers (Table 4). Farmers were generally neutral about sources they did not seek information from. Rarely were any farmers distrusting of information sources.

Familiarity with a practice speaks to how much the farmer has read or heard about a practice, thus how often these practices come up in conversation or in written resources. Perception relates to the tone of that information. One would expect greater familiarity and a more positive perception would relate with higher rates of adoption. Both types of farmers had varying degrees of familiarity regarding most crop diversification practices discussed in the interview (Figure 3). Conventional farmers expressed greater familiarity with diversification practices overall. Organic farmer responses had a greater range of familiarity with more farmers selecting 'little' or 'none'. Of all the practices, organic farmers stated they were very familiar with pasture, perennial crops, and cover cropping (Figure 3). Conventional farmers were most familiar with perennial crops (Figure 3).

Table 2. 4. Average trust and standard deviation (SD) for all information sources by farm type. NRCS is the Natural Resource Conservation Service and SWCD is the Soil and Water Conservation District.

Category	Position	Conventional		Organic	
		Mean	(SD)	Mean	(SD)
Growing Feed	Agronomist	4.91	(0.31)	3.92	(0.86)
	Grazing group	3.09	(0.31)	4.00	(0.71)
	Nutritionist	4.45	(0.93)	3.77	(1.17)
Community	Church	3.00	(0)	3.38	(0.65)
	Family	3.91	(0.83)	4.23	(0.60)
	Friend	4.10	(0.74)	4.00	(0.58)
	Neighbor	3.55	(0.52)	3.85	(0.69)
Cow Care	Milk cooperative	3.00	(0.89)	3.31	(0.85)
	Veterinarian	3.82	(0.75)	3.77	(1.01)
Land Grant	4H & FFA	3.09	(0.30)	3.38	(0.65)
	Cornell	4.09	(0.70)	3.69	(1.03)
	Extension	4.00	(0.63)	3.85	(0.90)
Finance	Bank	3.55	(0.69)	3.31	(0.75)
	NRCS	3.91	(0.94)	3.46	(0.88)
	SWCD	4.00	(0.89)	3.62	(0.96)
Input	Input salespeople	3.18	(0.75)	3.08	(0.86)
	Feed cooperative	3.09	(0.30)	3.00	(0.58)

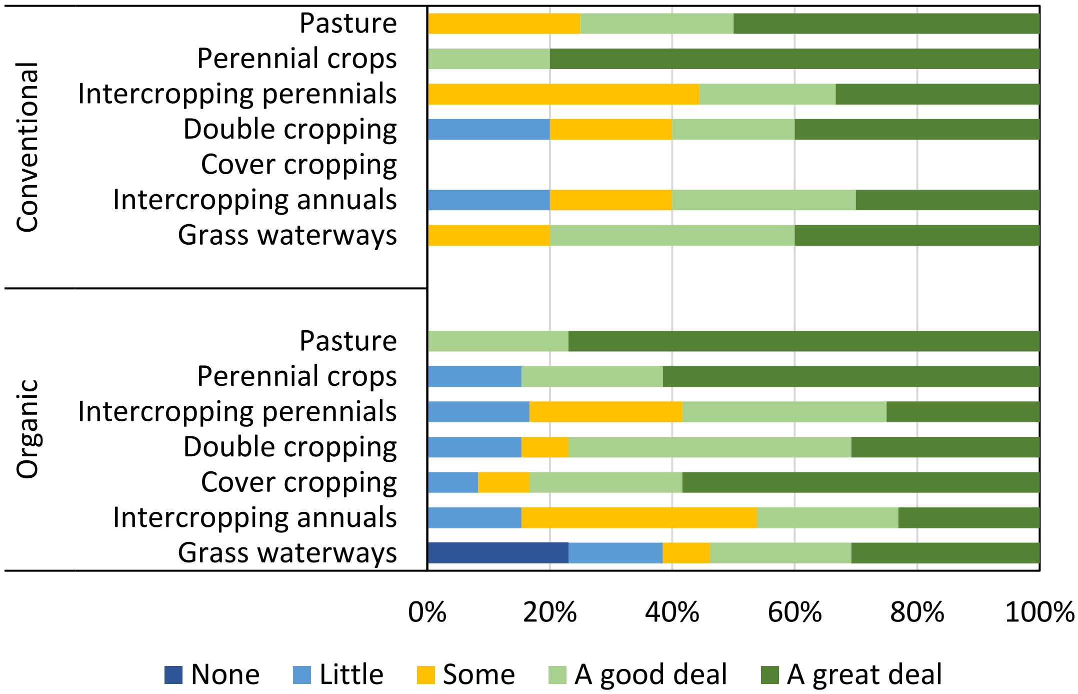

Figure 2. 3. Familiarity of conventional and organic farmers to crop diversification practices on a five-point scale. Cover cropping for conventional farmers is missing due to a surveying error.

Overall, farmers generally had heard of or developed favorable perceptions toward crop diversification practices with some notable differences (Figure 4). For example, regarding pasture, organic farmers reported favorable perceptions from their sources while conventional farmers reported majority neutral or negative. Similarly, conventional farmers also had more neutral perceptions of intercropping perennials compared to organic farmers (Figure 4).

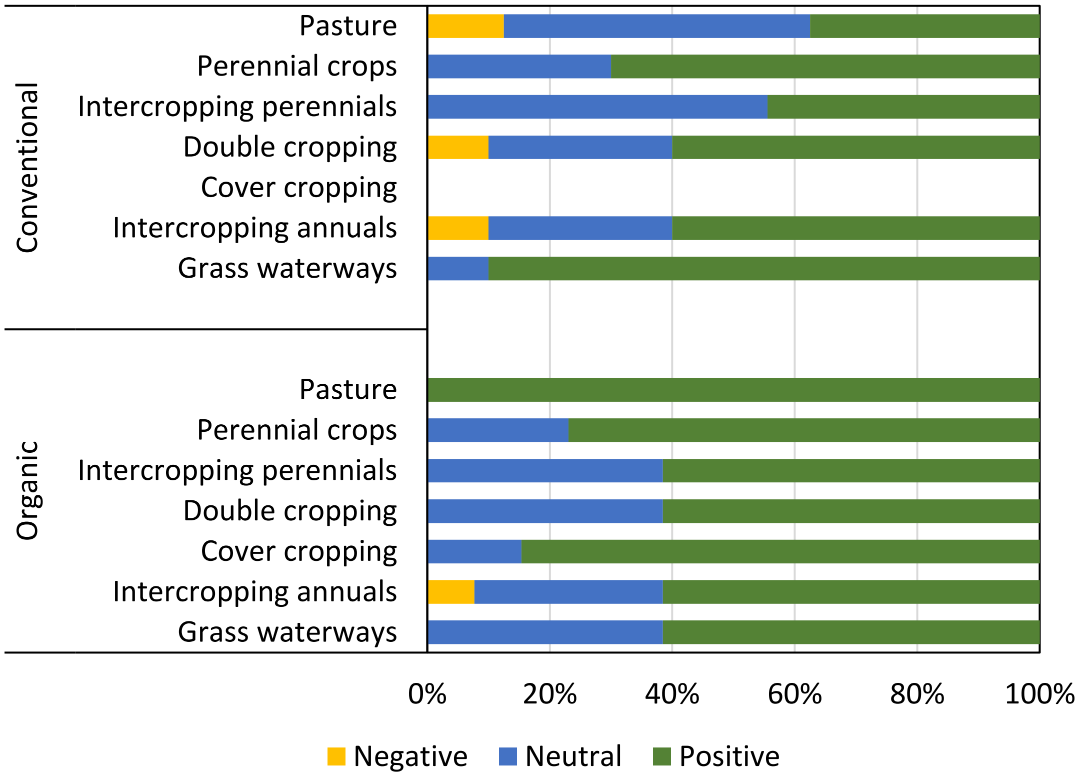

Figure 2. 4. Perception of conventional and organic farmers to crop diversification practices on a three-point scale. Cover cropping for conventional farmers is missing due to a surveying error.

2.4.5 Advice sources

The social-ecological network linking information sources and adoption of crop diversification practices incompletely describes the actors who farmers learn from when seeking information about land management practices. For this reason, I also asked who farmers sought advice from with an understanding that information was general, and advice was personally delivered information specific to the farm. For advice, farmers, both organic and conventional, listed members of their Community, who were predominately other farmers or specialists who had grown up on farms (Table 5, Table A2).

Table 2. 5. Percent of information category normalized by size that farmers sought advice from for each farm type. For example, conventional farmers named 18 people they sought advice from in the Growing Feed category (18/(3*12)). See Appendix A for greater breakdown by position, trust, and frequency of interactions.

	Conventional	Organic
	%	%
Growing Feed	50	15
Community	58	87
Cow Care	21	15
Land Grant	8	8
Financial	6	3
Input	25	54
Big data	8	0

After Community, the Growing Feed category was the second most often named category for conventional farmers (Table 4). More than half of the positions in this group were agronomists, followed by nutritionists and farm employees, such as crop managers (Table A2). One conventional farmer who had embraced digital agriculture instigated the Big Data category. This farmer collected large quantities of fine-resolution data (e.g., daily satellite imagery of each field) and needed assistance to organize, manage, and apply the information collected. Conventional farmers turned to a more diverse range of professional advisors than organic farmers (Table 5, Table A2).

After Community, Inputs was the second largest advice category for organic farmers (Table 5). Interestingly, only one organic farmer had selected ‘input salespeople' as an information source (Table 3). Many organic farmers referenced seed companies - Lakeview Organic (Penn Yan, NY) and Lancaster Agricultural Products (Ronks, PA). Both of these companies are operated by organic farmers and endeavor to build long-term relationships with their customers (e.g., farmers referred to them by their first name, the seed salespeople sent hand-signed holiday letters, or had offered free bedding of barley hulls after processing the barley). Organic farmers sought the expert advice of input salespeople who specialized in organic production. These organic-focused dealers also helped farmers navigate the certification process.

> We did business with him quite a bit in the earlier years in '94…we were growing organic crops for Klaas-- for the market and that was spelt and soybeans…then Klaas helped us to get started on how to certify it organically and so then he would buy those crops from us.
> —Organic farmer, October 29, 2019

The quote speaks to a social-ecological system that privileges information and experience about the socio-technical systems of organic production specifically. It also shows how economic incentives and access to markets can determine how farmers seek advice. Studies have found that organic farmers may feel socially isolated from their non-organic peers because of their decision to pursue organic production (Constance and Choi 2010, Blesh and Wolf 2014). This can leave farmers separated from typical sources of information, like neighbors or extension agents (Carolan 2006). Many organic farmers in the interviews brought up how differences in their management style separated them from their surrounding farm community:

> Oh, I don't know that I get a lot of advice from [nearby, non-organic] farmers. The organic thing kind of separated us.
> —Organic farmer, July 24, 2019

Levels of trust were quite high among those the farmers named for advice (Table A2). Farmers often expressed close relationships with those they sought advice from, including external specialists, and described working as a unit. Often these specialists grew up on farms which provided them insight on the decision-making process of farmers.

> When he left the vet practice, it was very discouraging because I'd really gotten to like and trust him. Because he did come from a family farm, he knew what it was like on this side. And as soon as he contacted me and said he was going out on his own to be a nutritionist, I said, you have my business whenever you want to stop here. It was an immediate decision. I didn't have to think about it. I was glad to have him back involved with things.
> —Conventional farmer, July 3, 2019

Organic farmers had higher trust for input salespeople from whom they sought advice compared to input salespeople as information sources, generally (Table 4). Farmers often mentioned that the frequency in which they sought advice was seasonal, especially for the Growing Feed category. In the springtime during planting season, farmers tended to speak to the agronomists on a daily or weekly basis while during the winter months speaking monthly was more common. The farmer’s trust of information and advice sources and perceptions of diversification practices indicates how they navigate the socio-technical configuration to make decisions on their farm.

2.5 Discussion

Farms in different socio-technical configurations managed crop diversification differently. Drawing from the components of a socio-technical configuration as described by Geels (2004), the manner of how the two farm types handle diversification, thus resilience, is organized into three parts - Production, Learning, and Coordination. The parts correspond with land management of the farm, the learning processes of the farmer, and the institutional and regulatory support from the broader socio-technical space (Table 6).

Table 2. 6. A generalization of divergent aspects of organic and conventional agriculture socio-technical configurations as detailed in farmer interviews.

	Conventional	**Organic**
Production		
Farm size	Larger, more specialized	Smaller, more diversified
Ratio of annuals to perennials	Higher	Lower
Weed management	Chemical	Physical, ecological
Agency of animals	Lesser	Greater
Learning		
Cognitive rules	Efficiency	The farm as an organism
Normative rules	Feed the world	Farm with nature not against nature
Skills	Universal	Local
Problem framing	How do I get rid of this problem? (Treat symptoms)	Why did this problem occur? (Treat problems)
Useful knowledge	Focus on one component of the system	Systems-understanding through ecological lens
Knowledge synthesis	Of the specialists	Of the land
Coordination		
Regulatory environment	No special regulations, CAFO if 300 + cows	Organic certification requirements
Market environment	Commodity markets	Price premium, specialty markets

Analysis of these different network components show that the conventional farmers had higher levels of connectedness to information sources, and in order to remain competitive, they worked to control variability on their fields through standardization of their practices. In contrast, organic farmers had lower levels of connectedness and actively managed field variability with diversification practices. In this sense, the socio-technical configuration of organic farmers promoted crop diversification.

2.5.1 Production

At the field-level, I identified factors contributing to resilience as increased complexity of crop production, low chemical-based weed management, smaller farm size, and an increased agency of the cows. The research shows that when it comes to field-level production issues, the socio-technical network of organic farming was more suited to adopt a wider range of diversification practices compared to conventional farmers.

Conventional farmers intercropped perennials less than organic farmers because of larger farm sizes where farmers could select well-drained fields to be planted in pure stands to increase production of quality feed, relying on herbicides for weed management. This permitted conventional farmers to absorb risk at the farm-level but limited their ability to adapt, diffuse risk or withstand extreme weather events at the field-level.

Organic farms performed a greater variety of diversification practices on their farms which also increased the amount of crop variance, both spatially and temporally. Organic farms, which on average were smaller, appeared better enabled to actively manage within-field variability. Organic farmers often depended on tillage for weed management, but many talked about using intercropping to manage weeds as grass crops can grow vigorously and can shade out other unwanted species. Organic farmers also described temporal response diversity, describing how the grass in the perennial intercrop would give a great cutting in the spring, but then alfalfa would support through subsequent cuttings. In the simplest terms, organic farms had more pasture, always intercropped perennials, and often performed intercropping with annuals and double-cropping or cover cropping whereas only some conventional farms had small amounts of pasture, intercropped perennials, and planted cover crops on their annual acres.

Farmers in the two configurations also differed in their approach to grazing and this difference further explains the differences in adoption of pasture and extent of other diversification practices. It is well recognized that farms with pasture provide animals with greater agency to ambulate. Organic farmers spoke frequently about the cows finding their own feed, spreading their own manure, health of the animals (i.e. less hoof and leg problems, longer lifespan) to be outside walking around, and their own enjoyment to be outside caring for the animals. Hanson et al. (2013) found that management intensive grazing dairy operations reduced veterinary, breeding, and medicine costs for dairy cows.

In contrast, interviewed farmers that did not have pasture spoke about cow comfort which is linked to higher milk production as the cows expend less energy by not moving around nor being exposed to the elements. Conventional farmers understood that some of the health issues, particularly foot and leg issues that arose from a sedentary lifestyle, could be ameliorated with grazing. However, the need for simplification and convenience on large operations was prioritized. In their survey of 987 dairy farmers in the Northeast, Winsten et al. (2010) also found this divergence of large confinement operations simplifying to capture economies of scale versus management-intensive grazing operations the reducing external costs to be profitable. The socio-technical systems of conventional and organic dairies have diverged to the point of prioritizing different breeds of cows based on whether they graze or are in confined operations (Haas et al. 2013, Rodríguez-Bermúdez et al. 2019). These aspects highlight the cross-scale, nestedness of animal and crop production systems (Gunderson and Holling 2002).

2.5.2 Learning

A farmer's approach to understanding a problem is shaped by their normative and cognitive rules about how they conceptualize being a farmer (Table 6). I found that organic farmers tended to view the farm as an organism and strived to 'mimic nature', an understanding held by practitioners since organic agriculture's inception (Howard 2010). Organic farmers in the interviews described working through problems by asking 'why is this happening', i.e. situating the problem into the larger context. Many conventional farmers took a more engineering perspective, worked to optimize production in order to 'feed the world', and generally framed their troubleshooting around the symptom of the problem. These differences drive their learning processes.

Similar to Carolan (2006), I found that conventional farmers more often engaged with formalized, universal information sources and organic farmers more often engaged with local sources of those in the community. Prioritization of local knowledge can be indicative of higher degrees of self-organization (Milestad and Darnhofer 2003) and the importance of place-based knowledge (Carolan 2006). Morgan and Murdoch (2000) also ascribed conventional farmers with keeping highly standardized, codified knowledge, while organic farmers used more tacit or negotiative knowledge forms. Tacit knowledge (i.e., weeding with cultivation [tillage] equipment) is more difficult to communicate because it is not standardized, thus easier to learn through in-person context or shared experiences (Morgan and Murdoch 2000). While the different attitudes toward problem-solving explains the preferences for formal/standardized or informal/tacit, it is also true that to-date organic farmers have fewer relevant ‘formal’ knowledge resources available.

The level of specialization of knowledge relevant to the two configurations is also explained by their approach to cow confinement. Confinement operations that separated the cows from the land resulted in knowledge systems where crop and animal production were understood separately. Conventional farmers not only drew on more resources of information, but also more specialized sources like agronomists and nutritionists. This is likely due to a socio-technical system that prioritizes specialization to improve efficiency (Hamlin and Shepard 1992). One conventional farmer reported that the variability in intercropped perennials (i.e. mixed stands) posed difficulties because it led to inconsistent forage quality:

> The part with the grasses for us and the dairy here is, so we're always planting… corn. So we can't get-- the first cutting is always variable because we can't get to the grass as fast that's in the alfalfa because we're planting corn and everything, you

> know, the weather…so I'm more of a fan of clear stands than mixed ones.
> —Conventional farmer, June 26, 2019

This farmer preferred to reduce field-level diversity to improve forage quality and increase annual yields, increasing milk production, and reducing the marginal cost of production (Mayen et al. 2010). Moreover, clear stands of alfalfa would likely have to be mixed for feed to avoid health issues, indicating the engagement of a nutritionist.

In order to exist in a conventional socio-technical configuration, farmers must reach a high level of productivity. For a large farm to succeed, the decision-maker must understand how and when to weigh the multiple aspects of crop and milk production. I conject that managing these multiple sources of specialized knowledge is easier if they are focused toward a common, simply expressed goal, such as increasing milk production, as supported by (Morgan and Murdoch 2000). However, organic farmers reported that the single-minded focus of increasing milk production was problematic because it constrained flexibility.

> The consultants come in. You've got to do this. No more grazing. Bring them all in. Control everything. Feed the cows this way…This business is getting frustrating. We're told to do all this… You're walking a tightrope with them [the consultants], partly because you're trying to get 90-pound average cows, 100-pound average cows [milk production per day]. And it doesn't take much to tip the scale…
> —Organic farmer August 13, 2019

In this quote, we learn that a reliance on external experts whose goal is productivity can be unfavorable as it required high levels of operational precision which was precarious to maintain and eventually prompted the farmer to convert to organic.

Unlike the reliance on specialized knowledge among conventional farmers, organic farmers used information mostly from community members. They had lower trust for information sources they did not engage with. Grazing entails partitioning the land into areas containing cows and other areas where the pasture is re-growing. To operationalize grazing, the knowledge of an expert was less important compared to the farmer's own functional knowledge of their land or that of their peers who also had grazing operations.

I conclude that knowledge synthesis of differed between farm types. Conventional farms generally synthesized knowledge top-down using more information from other actors in the socio-technical configuration. The reliance on external specialists for production practices limits the ability of the farmer to self-organize and can prevent them from adaptively managing their farm. Organic farms generally synthesized information from the bottom-up with regard to ecological knowledge of the farm understood as a whole. Nelson et al. (2014) point out that the information network of low-intensity grazing operations may not result in transformative resilience unless the networks of such practices substantially expand.

2.5.3 Coordination

Dairy farms must also coordinate their operations with the regulatory and market environment to maintain its function. There are stark differences in the regulatory and market environment for organic and conventional farms, which contributes to their adoption of diversification practices. Organic farms, by regulation, are required to have land in pasture to qualify for the organic certification (Northeast Organic

Farming Association of Vermont 2014). Regulations around conventional farms such as the CAFO regulations do not prohibit pasture (Department of Environmental Conservation 2017), yet many conventional farmers spoke about CAFO regulations as a prohibitive factor. However, the two organic CAFOs in the sample provide a counterexample because they were both large operations and had pasture. This raises a need to examine other conflating factors that explain the lack of pasture for conventional farming systems, including farm size and the motivation to maintain a high level of productivity.

> …being able to make the CAFO compliance and so forth is a little bit of a challenge with pastures too. And when you get to this size dairy, it takes a lot of acres for pasture…we just don't have the acres to consider it. And it's really a-- cow comfort, cow cooling, and high levels of production per cow-- I think it's more difficult in a pasture situation than it is as we're doing. We have our cows laying on water beds and lots of bedding and everything we can to give them comfort and to get the production for a cow.
> —Conventional farmer October 2, 2019

2.5.4 Cross-scale feedback cycles

The three components of resilience – production on the farm, farming learning, and coordination with larger socio-technical configurations - interact in important ways. These cross-scale relationships function as feedback cycles in the social-ecological system. Gunderson and Holling (2002) argue that one contributing factor to the resilience of any social-ecological system is the independence at the level of the different components to adapt and reorganize.

I observed that the interactions across components created lock-ins for conventional farmers more so than for organic. For example, the following quote by a conventional farmer detailed his consideration about his cropping practices and management trade-offs based on the cow's lifecycle (production, learning) and a need to be competitive (coordination) in the existing socio-technical configuration:

> Well one thing right now, the economics of the dairy industry. Raising heifers, they're very cheap to buy, so we can make more money off of putting a crop on most of the pasture ground than we can offer raising a heifer. In order to really capture the efficiency of raising the heifers and get them to freshen at that 22- month average, we [would] need to rotationally graze and supplement. And it's not a cheap or labor-free way to do it. To do it right it takes time and money-- with everything. We don't have a lot of very steep, ledgy areas that would lend themselves to pasture more so than cropping...
> —Conventional farmer, July 17, 2019

The quote illustrates a decision-making process where top-level factors (coordination) dictate farmer behaviors at lower levels (production, farmer learning). The lock-in mechanisms stymieing greater crop diversification have been identified as market forces, technologies, and research agendas (Roesch-Mcnally et al. 2018, Magrini et al. 2019, Tittonell 2020). Beyond the lack of technical knowledge on diversification practices, lock-in mechanisms also include agricultural policies (Allison and Hobbs 2004a), lack of cross-scale coupled innovation design (Meynard et al. 2017), nascency of alternative market structures (Valencia et al. 2019), the politics of social-ecological and socio-technical systems (Smith and Stirling 2010), and the apolitical nature of agronomists (Jordan et al. 2020). These systemic lock-in mechanisms prevent the farmer from being able to adaptively manage for the weather or lower level ecological processes and instead promote management to advance the farm's profitability, reducing social-ecological resilience.

In summary, a small and rich set of mixed method interviews provide insights to the information sources farmers draw from, their understanding of the ecology of their farm across spatial and temporal scales, and how farmers understand themselves within the context of the dairy industry when making decisions surrounding land management and adopting crop diversification practices.

2.5.5 Limitations of Study

This case study examines how socio-technical configurations advance or constrain the adoption of crop diversification practices to understand strategies to enhance the resilience of farms in the face of extreme weather. In order to develop the argument and the empirical analysis, some assumptions were made. Reflecting on the assumptions can help situate the results of the study and guide further research.

The study treated organic and conventional farming as two distinct socio-technical configurations but this binary distinction merits unpacking. At the granularity of individual farms such differences may not be particularly pronounced. Rather, the two types of farms exist in a dynamic state with overlapping norms, actors, rules, and practices. Organic exists in the context of the dominant, conventional configuration, thus it subsumes some of its characteristics (Smith 2006; Guptill 2009). For example, one conventional dairy farm had certified-organic land that was used for vegetable production. Further studies may consider proceeding from multiple scales and examine ecological factors more centrally. Enlarging the categories of socio-technical configurations can also help understand factors shaping adoption.

Future studies may also consider different research designs. Specific concerns relate to issues of sampling, question-phrasing, and analysis. Initially, I attempted heterogenous snowball sampling for both farm types, using initial starts on recommendations and contact information from Cornell Cooperative Extension agents. However, many extension agents were reluctant to share farmer contact information. In the absence of alternatives, sampling proceeded by asking farmers to suggest other farmers. Such a sampling technical is useful when identifying “hard to reach” populations as in this study but may have also biased the sample toward larger conventional farms.

Most interview questions were answered, but initially I had mistakenly omitted cover crops in the familiarity and perception questions, which mostly were conventional farmers. For this reason, I did not report those findings on the practice. I also learned the farmers did not share a similar terminology regarding crop diversification practices as developed in the academic literature. Semantical issues arose when farmers stated unfamiliarity with practices. This was especially true for the terms double-cropping and intercropping. Some farmers understood double-cropping to encompass an annual to perennial transition where annuals are harvested in late spring and summer and perennials were planted but not harvested. Such management is commonly referred to as relay intercropping. Perennial crop (i.e. alfalfa) was also a term that required clarification. Intercropping perennials was not a term commonly used by farmers. Additionally, perennial fields are managed for stored feed, either as hay or baleage (stored in anaerobic conditions with a higher moisture content). Differentiating land by pasture and perennial crops for hay or baleage components was complicated for organic farmers as they can graze and make feed for storage on the same land depending on the weather and growing conditions. For future work, it would be beneficial to use terms more aligned with farmers mode of thinking.

The selection of crop diversification practices that farmers were asked about may also be reconsidered. For example, I did not ask about the use of a nurse crop when establishing perennials, although some farmers mentioned it in the free response components of the interview. Nurse crops are a common diversification practice for dairy farmers. They are typically oats (*Avena sativa* L.) and/or peas (*Pisum sativum* L) and planted to suppress weeds and provide some coverage on the field to protect the alfalfa from winterkill (Barnes et al. 2003).

Lastly, a network approach is useful for illustrating linkages across the socio-technical and field-level scales, but the extent of adoption question treated all land the same. In fact, some diversification practices might be more appropriate for some farms than others due to the given topography of the farm. It is also possible for farmers to perform a diversification practice without engaging with any information sources and without their contribution reflected in the network. This was not the case in these interviews. The networks presented here are also static. They reflect the perception and behavior of the farmer at the time of the interview (Borgatti et al. 2013), thus do not capture changes over time as Nelson et al. (2014) saw in their work on information networks of dairies. Repeated interviews with the same farmers may help address this concern.

2.6 Conclusion

The main contribution of the chapter lies in bringing the literature on social-ecological systems into dialogue with the socio-technical perspective. The chapter advances a theoretical approach that centralizes the farmer as the focal point of analysis but pays clear attention to broader social and institutional forces at play. The decision-making of an individual farmer links to the socio-technical configuration in which they are embedded and together these linkages explain ecosystem management including adoption of diversification practices.

The research also shows that the least frequently adopted crop diversification practice was intercropping annuals. This is likely because the benefits of within field variability did not merit the increased complexity in management. Intercropping with annuals has been identified as a meaningful incremental step toward retrofitting the current industrialized agroecosystem to be more dependent on ecological processes rather than high, energy-expensive inputs (Lithourgidis et al. 2011). To encourage the adoption of this practice, more research on the costs-benefits of the practice and ways to reduce the barriers and increase benefits will help (Brooker et al. 2015). However, given the single season of annual production, more benefits in diversification are likely to be seen in perennial production that has multiple years for the functional and/or response diversity to take effect (Tilman 1999).

In this study, the dominant socio-technical configuration is characterized by conventional farming. This configuration is oriented toward a social-ecological system that prioritizes productivity and efficiency. In contrast, organic certification requires pasture and this configuration facilitates organic farmers to engage with more crop diversification practices. The research also finds that organic farmers engaged fewer information sources compared to conventional farmers. This observation highlights an opportunity to expand the information resources available for organic production and consider ways to facilitate tacit knowledge-sharing. These findings indicate that to enhance the resilience of farms in the face of extreme weather, it is crucial to understand how to transform socio-technical configurations in ways to facilitate further adoption of crop diversification.

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CHAPTER 3

ADVANCING INTERCROPPING RESEARCH AND PRACTICES IN INDUSTRIALIZED AGRICULTURAL LANDSCAPES

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3.1 Abstract

Sustainable intensification calls for agroecological and adaptive management of the agrifood system. Here we focus on intercropping and how this agroecological practice can be used to increase the sustainability of crop production. Strip, mixed, and relay intercropping can be used to increase crop yields through resource partitioning and facilitation. In addition to achieving greater productivity, diversifying cropping systems through the use of strategic intercrops can increase yield stability, reduce pests, and improve soil health. Several intercropping systems are already implemented in industrialized agricultural landscapes, including mixed intercropping with perennial grasses and legumes as forage and relay intercropping with winter wheat and red clover. Because intercropping can provide numerous benefits, researchers should be clear about their objectives and use appropriate methods so as to not draw spurious conclusions when studying intercrops. In order to advance the practice, experiments that test the effects of intercropping should use standardized methodology, and researchers should report a set of common criteria to facilitate cross-study comparisons. Intercropping with two or more crops appears to be less common with annuals than perennials, which is likely due to differences in the mechanisms responsible for complementarity. One area where intercropping with annuals in industrialized agricultural landscapes has advanced is with cover crops,

where private, public, and governmental organizations have harmonized efforts to increase adoption of cover crop mixtures.

3.2 Introduction

Calls for sustainable intensification (SI) have been resounding in global-scaled rhetoric of agrifood systems to produce food for a growing population, while minimizing the negative environmental impacts. However the conceptualization of SI varies based on the ascribed agricultural philosophy of the user of the term (Loos et al. 2014). Here, we consider SI as a holistic concept best described by Struik and Kuyper (2017) as one that considers societal negotiations, institutional innovations, justice, and adaptive management for improving agrifood systems (Struik and Kuyper 2017).

In this paper, I discuss the potential of intercropping as an agroecological land management practice for SI. Intercropping is the practice of growing multiple crop species at the same time in the same place and has widely been utilized throughout the history of agriculture. Traditionally, intercropping has been used to increase crop production and the efficiency of the land, as well as a strategy to mitigate risk. It is an essential component of smallholder cropping systems, but in industrialized production where nutrient cycles are more externally regulated, intercropping is underutilized.

3.3 Fundamentals of Intercropping

Intercropping is different than other strategies that farmers use to increase diversity in cropping systems such as crop rotation, insectary strips, and buffer plantings. Crop rotations are a more common strategy than intercropping in large-scale agriculture and often involve growing different crops in the same field at different times (i.e. temporal diversification). Because different crops are grown in different fields, (i.e. spatial diversification), competition between crop species does not typically occur as with intercropping. However, the spatial scale of crop diversification is much larger (i.e., farm-scale rather than field-scale). Other forms of diversification also exist, such as insectary strips and buffer plantings of non-crop vegetation that provide many of the ecosystem services but with less crop-crop competition than intercropping.

3.3.1 Types of Intercropping

Crops can be grown together as intercrops in a variety of ways (Figure 1). Mixed intercropping is the practice of growing two or more crop species together at the same time in a field without using any particular spatial configuration. In contrast, strip intercropping is the practice of growing two or more crop species in separate but adjacent rows at the same time. Whereas these types of intercropping vary by spatial configuration, crops can also be intercropped in different ways that vary temporally. Relay intercropping involves the staggered planting of two or more crops together in a way whereby only parts of their life cycles overlap.

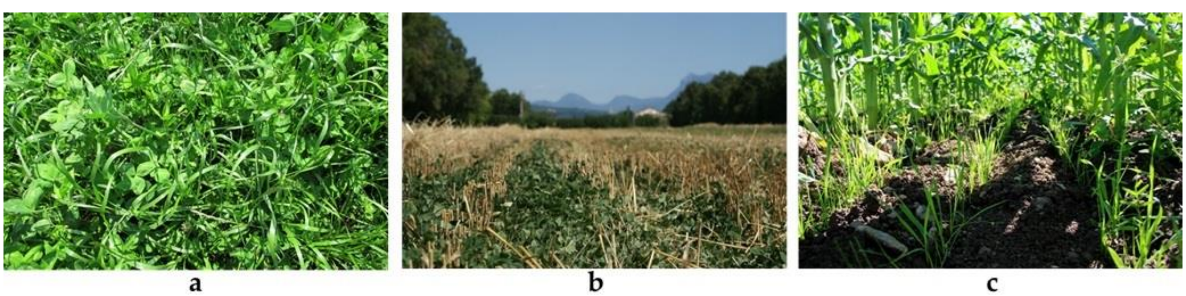

Figure 3. 1. Examples of intercropping in (a) mixed perennial forage crop, (b) mixed relay intercrop of red clover (*Trifolium pratense* L.) into winter wheat (*Triticum aestivum* L.), and (c) strip relay intercropping of corn (*Zea mays* L.) and cereal rye

(*Secale cereale* L.). Photographs by Sarah Ziegler, Joséphine Peigné, and Sandra Wayman, respectively.

3.3.2 Mechanisms

Complementarity is a general term used to describe the positive effects that can result from intercropping. Primarily, there are two mechanisms that contribute to complementarity: resource partitioning and facilitation. Resource partitioning, also known as niche partitioning and niche differentiation, describes the more complete utilization of available resources by crops that are intercropped compared to when they are grown separately. Resources are partitioned as a result of differentiation in resource acquisition traits. Selecting for differences in rooting depth, phenology, and vegetative architecture between crop species grown in an intercrop can minimize competition and increase resource partitioning (Litrico and Violle 2015). A classic example is the Three-Sisters mixed intercrop of corn-beans-squash (*Zea mays* L., *Phaseolus vulgaris* L., and *Cucurbita pepo* L., respectively) used by indigenous people in North America (Mt.Pleasant and Burt 2010). In this case, resource partitioning is driven by differences in traits among the nitrogen-fixing beans, the low-growing squash that covers the soil and suppresses weeds, and the tall corn that acts as a trellis for the beans.

Facilitation refers to processes by which one crop species provides a limiting resource or improves the environmental condition to another crop species. The most common example is a legume providing nitrogen to a grass. But other examples exist, such as one species with a deep taproot supplying water to other species by hydraulic lift. In their review of complementarity and soil microorganisms, Duchene et al

(2017) categorizes facilitation as being indirect, where a beneficial change in the rhizosphere improves nutrient availability, or direct, where the rhizosphere acts as an interface for the transfer of nutrients from one plant to another (Duchene et al. 2017).

In this paper, I focus our attention on intercropping with multiple species. While this is the most common intercropping approach, it is not the only way to intercrop. Rather than species diversity, selecting for functional diversity is a pragmatic approach that aims to maximize complementarity. As function is often context-dependent, selecting for greater phylogenetic diversity (i.e. evolutionary distance) has been suggested as a method to increase resource partitioning (Cadotte et al. 2009, Brooker et al. 2015). Another way to intercrop is to plant multiple varieties of the same species together. Increasing genetic diversity of a species in the field has been shown to extend the growing season, mitigate transfer of diseases, and increase productivity in crops such as wheat, corn, and oats (Smithson and Lenné 1996, Tooker and Frank 2012, Chateil et al. 2013, Borg et al. 2017). A meta-analysis of 91 studies with more than 3,600 observations of intraspecific mixtures found a 2.2% increase in yield compared to their monoculture components (Reiss and Drinkwater 2018). Greater diversity effects were seen under higher stress conditions (e.g., low nutrient availability, high pest pressure) (Reiss and Drinkwater 2018). Moreover, varietal mixtures exhibited significantly higher yield stability compared to monocultures, especially in response to annual weather variability at a site over time (Reiss and Drinkwater 2018).

3.3.3 Benefits of Intercropping

3.3.3.1 Productivity and Yield Stability

Increased crop productivity is among the most important and frequently cited benefits of intercropping. Overyielding occurs when the productivity of an intercrop is increased relative to the average of each component species grown in a monoculture. This is the most common way that crop productivity is increased with intercropping and is often driven by resource partitioning. Transgressive overyielding is when the productivity of an intercrop is increased relative to the highest-yielding component species grown in monoculture. This occurs less frequently and is typically the result of facilitation, rather than simply resource partitioning. In addition to increased productivity, there are other benefits that intercropping can provide, including yield stability, pest suppression, and soil health.

Intercropping has been shown to decrease risk of crop failure by increasing crop yield stability over time and across locations (Bybee-Finley et al. 2016, Raseduzzaman and Jensen 2017). Crop yield stability can be increased by reducing variation over years at the same site, or by increasing production consistency throughout the year. For example, growing a mixture of cool and warm season perennials for forage can counter seasonal slumps in production (Williamson n.d.). Crop yield stability can also be increased spatially by reducing variability in production within fields (e.g. wet spots) and by maintaining production across different fields. The coefficient of variation (CV) is a metric used to evaluate production consistency across space and over time. This is calculated by dividing the standard deviation of crop biomass in each treatment by the mean biomass of that treatment. It is a measure of dispersion with a lower number, indicating greater yield stability. A meta-analysis of 69 intercropped systems found greater yield stability in grass-grain legume intercrops compared to those crops in monoculture with CVs of 0.25, 0.30, and 0.19 for the grass monocultures, legume monocultures, and the intercrops, respectively (Bybee-Finley et al. 2016, Raseduzzaman and Jensen 2017). Another study with 9 site-years which compared four annual species in monoculture and five intercropping treatments of those species found that the 4-species mixture had similar yields to the highest-producing grass monoculture, but greater yield stability (Bybee-Finley et al. 2016). Despite the lack of transgressive overyielding in that research, the average CV was 0.55, 0.47, and 0.36 for the monocultures, 3-species mixtures, and the 4-species mixture, respectively (Bybee-Finley et al. 2016).

3.3.3.2 Pest Reduction

Intercropping has been shown to reduce the risk of weeds, insects, and diseases, a benefit that partially explains increased yield and yield stability. Typically, intercrops can more effectively utilize available resources (e.g. light, water, nutrients) than if crops were grown separately, thus reducing the amount of resources that are available to weeds. In a review by Liebman and Dyck (1993), a cash crop intercropped with a “smother” crop had lower weed biomass in 47 out of 51 cases (Liebman and Dyck 1993). Trends were similar when the intercrop was composed of two cash crops, but not to the same degree (Liebman and Dyck 1993). A recent meta-analysis of 34 articles about cash crops (e.g., corn or forage) intercropped with legume companion crops containing 476 experimental units (site × year × cash crop × legume companion plant species × agricultural practices) determined that intercropping decreased weed biomass by 56% relative to non-weeded monoculture treatments (Verret et al. 2017).

More generally, intercrops can diminish the damage by pests and diseases by reducing the number of susceptible hosts (dilution effect), resistant plants acting as a physical barrier to susceptible plants (barrier effect), inducing resistance by increasing the diversity of pests and diseases, reducing the speed by pest adaption through disruptive selection, and compensation of one species that performs poorly (Borg et al. 2017). A meta-analysis of 21 agroecosystem studies of diversified cropping systems showed a moderate reduction in herbivorous insect populations compared to more simplified cropping systems that served as the control (Tonhasca and Byrne 1994). Another meta-analysis of 43 studies found that increasing complexity of plant architecture resulted in a significant increase in predator and parasitoid natural enemies, mainly driven by increased plant detritus in intercropped systems (Langellotto and Denno 2004). In a review of more than 200 studies of foliar fungi, intercropped systems had on average a 73% reduction of disease compared to their respective monocultures (Boudreau 2013).

Trap crops that attract pests away from main crops as well as crops that repel pests can be intercropped for enhanced pest management. One of the most well known examples using trap and repellent crops together is the push-pull system that is used to manage corn stemborers (*Busseola fusca* Fuller.) and weeds like Striga spp. (Khan et al. 2011). The strip intercropping method involves planting corn (the cash crop), a "pull" crop, like Napier grass (*Pennisetum purpureum* Schumach.) that uses semiochemicals to attract corn stemborers, and a "push" crop like the legume

Desmodium spp. planted between rows to repel corn stemborers from the corn (Figure 2) (Eigenbrode et al. 2016). The Desmodium spp. also elicits a fatal gemination response from the parasitic weed Striga spp., reducing weed density and competition with the corn. In a review article by Khan et al in 2011, the push-pull system has increased corn yields from below 1 to over 3.5 t ha^{-1} largely in smallholder farms in East Africa (Khan et al. 2011).

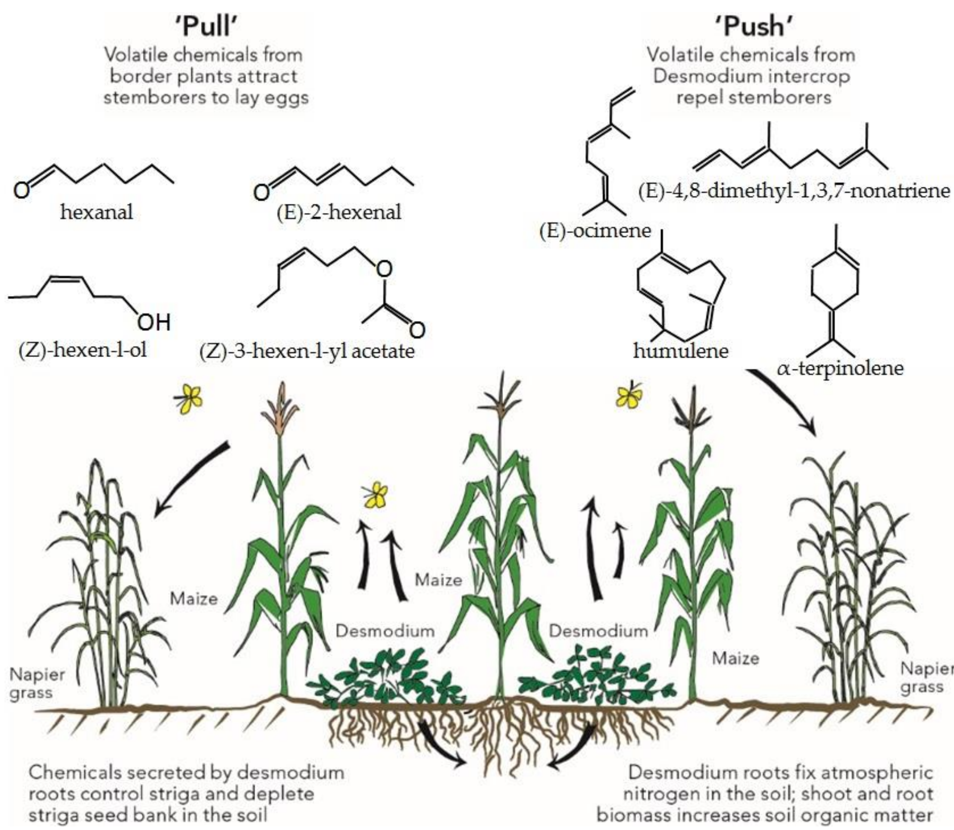

Figure 3. 2. Scheme developed by the African Insect Science for Food and Health at the International Centre of Insect Physiology and Ecology (ICIPE) of the push-pull system in corn illustrates the semiochemical ecology of attracting or detracting the corn stemborer and suppressing weeds. Used with permission from ICIPE (::"'PUSH-PULL'':: A Platform Technology for Improving Livelihoods of Resource Poor Farmers" n.d.).

3.3.3.3 Soil health

In addition to crop yield benefits, intercropping can increase soil health and reduce nonpoint source pollution by decreasing nitrogen losses (Sanderson et al. 2013, Lemaire et al. 2014). A seven-year study in northwestern China found soil organic carbon and nitrogen contents in the top 20 cm were approximately 4% and 11% greater in two-species strip intercropped systems of corn, wheat, and faba beans (*Vicia faba* L.) compared to those species in monoculture rotations, which led to sequestration rate increases of approximately 184 and 45 kg ha^{-1} yr^{-1} for carbon and nitrogen, respectively (Cong et al. 2015). Additionally, the study found 23% more root biomass in the intercropped systems compared to the species in monoculture (Cong et al. 2015). Increased plant diversity has been shown to increase soil microbial diversity making nutrient uptake by plants more effective and decreasing the effects of plant pathogens in the soil (Vukicevich et al. 2016). Although increased plant diversity is typically associated with more complete resource use, substantial benefits can be gained by intercropping even two crop species, especially if they are grass and legume crops. As grasses typically dominate in soils with high nitrogen availability, and legumes have an advantage in soils with low nitrogen availability due to their symbiotic relationships nitrogen-fixing bacteria, grass-legume intercrops are able to self-regulate based on soil nitrogen levels (Chapman et al. 1996). Self-regulation can play an important role in reducing reactive nitrogen in the soil, therefore reducing nitrate leaching and denitrification, which are major contributors to water quality problems and greenhouse gas emissions, respectively. For instance, a

3-year study in China on strip intercropping with sweet corn and soybean (*Glycine max* (L.) Merr.) showed a 40% reduction in soil mineral N at the time of harvest compared to the corn monoculture (Tang et al. 2017).

3.4 Examples of Successful Intercropping Systems

3.4.1 Grass - Legume Hay

Perennial intercropped systems are a way that farmers can mimic natural systems with native plant species. Pasture and rangeland often resemble traditional grassland landscapes and are the setting for a large amount of intercropping research (Tilman et al. 2001, Picasso et al. 2008). More managed systems include perennial forage crops typically grown for silage or dry hay (Figure 3). Grass-legume intercropping can be useful for forage production as forage quality in grass monocultures drops precipitously if the grass is harvested after peak maturity (~ 3 days) whereas if a legume is included with the grass, forage quality can be maintained for a longer duration (~ 2 weeks) (Barnes et al. 2003). Alfalfa (*Medicago sativa* L.) and cool season perennial grasses are often grown in a mixed intercrop. This intercrop can be particularly beneficial in locations with suboptimal soil drainage because the grasses can fill in areas that are too wet for good alfalfa growth ("Alfalfa-grass mixtures are complex" n.d.). Common cool season grasses for forage are tall or meadow fescue (*Festuca arundinacea* Schreb. and *pratensis* Huds., respectively), timothy (*Phleum pratense* L.) or orchardgrass (*Dactylis glomerata* L.). However, having more than one grass can make the mixture difficult to manage due to variation in maturity rates of the species, and thus cause difficulties achieving cuttings at peak forage quality.

Mixed stands tend to outperform in yield but have similar forage quality as pure stands of alfalfa in high fertility soils (Cherney, 2018).

Figure 3. 3. Photo of perennial ryegrass (*Lolium perenne* L.), orchardgrass (*Dactylis glomerata* L.), meadow fescue (*Festuca pratensis* Huds.), red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), chicory (*Cichorium intybus* L.). Photograph by Sarah Ziegler.

3.4.2 Winter Wheat and Red Clover

Grain crop farmers often intercrop red clover into winter wheat as a way to increase crop diversity, add ground cover during the winter, and increase labile nitrogen pools (Gaudin et al. 2013). This relay mixed intercropping system works particularly well because of the different phenology of the two crops that minimizes light competition, as well as differences in nutrient acquisition (Figure 4). While winter wheat is established in the fall, red clover, which persists for 2-3 years, is generally frost-seeded in the early spring when the soil is in a period of freeze-thaw cycles. Generally, the clover establishes but does not compete with the wheat and stays small until the wheat is harvested, at which point the clover grows considerably. Interseeded clover typically does not affect yield of the wheat, and because the clover fixes its own nitrogen, it can decrease nitrogen fertilizer requirements for the subsequent crop (Schipanski and Drinkwater 2011). Red clover that is intercropped with wheat also fixes a greater proportion of nitrogen than red clover grown in monoculture. Soil samples across 15 farm fields in the northeastern USA showed more than a 10% increase in biological nitrogen fixation by the red clover intercropped with winter wheat compared to red clover in monoculture (Schipanski and Drinkwater 2011).

Figure 3. 4. A relay mixed intercrop of red clover after winter wheat harvest. Photograph by Joséphine Peigné.

3.4.3 Cover Crop Mixtures

Cover crops are usually grown between cash crops and are not harvested. Farmers use cover crops to reduce soil erosion, prevent nutrient losses, and suppress weeds, as well as provide other ecosystem services (Schipanski et al. 2014). In areas where soil moisture is an issue, farmers have begun “planting green”, that is, planting their cash crop into overwintering cover crops. A 2017 survey of over 1,400 farmers in the US conducted by the Conservation Technology Initiative Center (CTIC) showed that almost 40% of farmers “plant green,” and more than half of those thought the practice helps with moisture management (CTIC-SARE-ASTA 2017). A 2-year study in Kansas, USA, found that cover crops increased soil moisture in the spring in comparison to chemical fallow, due to increased crop residue (Kuykendall 2015). Most cover crop mixtures are planted after the final harvest of a summer annual crop, and establishment timing often shapes what species are planted (CTIC-SARE-ASTA 2017). Thus, the majority of the growth happens in the spring. However, most species could also be relay intercropped mid-summer and that could increase the species options and more evenly distribute labor during the field season. Before planting the cash crop, cover crops are often terminated with mechanical or chemical means and release nutrients during their decomposition. Over the past decade, intercropping with highly diverse (e.g. 8 species) mixtures of cover crops has received a fair amount of attention (Figure 5). For example, the CTIC survey showed that 76% of farmers planted cover crop mixtures with 13% planting mixtures of 8 or more species (CTIC-SARE-ASTA 2017). Some of this increased interest in cover crop mixtures can be attributed to early adoption by farmers like Steve Groff (2008) and promotion by Natural Resources Conservation Service (NRCS) officials like Ray Archulata (USDA NRCS East National Technology Support Center n.d.).

Figure 3. 5. A mixed intercrop of summer annual cover crops consisting of pearl millet [*Pennisetum glaucum* (L.) R. Br.], sunn hemp (*Crotalaria juncea* L.), and cowpea [*Vigna unguiculata* (L.) Walp.] can be grown after winter wheat or other crops that are harvested in mid-summer. Photograph by K. Ann Bybee-Finley.

3.5 Considerations for Research and Practice

As intercropping can increase crop productivity and the overall sustainability of cropping systems, it is an important tool to facilitate sustainable intensification. Increasing crop diversity with intercropping can be used to provide supporting, regulating, and cultural ecosystem services. However, intercropping can be knowledge intensive and likely requires a greater understanding of ecology and the interconnectedness between crops and their environment, to fully realize the potential benefits. Researchers can help advance intercropping by carefully considering experiment designs and metrics to assess intercropping. Concurrently, farmers can improve their management practices by thinking critically and strategically about what intercropping practices would be most beneficial for their intended goals.

3.5.1 Fundamental Measurements

Measuring plant-plant interactions and gathering empirical evidence is important for understanding how, and to what degree, plants affect each other when planted together. If complementarity is the general positive effects, I define interference as the general negative effects from intercropping, such as competition or allelopathy. Competition is a specific type of interference involving the capture of limited resources.

3.5.1.1 Species Selection and Seeding Rates

It might seem obvious, but when selecting species for intercropping, all species should have a reasonable chance of growth and survival for a period after sowing. For example, in relatively cold regions such as the northeastern United States, highly diverse crop mixtures that contain warm season annuals (e.g. soybean) might not establish well when planted in the fall, which can add to seed costs and increase the cost-to-benefit ratio of the intercrop (Finney et al. 2016). Likewise, some species are simply poorly suited for intercropping; these species are often highly (e.g. buckwheat (*Fagopyrum esculentum* Moench.) (Berglund 2009) or weakly (e.g. cowpea) competitive (Bybee-Finley et al. 2016). Thus, including them in an intercrop may lead to asymmetric competition when one or more species suppresses the growth of another species.

Selecting justifiable seeding rates is tantamount to intercropping research because it likely shapes the outcome of the experiment. There is no one universally correct seeding rate for a species because the goals and the conditions of an intercrop are context specific. Two main approaches exist when selecting seeding rates. The first uses an equal number of plants from each species for an intercrop and assumes that plants of different species are equivalent. This introduces a discernable bias into the experiment design because species are not equivalent, but this approach might be simpler to explain and could serve as a good starting point for exploratory research. A second approach uses equal proportions of seed based upon the standard seeding rate for each species. While this does not assume that different crop species are equal, it often means that the number of individual plants differ greatly among crop species. For instance, if you are making a biculture with each species seeded at 50% of their standard seeding rate, you might end up planting 50 seeds of the first species and 500 seeds of the second species.

Another reason to consider standard seeding rates when intercropping is because it allows one to account for size bias. Size bias occurs in many intercropping experiments because the competitive effects of larger plants are exaggerated compared to smaller species (Connolly et al. 2001). The effects of size bias are greater in shorter duration experiments and tend to diminish over time (Grace et al. 1992). One approach to address size bias is to grow candidate species in monocultures in a range of densities and then use a response variable (e.g. biomass production, weed suppression, nitrogen uptake, etc.) to determine functional equivalents of each species that result in similar responses. Poffenbarger et al. 2015, used this approach for studying weed-crop competition by growing corn in a replacement design with giant foxtail (*Setaria faberi* L.) or smooth pigweed (*Amaranthus hybridus* L.) after determining that 4 corn plants were functionally equivalent to 36 plants of either weed species in terms of nitrogen uptake (Poffenbarger et al. 2015).

3.5.1.2 Evenness and Crop Growth Rate

To understand the dynamics of an intercrop, one can measure the crop growth at different times throughout the season and calculate crop growth rates (CGR) of the species in the intercrop (Eq. 1). As faster-growing species can often dominate slower-growing species when grown together in a mixed intercrop scenario, CGR can be interpreted as a measure of competitiveness. If multiple mixtures are being compared, the CGRs for species in the different mixtures can be used to evaluate differences in competition across the mixtures. In the following equation for CGR, t_1 and t_2 are times of sampling.

$$CGR = \frac{Biomass_{t2} - Biomass_{t1}}{t_2 - t_1} \qquad \text{(Eq. 1)}$$

Species evenness measured from crop biomass data is another metric that can be used to evaluate competition outcomes (Eq. 2). It a measure of the relative abundance of species in an intercrop. Ranging from 0 and 1, an evenness value of 1 means there is an equal amount of biomass for each species in the intercrop. The numerator is the proportion (P) of the amount of biomass of a species (i) in an intercrop multiplied by the natural log (ln) of that proportion and summed across the species present in the intercrop. The denominator is the natural log of the number of species (S) in the intercrop. In a comparison of warm season annuals that were grown in monoculture and in 3- and 4-species intercrops, the intercrops with high species evenness were often composed of species that had similar growth rates and species evenness tended to be lower in intercrops that were composed of species with different growth rates (Bybee-Finley et al. 2016).

$$Species\ evenness = \sum \frac{P_i ln P_i}{\ln{(S)}} \qquad \text{Eq. (2)}$$

3.5.1.3 Stability

As discussed in Section 2.1.1 above, greater CVs indicate a greater dispersion across environments, and thus, a decrease in stability. Despite the simplicity of evaluating CVs and assessing yield stability in intercropping studies, such analyses are rare in the intercropping literature. Reiss and Drinkwater noted in their 2018 meta-analysis of intraspecific diversity that only a few of the 91 studies evaluated stability, despite having results over multiple years and/or sites (Reiss and Drinkwater 2018). Another way to measure stability of intercrops across sites and/or years is to conduct a stability analysis. Mostly used in plant breeding programs, stability analysis assesses variability of crop performance across different environments (Berzsenyi et al. 2000). Typically a stability analysis involves linear regression between the mean crop biomass for each treatment (y-axis) and the environmental mean yield, which is the mean crop biomass for all treatments in one environment (x-axis) (Finlay and Wilkinson 1963, Grover et al. 2009). Regressions with high intercepts and low slopes indicate good performance across the range of environments, while steeper slopes indicate a greater yield response due to improved conditions, but depending on the intercept, also poor performance in sub-optimal environments.

3.5.2 Quantifying Complementarity

In general, plants can experience two types of competition. Intraspecific competition pertains to the competition among individuals of the same species, i.e., the competition a crop faces from increasing its density. Interspecific competition pertains to the competition between different species. Importantly, both components of competition occur simultaneously and are often not parsed out by researchers. When exploring complementarity, it is important to recognize that experimental design dictates the types of analyses that are possible and what kind of conclusions can be made. While not a review of competition metrics, for which I recommend the works of Weigelt and Jolliffe (2003), Bedoussac and Justes (2011), and Connoly et al. (2001) (Connolly et al. 2001, Weigelt and Jolliffe 2003, Bedoussac and Justes 2011), I highlight how experiment design and data collection methods influence options for analyses.

3.5.2.1 Replacement and Additive Experimental Designs

Replacement and additive designs are the two most commonly used experimental frameworks for intercropping research (Cousens 1996). Many intercropping studies examine mixtures at only one seeding rate. In a biculture, replacement and additive design refers simply to whether the seeding rate of the biculture is similar to a monoculture or doubled (e.g., if 2 is the standard monoculture seeding rate for species A and B, in a biculture, a replacement design would be 2A + 2B = 1A1B and an additive design would be 2A + 2B = 2A2B). However, an intercropping study where the mixture is grown at a single seeding rate provides limited insight into the potential for complementarity between the species.

Replacement, sometimes called substitutive, designs hold the total density of the intercrop constant and vary the ratio among included species (Figure 6), meaning the results of the experiment will depend on the total density. Rather than holding a specific density constant, replacement designs are also constructed when a proportion of a monoculture seeding rate is used for each species and the sum of those proportions do not surpass 1. For example, a replacement design is used to construct a 3-species intercrop when the proportions of each species are 1/3 of their respective monoculture rates. Whether total density of the intercrop is held constant or the monoculture seeding rate of each species is held constant, the crop densities used need to be justified (e.g., standard seeding rates or functional equivalents). Moreover, because the densities of all species are being changed in replacement designs, the effects of intraspecific and interspecific competition are confounded.

Additive designs hold the density of one species constant while varying the density of other species (Figure 6). Because changes in the constant-density species can be measured as an effect of changing the other species' density, interspecific competition can be measured, but intraspecific competition cannot. However, similar to replacement designs, the density of the main species (e.g. species x in Figure 6b) must be justified. A main criticism of additive designs is that observed benefits of the intercrop (e.g. greater biomass than the monocultures) are confounded with the greater plant density in the intercrop compared to the monocultures. Since farmers are often interested in reducing input costs, the greater amount of seed required for intercrops when using an additive design may result in lower adoption unless other benefits from higher plant densities are clear.

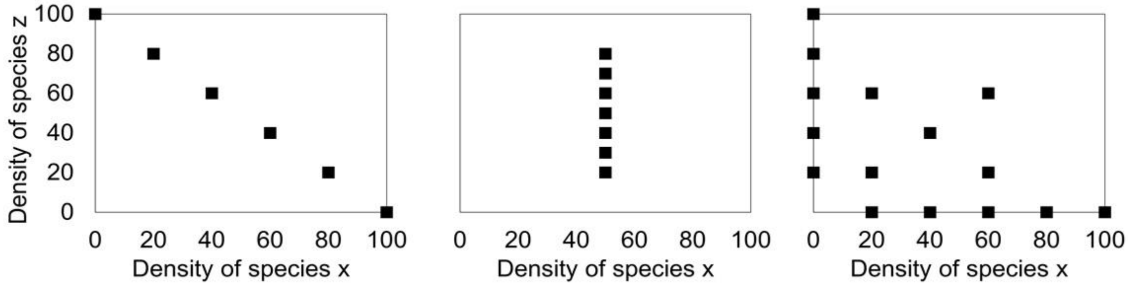

Figure 3. 6. Examples of different experimental designs for intercropping research a) replacement, b) additive, and c) response surface designs of a biculture intercrop. Replacement and additive designs are one-dimensional (linear) and components of competition cannot be parsed out, whereas, response surface designs are two-dimensional (planar) and intra-and interspecific competition can be parsed out.

3.5.2.2 Comparing Intercrops to Monocultures

Many intercropping experiments also grow the intercropped species in monoculture. Although it adds more treatments to an experiment, growing species in monoculture allows for greater quantification of complementarity. Land equivalent ratio (LER) (Eq. 3) is the most common metric used to assess intercrops compared to their respective monocultures (Mead and Willey 1980). It is the sum of ratios of the biomass of each species in an intercrop to the biomass of those species in monoculture and describes the amount of land that would be required to get the yield of each species in an intercrop if grown as a monoculture.

$$LER = \frac{IC_a}{M_a} + \frac{IC_b}{M_b} + \cdots + \frac{IC_n}{M_n} \qquad \text{Eq. (3)}$$

Where IC is the intercrop biomass and M is the monoculture biomass and a, b, …, n are the species. An LER of 1 means that neither species performs better nor worse in an intercrop than they do in monoculture. An LER above 1 means the intercrop uses land more efficiently, and below 1, less efficiently. Relative Yield Total (RYT) is calculated in the exact same way (deWit 1960).

Partial LERs, a single term in the LER equation (i.e., $\frac{IC_a}{M_a}$), can provide an indication of competitive interactions between different species grown together (Bedoussac and Justes 2011, Bybee-Finley et al. 2016). When illustrated in radar plots across treatments and environments, partial LER values detail the size and shape of the total LER and visualize emergent patterns in competition (Figure 7). Partial LER values contribute to a more substantial understanding of competition and complementarity than simply whether the LER was above or below 1.

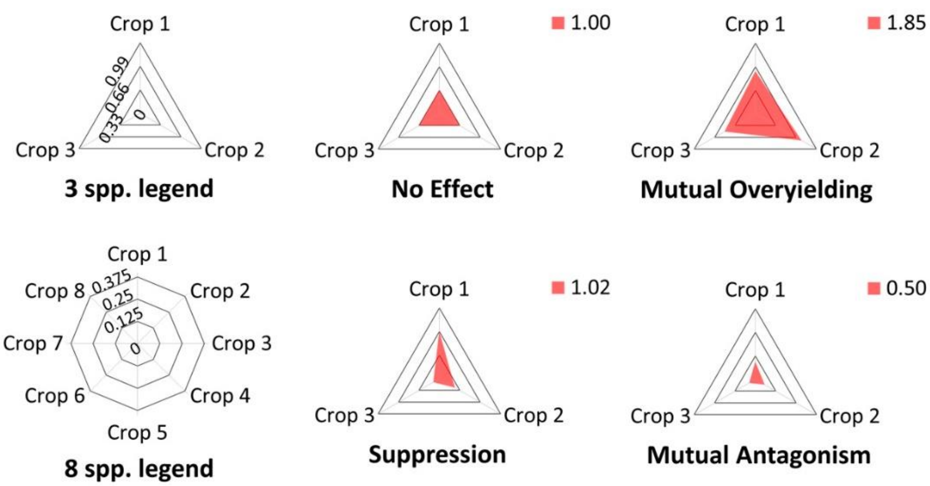

Figure 3. 7. Radar plot framework for evaluating species interactions for a 3-species intercrop (triangle) and for an 8-species intercrop (octagon). Numbers in the top right corner denote the LER of each example. No effect occurs when all species in the intercrop have partial land equivalent ratios (LERs) that are 0.33 for a 3-species intercrop or 0.125 for an 8-species intercrop. Mutual overyielding occurs when all species in a 3-species intercrop have partial LERs that greater than 0.33 for a 3-species intercrop or 0.125 for an 8-species intercrop. Mutual antagonism occurs when all species in a 3-species intercrop have partial LERs that are less than 0.33 or 0.125 for an 8-species intercrop. Suppression is a result of asymmetric competition and occurs when a species performs better in an intercrop by suppressing the growth of other species in the intercrop. Modified from Bybee-Finley et al (2016).

3.5.2.3 Response Surface Experimental Designs

Response surface designs are more powerful than replacement or additive designs because the effects of both intra- and interspecific competition can be measured (Figure 6). They have also been referred to as factorial designs, complete additive designs, replacement series, or addition series (Inouye 2001). Response surface designs vary the densities of two or more species. Treatments include a range of monoculture densities and different proportions of each species in an intercrop. In addition to the treatment structure in the response surface design that is illustrated above, Inouye (2001) compares various forms of response surface designs and their effects on model output (Inouye 2001). The downside to this design is the complexity which likely requires a greater number of experiment plots. If regression is the primary tool for data analysis, including multiple levels across the range of crop densities is more important than treatment replication at a specific density in response surface designs (Inouye 2001).

3.5.2.4 Parsing Out Intra- and Interspecific Competition

Response surface designs allow for a more direct connection between simulation models and empirical agronomic approaches. Although data from simpler experiment designs can be used to fit competition models and calculate competition coefficients of species, the manipulation of the densities of both species at the same time by response surface designs, leads to more accurate calculation of coefficients. Knowing the competition coefficients means more effective intercrop mixtures can be designed to limit competition and increase complementarity (Inouye 2001).

The fundamental variables of crop competition models are yield and density. Willey and Heath (1969) described the hyperbolic relationship between these variables (Figure 8) (Willey and Heath 1969). The average weight per plant can be calculated from regression analysis of the yield-density relationship. That is, I can understand how increasing the density can increase the yield and the per plant weight, up to a point where adding more plants does not change the yield and the per plant weight declines. The reciprocal of this hyperbolic relationship is linear. Thus, the reciprocal of the average weight per plant is equal to the intercept b_{x0} (plant g^{-1}) and the slope b_{xx} (m^2 g^{-1}). The term $1/b_{x0}$ (g $plant^{-1}$) describes the predicted biomass of an isolated plant that faced no intraspecific competition (i.e., the theoretical maximum weight of a plant) (Figure 8). The slope describes how the per plant weight (W_x) decreases when additional plants of the same species are added. Thus, b_{xx} represents intraspecific competition. Dividing b_{xx} by b_{x0} (i.e., taking the ratio of the rate of weight change and the theoretical maximum weight of a plant) normalizes the intraspecific competition and allows for comparison of intraspecific competition across species regardless of size.

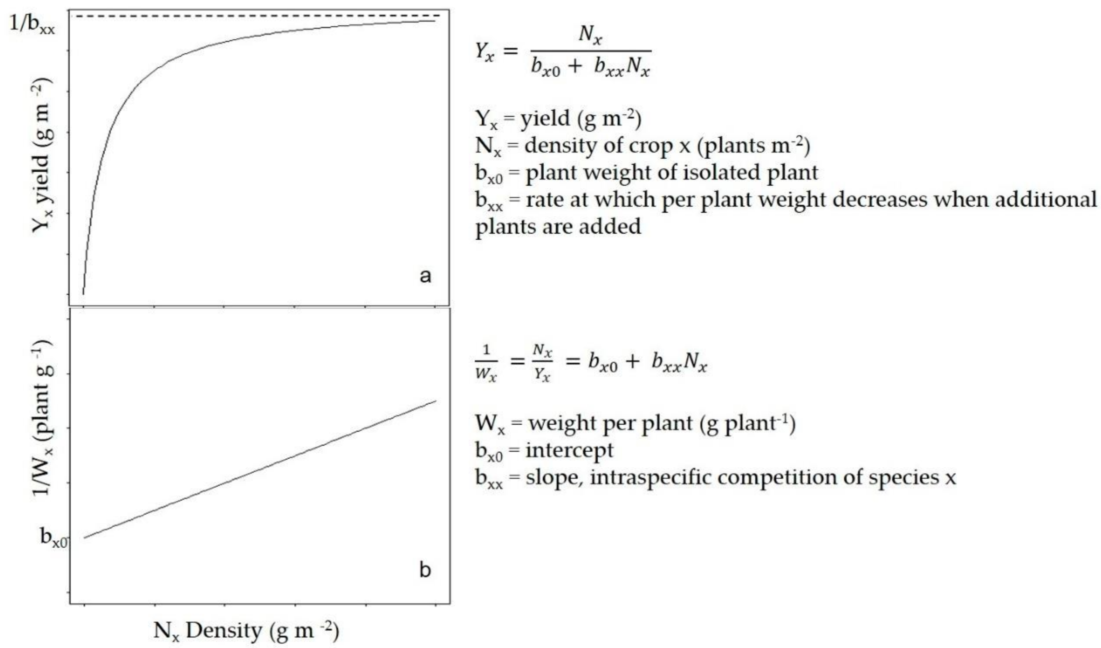

Figure 3. 8. Graphical depictions of the relationships between crop yield, crop density, and per plant weight, and their related equations used to model competition for species x. (a) illustrates the rectangular hyperbolic relationship between plant density and yield, where increasing plant density results in an increase in yield until a maximum limit is approached, denoted by the equation to the right of the graph. (b) is the linear reciprocal of the first equation and describes the relationship between plant density and the reciprocal of the per plant weight, denoted by the equations on the right of the graph.

Spitters (1983) assumed that additional species also affected $1/W_x$ in a linear fashion so that the hyperbolic and linear equations can be expanded (Eq. 4). In this work, Spitters used an additive design with corn at different densities in the presence and absence of groundnut (*Arachis hypogaea* L.). The presence of the second species caused an explicit shift in the y-intercept as a result of interspecific competition (Helenius and Jokinen 1994). The causal effects of an additional species are more dynamic when using a response surface design as data from both species are accounted for simultaneously to determine more realistic competition coefficients. Regardless of the design, the term b_{xz} is a measure of interspecific competition of species z on species x. Because it is important in intercropping to understand how both species affect each other, calculating the influence of species x on species z can also be done by adjusting the equation and replacing variables and parameters associated with species x with variables and parameters associated with z. These interspecific competition coefficients can also be normalized by dividing the term by the appropriate y intercept (e.g., b_{xz}/b_{x0}).

$$Y_x = \frac{N_x}{b_{x0} + b_{xx}N_x + b_{xz}N_z} \qquad \text{Eq. (4)}$$

More conclusions about competition can be drawn by taking the ratio of intraspecific competition to interspecific competition. The relative competitive ability (RC) of species x to species z refers to the number of plants of species x that can be replaced by plants of species z without changing the weight per plant of species z (Eq. 5) (Helenius and Jokinen 1994). The inverse of RC is the substitution rate and provides a measure of equivalence between species (Connolly 1987). Both are independent of the density of either species in an intercrop.

$$RC = \frac{b_{xx}}{b_{xz}} \qquad \text{Eq. (5)}$$

The niche differentiation index (NDI) is another ratio that uses the four competition coefficients (Eq. 6). If the ratio is above 1, niche differentiation is thought to exist because intraspecific competition was greater than interspecific competition, meaning that the plants of one species were more competitive with other plants of that species than to the plants of a different species. Niche differentiation points to more resource partitioning by the intercrop, and hence greater complementarity (Helenius and Jokinen 1994).

$$\mathrm{NDI} = \frac{b_{xx} * b_{zz}}{b_{xz} * b_{zx}} \qquad \text{Eq. (6)}$$

3.5.3 Standardizing Data Collection

Researchers should be clear about their research questions and base their experiment design, data collection, and analyses on the hypotheses they are testing. I recommend Competition and Succession in Pastures (Tow and Lazenby 2000) and the Statistical Design and Analysis for Intercropping Experiments (Federer 2012) as useful resources when designing experiments.

For greater, wider use of intercropping research, methods and site conditions need to be reported in as much detail as possible. Here I list some suggestions on criteria to include when reporting intercropping studies, along with some units I think would be most useful as a starting point (Table 1).

Table 3. 1. Suggested criteria to be described in intercropping publications and their metadata to ease difficulties of meta-analyses and build empirical evidence of intercropping outcomes across experiments.

Topic	Criteria	Units	Frequency
Environment	Locations	GPS coordinates, name of site of experiment, town state/province	
	Years	Years	Annually
	Heat units	Temperature in Celsius, growing degree days with base unit specified	Monthly or daily
	Precipitation	mm	Monthly or daily
Soil	Type	Name and taxonomic class	

	Organic matter content	% of distribution of regional soils with similar texture	Before experiment starts
	pH	1-14 scale	Before experiment starts
	Nutrient status	Field-level, report N-P-K in ppm	Before experiment starts
Hypothesis testing	Purpose(s) of intercrop	E.g., for forage and water quality	
	Experimental design	E.g., additive, replacement, response surface	
	Seeding rate approach	Constant density, recommended seeding rates, or functional equivalent	
Intercrop treatments	Species	Scientific name	
	Cultivars	Name	
	Seeding rate(s)	kg ha^{-1}	
	Duration of planting	Days	
Management	Seeding date	Day-month-year	
	Seeding depth	cm, specify if varied by species	Every planting
	Fertilizer application	Type, equipment used, concentration and rate of practice	Every application
	Water management	Rainfed or irrigated, specify details in mm	Daily
	Pest control	Type, equipment used, product and rate	
	Tillage practices	Type, equipment used, depth in cm	Every tillage event
	Termination practices	Type, equipment used, product and rate	
Results	Sampling date(s)	Day-month-year	
	Biomass	Total and by species, kg ha^{-1}	Every sampling
	Crop growth rate	Kg ha^{-1} day^{-1}	Every sampling
	Pest pressure	Abundance, species	

Meta-data	Data repository	Description of where data are stored
	Data license	Description of how you want to be acknowledged for your data
	Persistent identifier	Unique code for identification (e.g., digital object identifier (DOI))

Sharing data can increase the impact of intercropping research by allowing researchers to validate research results, reuse data for further analyses and modeling, and conduct synthetic and comparative studies (Piwowar et al. 2007). Many publishers or funders require that data be shared either in a data repository (re3data.org n.d.) or a discipline-specific data center. Some of these places require specific formats and might come with templates, easing the burden of preparing data for sharing. Currently, no accessible, agriculture-specific data center exists, but Table 2 describes a list of possible homes for intercropping data sets in agricultural landscapes. Characteristics for a good repository allow for data to be discoverable, accessible, and preserved for the long-term (Research Data Management Service Group n.d.).

Table 3. 2. Description of possible data repositories for agricultural intercropping research

Name	Description	Requirements
Dryad	Not agriculture-specific	Affiliation with publication
KNB	Ecological and environmental sciences	Ecological metadata language (EML)
Panagaea	Earth and environmental sciences	
Ag Data Commons	US National Agricultural Libraries	United States Department of Agriculture-funded research

3.5.4 Temporal and Spatial Aspects of Complementarity and Multifunctionality

It is important to recognize how time influences intercropping outcomes and how valuing ecosystem services beyond crop productivity can affect what strategies are best. Indeed, managing for multiple ecosystem services reduces the need to focus narrowly on intercrops that result in facilitation and transgressive overyielding. Increased crop biomass in an intercrop can increase some ecosystem services, like weed suppression (Smith et al. 2014, Bybee-Finley et al. 2017). However, there are many ecosystem services, like providing habitat for beneficial insects and increasing forage quality, that are not driven by biomass production. Finney and Kaye (2017) called for shifting focus away from increasing biomass production and towards increasing ecosystem services (Finney and Kaye 2017).

Interactions between crop species in an intercrop vary across temporal and spatial scales. Although many researchers acknowledge the differences between annual and perennial systems and are aware that annual systems do not allow for the slow-emerging benefits of diversity found in perennial systems (Murrell et al. 2017, Finney and Kaye 2017), findings from perennial systems often are used to justify expectations for annual intercrops, particularly from grassland experiments (Tilman

1999, Tilman et al. 2001, Hector and Bagchi 2007, Naeem et al. 2012). The reasoning behind this is likely two-fold: 1) ecological studies of agricultural landscapes draw from ecological literature that is largely based in "wild" or "natural" ecosystems and 2) practices that aim to increase crop diversity are pragmatically incremental so that other changes to management are minimized (Schipanski and Drinkwater 2012). In an experiment conducted in Illinois in corn-soybean based cropping systems, Exner et al (1999) found that despite clear benefits from strip intercropping the two cash crops, farmers were reluctant to adopt the practice due to management changes that were required (Exner et al. 1999, Rogers 2003).

The dynamics of perennial cropping systems are more complex regarding potential nitrogen limitations with legume nitrogen-fixation, symbiotic relationships with soil microbiota (e.g., rhizobacteria, arbuscular mycorrhizal fungi), and relationships with macrofauna (e.g., habitats). Since perennial intercrops persist for multiple years, decomposition, and thus mineralization of nitrogen, has greater time to occur, leading to increased potential for facilitation and transgressive overyielding. Perennial species in an intercrop also have a longer time to fill into their respective niches, leading to a potentially wider range of resource partitioning and also allowing for greater differences in species maturity (e.g., agroforestry, silvopasture).

Annual intercrops, on the other hand, are more likely to exhibit resource partitioning than facilitation, particularly in grass-legume intercrops, as the amount of rhizodeposition of nitrogen from legume to non-legume species is often negligible (Ledgard et al. 1985, Ledgard and Steele 1992). Some researchers have suggested that transgressive overyielding should be a goal of intercropping (e.g. Duchene et al

2017). However, transgressive overyielding might be an unnecessarily high bar to determine if an intercrop is preferable than its respective monocultures. Rather, similar performance to the monocultures seems to be a more reasonable goal in annual intercropping systems, especially if the increased crop species diversity enhances an ecosystem service. Moreover, the goal of transgressive overyielding is inherently biased against highly diverse mixtures as it becomes increasingly difficult for species to perform better in an intercrop than in each monoculture as more species are included. This is also the case for mutual overyielding discussed above, where it becomes increasingly unlikely that mutual overyielding will occur as crop species richness of an intercrop increases (Figure 8). In a meta-analysis of biodiversity and productivity, Cardinale (2011) found that polycultures rarely outperformed their most productive species (Cardinale et al. 2011). This corroborates early reviews of such literature and findings from earlier meta-analyses of grassland and agronomic studies (Trenbath 1974, Cadotte et al. 2008).

Annual species have been bred for their rapid productivity and have a relatively short lifecycle. Relay intercropping is one strategy to circumvent competition in annual intercrops but is typically used with only two crop species. A quantitative synthesis of intercrop system properties and species trait combinations found that the temporal niche differentiation contributed substantially to high LERs in systems combining C3 and C4 species (Yu et al. 2015). In addition to relay intercropping and managing to promote temporal niche differentiation, asymmetric competition in intercrops can be minimized by 1) selecting crop species with similar growth rates (Bybee-Finley et al. 2016), 2) seeding crop species at appropriate densities (Poffenbarger et al. 2015), and 3) managing crop growth to reduce competitiveness of the dominant species. For example, farmers can tailor seeding rates of each species to account for differences in competitive ability, adjust ratios based on soil nutrient conditions or timing, and mow intercrops to reduce dominance of aggressive species.

3.5.5 Balancing Multifunctionality and Management Complexity

The optimal number of species to include in an intercrop depends on the intercropping goals, management practices, and environmental conditions, including soil nutrients, pest status, and weather. If the primary goal of intercropping is simply to produce more biomass, than a highly diverse mixture is likely no better than a mixture with fewer species. However, if the goal is to provide multiple benefits (e.g. high yield, increased yield stability, enhanced pest suppression, and improved soil health), the optimal number of species to include might be unclear.

Research in natural systems suggests that ecosystem function is heavily influenced by species richness (Cardinale et al. 2007, Therond et al. 2017), and so, more crop species might be able to provide additional ecosystem services and help maintain greater stability over variable environments. Typically ecosystem function in natural systems declines more rapidly with increasing species loss (Cardinale et al. 2011). Thus, redundancy is a characteristic of a functioning ecosystem, and after a point functionality disproportionally decreases with additional species losses. Applied to agricultural landscapes, such insights suggest that functionality can be rapidly increased by intercropping and that the greatest gains come from the first few species that are grown together. This implies that after some number of crops species, benefits from additional crop species will become difficult to measure and evaluate, and therefore more difficult to justify.

Intercropping often affects management complexity. For example, the herbicide options available to a farmer with a grass-legume intercrop are limited and would require knowledge of alternatives. Asymmetric competition is a major concern when intercropping, as abiotic factors (e.g. weather, topography, soil nitrogen) and biotic factors (e.g. particular pests or weeds) can influence the relative ability of crop species. Thus, knowledge of the field conditions and history is needed to optimize species selection and seeding rates in an intercrop. Sanderson et al. (2013b) studied seeding ratios of grass-legume intercrops and found that a wide range of ratios led to the targeted 30-40% legume proportion, indicating some flexibility for farmers in choosing seeding rates but difficulty providing a prescriptive intercropping seeding rates. In some situations, asymmetric competition might be tolerable if adding the poor competitor species to the mixture provides some benefit other than biomass (e.g. pollination or disease-resistance), provided it is present enough for those benefits to occur. Addressing the management complexity of intercropping requires integrating different kinds of knowledge than called for by current monoculture practices. For example, a farmer intercropping multiple grain crops must determine how to coordinate plant growth and maturation of multiple species, changes required for farm equipment to mechanically harvest different crops together, and how to separate the seeds of different species. The management complexity is compounded when integrating intercropping within a crop rotation, a more common practice for crop diversification in industrialized agricultural landscapes.

While crop diversity affects ecosystem functions in agricultural landscapes, the degree of crop diversity necessary for maintaining select ecosystem services remains undetermined (Szumigalski and Van Acker 2006). Theoretically, an optimum point exists when ecosystem services are maximized and management complexity is minimized (Figure 9). Fortunately, farmers can strategically select crops to maximize ecosystem services and minimize complexity, thus reducing the burden of adopting intercropping practices.

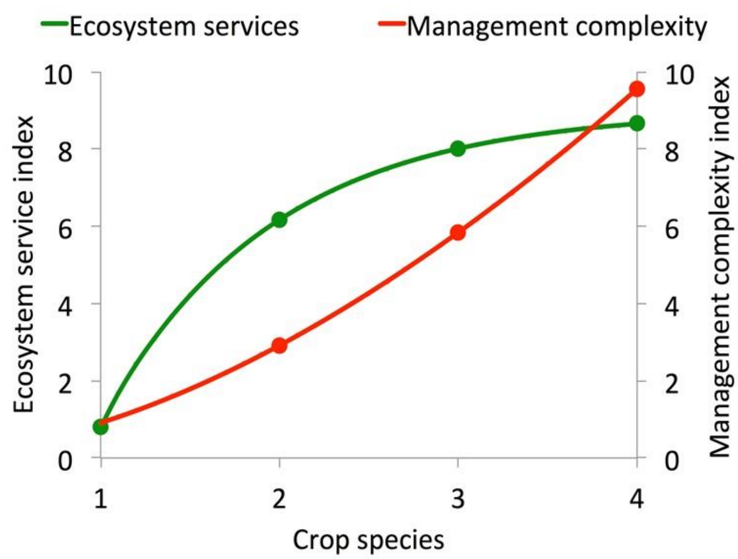

Figure 3. 9. Hypothesized relationships between ecosystem services (green line, left y-axis) and management complexity (red line, right y-axis) as a function of crop species in an intercrop. Modified from Ryan et al (2018).

3.6 Understanding the Socio-Political Context of Adoption through Cover Crop Mixtures

Although considerable evidence exists for the benefits of intercropping as a practice to increase sustainable crop production intensification, wide adoption of such practices will only occur with the support of policies, institutions, and markets that create the social structure and norms that influence individual farmer behavior. An effective strategy builds alliances across the research community, the farming community, advocacy groups, the private sector, and governmental organizations, predominantly at the state or national scales. Here we aim to raise awareness of some of the organizations in the United States and their actions within the context of cover crop mixtures.

I identify cover crop mixtures as an entry point for more transformative systems of intercropping since the planting of cover crops is relatively compatible with the current cash crop production system (i.e., it is much more feasible for farmers to adopt cover crops mixtures than to adopt silvopasture system or even strip intercropping with annual grain crops within the current agrifood system). While I suggest that intercropping with cover crops is a good starting point, I recognize that cover crops are only planted on 2-4% of the land in crop production in the United States due to perceived risks of yield loss and planting and termination timing (Gonzalez-Ramirez et al. 2017), as well as enduring structural and normative barriers (Dunn et al. 2016, Roesch-McNally et al. 2018, Plastina et al. 2018). However, to reiterate, 76% of the farmers who have adopted cover crops are planting mixtures, according to the 2017 Cover Crop Survey by the CTIC, indicating the high use of intercropping with cover crops (CTIC-SARE-ASTA 2017.). As I highlight below, new coalitions and concerted efforts are setting the foundation for wider adoption of intercropping mixtures, so there is a continuing need for scientific actors to strengthen the technical basis for integration and progress of intercropping in management practices.

3.6.1 Government

Economic incentives remain the main policy instrument to encourage the adoption of cover cropping. Incentives take the form of subsidies, cost-share programs, or conditioning financial support upon evidence of cover crops. The United States Department of Agriculture (USDA) Environmental Quality Incentives Program (EQIP) is an example of a federal program that offers incentives to farmers who plant cover crops, including mixtures. Between 2009-2014, the total farm acres receiving funding from the EQIP for cover cropping increased from 127,000 to 334,000 ha (Wade et al. 2015). There is also evidence of policy shifts at the level of state governments as well. For instance, the State of Maryland, through the Water Quality Cost-Share Program, pays its farmers to plant cover crops mixtures to alleviate nitrogen leaching and phosphorous run-off from entering the Chesapeake Bay Watershed (Cover Crop Program n.d.). The State of Iowa is also developing a program to subsidize crop insurance for farmers who plant cover crops (Bryant n.d.). Incentives could lead to direct adoption among farmers who receive payments, as well as, other farmers who are able to witness the demonstrable benefits of the practice.

3.6.2. Advocacy

Non-profit organizations and advocacy groups are also promoting intercropping. Groups like the Midwest Cover Crops Council, composed of researchers and farmers and agribusinesses, (Midwest Cover Crop Council n.d.) and the Practical Farmers of Iowa, a farmer-based group that advocates for more ecological practices, push state governments towards policies that would improve cover crop adoption by increasing the availability of resources and forming the community farmers need to do so (Practical Farmers of Iowa n.d.). Cover Crops Councils in other parts of the United States, like the Northeast and Southern regions, have also formed in recent years (SARE n.d.). In the future, coordinated efforts among the Cover Crops Councils may lead to policy changes at the federal level. As mentioned before, the CTIC is a national, public-private partnership among the USDA, Environmental Protection Agency (EPA), agribusiness, and universities that aggregates resources and news articles about cover crops (CTIC-Purdue n.d.). Since 2013, they have been conducting a national survey of cover cropping practices, capturing important longitudinal information about specific management practices (CTIC-Cover Crops n.d.). Another example of multi-stakeholder efforts was a public policy roadmap to increased cover crop adoption spearheaded by the National Wildlife Foundation (National Wildlife Foundation 2012).

In addition to advocacy from non-profits, on-farm research and farmer networks can play a powerful role in enhancing adoption of intercropping practices. They represent two characteristics to successful diffusion of innovations: trialability and observability (Rogers 2003). Farmers and researchers alike can try out a practice using farm-scale equipment and see firsthand the barriers and opportunities for such practices. Involving farmers early-on in the research process, allows for farmer's perspectives to be actively taken into account by other stakeholders (e.g., researchers, non-profits, government), and likely leads to improved outcomes for the farmers. The Soil Health Partnership is one such network with more than 100 farms. Established in

2014, based on an initiative from the National Corn Growers Association, on-farm measurements are taken for participating farms that implement practices like planting cover crop mixtures (Soil Health Partnership n.d.).

3.6.3 Private Sector

On the consumer side, large companies can set purchasing standards that shift farmer behavior. For example, Walmart asked their suppliers to promote planting cover crop mixtures after calculating that nitrogen fertilizer used by their producers was one of their largest sources of greenhouse gases (Walmart n.d.). Meanwhile, on the producer side, agribusinesses have begun to get involved. For example, many seed companies are already offering special blends of multi-species mixtures for forage or cover crops, making cover crop inputs more widely accessible. Similarly, agricultural machinery companies are offering equipment like interseeders, both drills and air seeders with variable rate technology that will allow large farms to include cover cropping as a part of their operation (Figure 10) (Hagie Manufacturing Company n.d.). Futuristic equipment that links high-resolution GIS maps to pre-determined intercrop mixtures and precision fertilizer application offer a bright vision for increasing crop diversity through intercropping with a reduced burden of management complexity (Future Farming n.d., CX-6 Smart Seeder n.d.). On a smaller scale, robots that fit in between rows can interseed cover crops when cash crops are too tall for other equipment to pass over (Rowbot n.d.).

Figure 3. 10. A high-clearance drill interseeder passes over a young crop of soybeans and plants a cover crop in mid-summer. Photograph by Matthew Ryan.

3.6.4 Cultural Change with Technological Tools.

Several programs exist to calculate intercrop mixtures, keep field-level records based on GPS that sync with their farm equipment, check markets and weather forecasts, and access real-time county-level yield estimations. These technological tools ease some of the burdens of more complex management practices of intercropping on an industrial scale. Moreover, some of these applications allow for information sharing to occur farmer-to-farmer which can enhance sharing across a wider social network of farmers. This, in addition to public information platforms, like eXtension (eXtension n.d.), create a cultural context that supports more complex management.

3.7 Conclusions

Intercropping can contribute to sustainable intensification of industrialized agricultural landscapes and play an important role in increasing productivity, stability, and ecosystem services. The concepts of multifunctionality and restoring ecosystem services call for increasing crop diversity at their core. Realistic expectations of complementarity in annual cropping systems, thoughtful research, and comprehensive reporting are key strategies to increasing intercropping adoption and aggregating knowledge of the intercropping discipline. Recent progress with cover crops provides a template for advancing intercropping in cash crops, but management complexity will need to be minimized for widespread adoption of intercropping.

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CHAPTER 4

QUANTIFYING THE ROLE OF INTRA- AND INTERSPECIFIC DIVERSIFICATION STRATEGIES IN FORAGE CROPPING SYSTEMS

4.1 Abstract

Dairy farms often report challenges with forage productivity, and this can be exacerbated by extreme weather events associated with climate change. Cropping system diversification via intercropping has been proposed as a strategy for improving productivity and increasing the resilience of agricultural systems to the effects of climate change. We conducted a three-year cropping systems experiment in New York, New Hampshire, and Vermont, USA comparing three approaches to increasing cropping system diversity via intercropping in both an annual forage crop rotation and a perennial forage crop: increase crop cultivar diversity (hereafter "Conspecific"), increase crop species diversity (hereafter "Heterospecific"), or increase both cultivar and species diversities (hereafter "High"). These three strategies were compared against a control crop in either system in which a single cultivar of a single species was grown (hereafter "Low"). Measurements included yield, weed biomass, forage quality, yield stability, and economic performance. Effects of the diversity strategies depended on crop type, site, and year. When pooled over sites and years, yield of winter annuals was 12% greater in the Heterospecific treatment compared to the Low treatment. Weed biomass in the summer annuals was 36% lower in the High compared to the Low treatment. In the perennial systems, forage yield was 25% greater and weed biomass was an order of magnitude lower in the High treatment compared to the Low treatment. Yield stability analysis showed

that perennial crop yields were consistently greater in the High treatment compared to the Low treatment all growing conditions, whereas in the summer annuals yields were greater in the High treatment compared to the Low treatment only in the low-yielding environment (20th percentile). Strategically selecting species and varieties for specific traits that maximize both functional and response diversity could further enhance the benefits of cropping system diversification. Future research should aim to develop guidelines for species and trait compatibility in mixtures and appropriate seeding rates to optimize production.

4.2 Introduction

Dairy farmers are likely to continue to face difficulties producing sufficient on-farm feed with annual temperatures, extreme precipitation events, and short- and medium-term droughts projected to increase in the Northeastern United States (Dupigny-Giroux et al. 2018). The amount of precipitation due to very heavy precipitation events (99^{th} percentile) was found to have increased 71% in the Northeast from 1958 to 2007 (Walsh et al. 2014), and the highest recorded precipitation amount in a given year, increased by an average of 1.6 mm yr^{-1}, a total increase of 58.0 mm since 1979 (Howarth et al. 2019). When feed shortages occur, dairy farmers must import grain and other feedstocks or reduce their herd size (Conrad et al. 2017).

Previous research has demonstrated that increasing the genotypic diversity of a cropping system may be a useful management strategy for improving productivity and coping with weather variability associated with climate change. In practice, there are three broad approaches for increasing the genotypic diversity of a cropping system via intercropping: (1) increasing the number of cultivars, (2) increasing the number of species, or (3) combining both the first and second approaches. Intercropping has been shown to improve yields and yield stability, reduce weed biomass, and improve economic performance. Schipanksi and Drinkwater (2011) found greater red clover (*Trifolium pratense* L.) biomass when interseeded with winter wheat than in monoculture, despite being seeded at one-third of the monoculture rate. In a meta-analyses of 33 grass-legume intercrop experiments, Raseduzzaman and Jensen (2017) showed that intercropping resulted in more stable yields conditions than either crop in monoculture. A meta-analysis of 476 experimental units by Verret et. al (2017) found that intercropping a cash crop with a companion crop resulted in lower weed biomass and higher yields compared to non-weeded or weeded control treatments in 52% and 36% of their experimental units, respectively. In another meta-analysis consisting of 91 experiments, Reiss and Drinkwater (2018) found that cultivar mixtures outperformed monocultures of one cultivar but more so under more stressful conditions. In addition to increased yield from resource partitioning, cultivar mixtures can also provide greater nutrition due to differing phytochemical content of cultivars and economic advantages stemming from other regulating and supporting ecosystem services (e.g. reduction in pest damage and increased soil health) (Snyder et al. 2020).

Mechanisms at multiple scales drive the outcomes of intercropping. Occurring amongst species and cultivars, complementarity from differential functional traits allow for improved resource use (Vandermeer 1989, Duchene et al. 2017, Bybee-Finley and Ryan 2018). Also at this scale, enhanced resistance from differential responses to stress (Elmqvist et al. 2003, Elsalahy et al. 2020). At the level of the crop mixture, increased redundancy (Cardinale et al. 2011) and a portfolio effect, change the likelihood and distribution of risk. At the largest scale, the diversity of crops increases the multifunctionality of agroecosystems (Finney and Kaye 2017, Tamburini et al. 2020) and enhance a farmer's ability to adapt to a given condition (Milestad and Darnhofer 2003, Darnhofer et al. 2010). Advancing the scholarship of crop diversification requires not only determining the role of different mechanisms, but also applied experiments that work to understand diversification strategies that farmers could quickly adopt.

In this experiment, our aim was to deploy examples of different crop diversification strategies across the Northeast using species and cultivars commonly grown in the region. We conducted a three-year cropping systems experiment in New York, New Hampshire, and Vermont, USA comparing three approaches to increasing cropping system diversity via intercropping in both an annual forage crop rotation and a perennial forage crop: increase crop cultivar diversity ("Conspecific"), increase crop species diversity ("Heterospecific"), or increase both cultivar and species diversities ("High"). These three strategies were compared against control crops consisting of a single cultivar of a single species was grown ("Low"). The effects of the different strategies were quantified in terms of crop productivity, weed abundance, forage quality, yield stability, and economic performance. We hypothesized that mixtures with greater crop diversity will have higher and more stable yields, lower weed biomass, improved forage quality and greater economic performance than treatments with lower diversity.

4.3 Materials and methods

The experiment was conducted from August 2016 to June 2019 at Cornell University in Aurora, NY (42°45’ N, 76°35’ W) on a Honeoye (fine-loamy, mixed, semiactive, mesic Glossic Hapludalfs) and Lima (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs) silt loam, USDA plant hardiness zone 5b; the University of New Hampshire in Madbury, NH (43°10' N, 70°56' W) on a Charlton (coarse-loamy, mixed, superactive, mesic Typic Dystrudepts) fine sandy loam, USDA plant hardiness zone 5b; and the University of Vermont Alburgh, VT (45°N, 73°18’ W) on a Benson (loamy-skeletal, mixed, active, mesic Lithic Eutrudepts) rocky silt loam, USDA plant hardiness zone 4a. In all sites, it was managed organically.

In NY, the previous crop was organically managed, high density 50-50 mixture of pearl millet [*Pennisetum glaucum* (L.) R. Br.] and sorghum sudangrass [*Sorghum bicolor* (L.) Moench × *S. sudanense*] and no fertilizer was applied. In NH, the previous crops were non-organic cucurbits (*Cucurbitaceae*) with 101 kg ha^{-1} of N and K applied per year, followed by a winter cereal rye cover crop (*Secale cereale* L.). In VT, the previous crop was non-organic winter barley (*Hordeum vulgare* L.) with varied calcium ammonium nitrate (27-0-0) rates harvested at the beginning and end of July 2016.

4.3.1 Diversity treatments

The split-plot design contained system (annual or perennial) as the block and diversity treatment at the plot level. Both block and plot within block were spatially balanced in complete block designs. The diversity treatments in each system remained on the same plots for the duration of the experiment. The annual system was a rotation containing summer and winter annuals. Diversity strategies as treatments consisted of a single cultivar of a single species (Low), four cultivars of a single species (Conspecific), a single cultivar of four species (Heterospecific), and four cultivars of four species (High) (Table 1, Table B.1). The cultivar used in the Low treatment was the same one in the Heterospecific. The cultivars used in the Heterospecific treatment were the same ones in the High treatments. In this way, we were 'adding' different kinds of diversity to the cultivar featured in the Low treatment. In NY, plots were 9.1 by 15.2 m with four replicates. In NH, plots were 13.7 by 6.1 m with five replicates. In VT, plots were 10.7 by 6.1 m with four replicates.

Table 4. 1. Seeding rates for the four diversity treatments by weight and population. Information about the specific cultivars used can be found in the Appendix Table B. 1.

Diversity level	Contains	Winter annuals			Summer annuals			Perennials		
		Species	kg ha^{-1}	(seeds m^{-2})	Species	kg ha^{-1}	(seeds m^{-2})	Species	kg ha^{-1}	(seeds m^{-2})
Low	1 species, 1 cultivar	Triticale	237	(546)	Sudangrass	59	(346)	Alfalfa	25	(626)
Conspecific	1 species, 4 cultivars	Triticale	234	(546)	Sudangrass	57	(346)	Alfalfa	19	(626)
Heterospecific	4 species, 1 cultivar each	Triticale	59	(137)	Sudangrass	15	(86)	Alfalfa	6	(156)
		Cereal rye	63	(153)	Pearl millet	11	(130)	Timothy	4	(958)
		Red clover	4	(142)	Sorghum sudangrass	16	(64)	Orchardgrass	7	(464)
		Winter pea	49	(41)	Annual ryegrass	8	(232)	White clover	1	(89)
		Total	176	(472)		50	(512)		19	(1667)
High	4 species, 4 cultivars each	Triticale	52	(137)	Sudangrass	14	(86)	Alfalfa	5	(156)
		Cereal rye	54	(153)	Pearl millet	11	(130)	Timothy	4	(958)
		Red clover	4	(142)	Sorghum sudangrass	19	(64)	Orchardgrass	6	(464)

	Winter pea	59	(41)	Annual ryegrass	8	(232)	White clover	1	(89)
	Total	183	(472)		53	(512)		17	(1667)

Species and cultivars were selected based on their prevalence in crop production in the Northeast and success in previous experiments at the research farms. The winter annuals were triticale (x *Triticosecale* Wittmack), cereal rye, red clover, and winter pea (*Pisum sativum* subsp. *arvense* L.). The summer annuals were sudangrass [*Sorghum sudanense* (Piper) Stapf], pearl millet, sorghum sudangrass, and ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.)]. The perennial system contained alfalfa (*Medicago sativa* L.), orchardgrass (*Dactylis glomerata* L.), timothy (*Phleum pratense* L.), and white clover (*Trifolium repens* L.). Species and cultivars were selected for similar rates of maturity but also a range of other traits with efforts made to purchase cultivars from different seed companies that likely used different genetic lines (Appendix Table B.1).

The Conspecific treatment was seeded using a replacement rate so that each of the cultivars matched the population density of the cultivar used in the Low treatment. The Heterospecific treatment was seeded using a replacement rate so that each species in the four-species mixture was planted at one-quarter of their recommended monoculture rate. The High treatment was seeded using a replacement rate so that each of the species' cultivars matched the population density of the cultivar of the species used in the Heterospecific treatment. Matching populations of cultivars ensured the same plant density in mixtures with multiple cultivars despite variations in seed size. Seeding rates were adjusted for germination rates and made on a pure live seed basis. Initial establishment of the perennials in NY and VT was poor. New York faced strong weed pressure in the fall and required reseeding the perennials of in the spring of 2017 (Table 2). Vermont experienced poor winter survival and reseeded the alfalfa and white clover in the late summer 2017.

Table 4. 2. Planting and harvest dates for each crop at each site. Multiple harvests were taken for the summer annuals and the perennials. Cumulative growing degree days (GDD) were split (“/”) for overwinter crops between the years.

Crop	Site	Year	Planting date	Harvest date (cumulative GDD)							
				1st		2nd		3rd		4th	
Winter annuals	NY	2016-2017	Sept. 9	May 16	(817/617)						
	NH		Sept. 8	May 24	(610/619)						
	VT		Sept. 12	May 25	(772/591)						
	NY	2017-2018	Sept. 20	May 22	(781/429)						
	NH		Sept. 21	May 22	(728/490)						
	VT		Sept. 11	May 25	(933/537)						
	NY	2018-2019	Sept. 6	May 16	(839/417)						
	NH		Sept. 21	June 25	(494/1057)						
	VT		Aug. 31	May 28	(847/488)						
Summer annuals	NY	2017	June 18	Aug. 9	(556)						
	NH		June 28	Aug. 17	(522)						
	VT		June 8	Aug. 3	(591)	Sept. 6	(296)				
	NY	2018	May 26	July 13	(495)	Aug. 21	(474)				
	NH		June 7	July 16	(378)	Aug. 23	(535)				
	VT		May 31	July 16	(475)	Aug 20	(454)				
Perennials	NY	2016-2017	Aug. 20; May 4	June 8	(864/468)	July 25	(748)				
	NH		Aug. 31	June 13	(574/493)	July 26	(674)				
	VT		Aug. 24; Sept. 1	June 1	(711/365)	July 21	(733)				
	NY	2018	--	May 23	(1197/270)	July 3	(601)	Aug. 9	(637)	Oct. 3	(783)
	NH		--	May 31	(1202/345)	July 10	(560)	Aug. 8	(509)	Oct. 11	(838)
	VT		--	May 30	(1292/344)	July 3	(479)	Aug 13	(747)		

4.3.2 Management

Fields were moldboard plowed before the experiment was initiated, and in subsequent years the annual system was chisel plowed when rotating between summer and winter crops (see Appendix for specific site details: Table B.2-B.4). Crops were planted in 19 cm rows. Legumes were inoculated with a suitable rhizobium mixture prior to or immediately after planting (N-Dure, Verdesian Life Sciences Cary, NC). Planting dates, fertilizer amounts, and harvest times were based at the system-level for the Low diversity treatment (i.e. single cultivars of triticale, sudangrass, and alfalfa) (Table 2). Summer annuals were managed for two cuts and the perennials for four cuts. For a graphical overview of the experiment management see Figure 1.

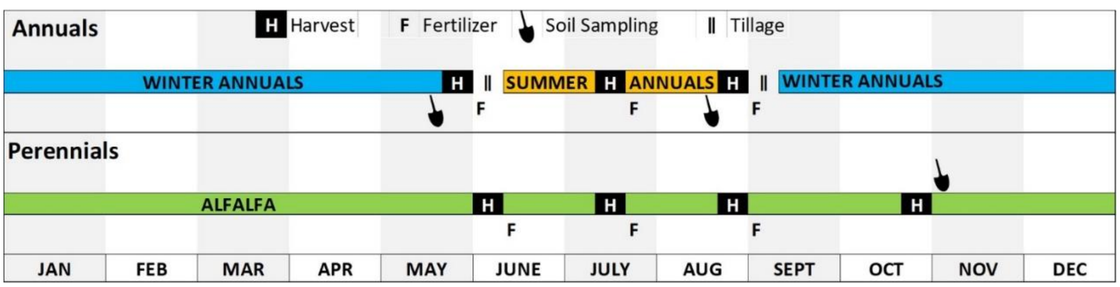

Figure 4. 1. Timeline for planting times, fertilizer application, tillage, and soil tests based on the intended number of harvests for the annual and perennial systems.

4.3.3 Soil sampling and fertilizer

Fertilizer applications were based on the soil conditions and estimated crop nutrient removal rates for the Low diversity treatment of each crop and uniform for each system. To fully characterize the soils in each plot, and to provide initial fertilizer recommendations five soil cores were taken to a depth of 20 cm with a width of 10.8

cm in each plot, homogenized, and submitted to Dairy One (Ithaca, NY) with future crops in rotation at the start of the experiment.

Soil was sampled again using same depth and core width at the end of the experiment in October 2018. Five, four, and two cores were randomly taken within each plot at NH, NY, and VT, respectively. Soil was homogenized at the plot-level and wet soil was sieved to 2 mm. Bulk density was calculated as the quotient of dry soil by the core volume corrected for gravel. Bulk density and gravimetric moisture calculations were made with the assumption that gravel had a density of 2.65 g cm^{-3} (Buckman and Brady 1990). Gravimetric moisture was the difference in weight of soil before and after 24 hours in a 100°C oven. Samples were sent to Dairy One for physical and chemical analysis and to Cornell Soil Health Lab (Ithaca, NY) for active carbon, soil respiration, and aggregate stability. For more details on analysis methods, see Menalled et. al (2020).

Additionally, to provide ongoing fertilizer recommendations, we sampled the Low diversity plot before each annual planting and at the end of the perennial growing season. In the annual system, soil samples were collected approximately two weeks before the planting of the subsequent crop (Figure 1). In the annual system, poultry manure was applied to meet the N needs based on 50% assumed availability (Kreher's 5-4-3 or 8-2-2) (Clarence, NY). Fifty-six kg ha^{-1} of nitrogen (N) was added after each harvest date. Phosphorous (P) and potassium (K) were applied based on the recommended rate from the soil test results by way of mixing the two types of poultry manure and potassium sulfate (0-0-51, 18% S) or sul-po-mag (0-0-22, 11% Mg, 13% S) to reduce overapplication of nutrients. Residual N was not taken into account.

In the perennial system, soil samples were taken after the last harvest each year and then recommended amounts of nutrients were divided by the number of predicted harvests for the following year. In the perennial system, poultry manure was applied to meet the P needs and potassium sulfate or sul-po-mag was applied to meet the K needs of the perennial crop after each harvest. New York applied all fertilizer required for the year after the first cut in 2017. New York was the only site with a P deficiency so poultry manure which also contained N was applied.

4.3.4 Biomass sampling

Harvests times were set to optimize yield and forage quality and based on defined criteria for each crop which varied by site (Table 2, Figure 1). The winter annuals were harvested when the triticale was in the swollen boot stage (Zadok's growth stage 47) (Ketterings et al. 2015). The summer annuals were cut when the sudangrass was 0.91 m in height (Darby et al., 2010). The perennial system was cut when the alfalfa was in stage three of development with one to two buds per node and before flowering (Kalu and Fick 1983).

Crop and weed biomass were clipped 10 cm above the soil surface to mimic a forage harvest and collected from two 0.25 m^2 quadrats per plot away from borders to reduce the edge effect. Crop and weeds were identified at the species-level. However, triticale and cereal rye were combined in the winter annuals, and sudangrass and sorghum sudangrass were combined in the summer annuals because certain cultivars were difficult to distinguish. Quadrat samples were used to report crop yield and weed biomass. Samples were dried at 60°C for at least one week and yields, yield per cost, and weed biomass are reported on a dry matter basis.

Additionally, grab samples of approximately 500 g from forage choppers were used to assess forage quality. Choppers harvested at a height of 10 cm and took two swaths down the center length of each plot. New York and NH used a RCI 36A forage chopper (Mayville, WI 53050) and VT used a Carter flail forage harvester (Deerfield, IL 60015). All cut a 91 cm wide swath. After a system had been harvested, plots were mowed completely to 10 cm and the biomass was removed.

4.3.5 Forage quality

Forage chopper samples were dried at 60°C for at least one week and then ground to 1 mm using the Wiley Mill (Thomas Scientific, Swedesboro, NJ) and submitted to Cereal and Forage Lab at UVM (Burlington, VT) for forage quality analysis. Crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF) were determined using near-infrared spectroscopy by the FOSS NIRS DS2500 instrument (FOSS, Hilleroed, Denmark) and reported on a dry matter basis. As calibrations have not been developed for most mixtures used in this experiment, calibrations used were those that best fit the given sample parameters. These calibrations were developed by the NIR Forage and Feed Testing Consortium (Hillsboro, WI). In 2018, this library was combined with the Dairy One calibration library. The forage samples from the first and fourth perennial cuts in NY in 2018 became moldy when drying and were excluded from the forage quality analysis.

4.3.7 Costs and weather

Costs of diversity treatment were based on the seed costs from the first season of each crop (Table B5). Yield per cost was calculated by taking the yield and dividing it by the seed costs ($\$ ha^{-1}$) of the diversity treatments.

Temperature and precipitation data were collected daily (Table 3). Thirty-year averages were taken from the National Research Council's Climate Information for Management and Operational Decisions (CLIMOD2) tool for NH and NY, and the Burlington airport for VT, approximately 80 km away. Growing degree days were calculated by subtracting the lower threshold temperature for triticale (0 °C), sudangrass (10 °C), and alfalfa (5 °C) from the average daily temperature:

$$GDD = \frac{T_{max} - T_{min}}{2} - crop_{min} \qquad \text{(Eq. 1)}$$

(Gallagher 1979, Gerik et al. 2003, Parsons et al. 2006). Upper thresholds for sudangrass (30 °C), or alfalfa (43.3 °C) were not reached during the experiment. Cumulative GDD are reported for each cut in each site and year. For overwintering crops (winter annuals and the first cut of the perennials), cumulative GDD for fall and spring are reported separately (Table 2). Following Parsons et al. (2006), growing degree days for all crops only accumulated when the mean temperature was greater than the base temperature for five consecutive days.

4.3.7 Data analysis

Statistical analyses were performed in R version 3.6.1 (R Core Team, 2019). Linear and linear mixed-effects models were performed with the 'lmerTest' package

(Kuznetsova et al. 2017) with their fit assessed with the ‘car’ package (Fox and Weisberg 2019), and the estimated marginal means were compared with the ‘emmeans’ package (Lenth et al. 2019). Normality and heteroscedasticity were assessed graphically. If the assumptions were not met, response variables were transformed as appropriate.

4.3.7.1. Soils

Linear mixed effects models were used to determine how the diversity treatments and cropping system (annual or perennial) management affected the physiochemical and biological qualities of the soil. The model contained cropping system, diversity treatment, and their interaction as fixed effects and block was considered a random effect. To account for the differences in soil nutrient extraction methods (i.e. a Morgan test was used for NY soils and a modified Morgan test was used for NH and VT soils), each site was modeled separately. To accomplish linearity, K, P, and Zn values in NY and Al, Ca, Mg, and Zn values in VT were log transformed. Significant diversity and cropping system effects were described through Tukey's HSD or T-tests, respectively.

4.3.7.2 Yield, yield per cost, weed biomass, and forage quality

Each crop was analyzed separately. The winter annuals were harvested once per year (nine in total), while the summer annuals, and perennials had multiple harvests within a year (summer annuals and perennials had a total of 10 and 17 harvests, respectively). Yield and weed biomass were summed across multiple harvests for each site-year. Likewise, weighted averages were taken for the forage quality metrics for the summer annuals and perennials for each site-year.

Linear mixed effects models were used to determine the effect of diversity treatments on response variables while controlling for variability of the growing conditions. Response variables were yield, yield per cost, weed biomass, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). The model contained diversity treatment, site, year, and all two-and three-way interaction terms as fixed effects. Block was a random effect, unique to site, and plot nested in block was a random effect that accounted for any accumulated treatment effects and addressed the lack of independence of the diversity treatment plots over the course of the experiment. A type III analysis of variance (ANOVA) assessed fixed effects and then multiple comparisons test were performed for each significant model term using Tukey's HSD. Contrasts were also performed at level of the site, year, and diversity treatment to determine if differences existed between presence and absence of intraspecific diversity (Conspecific and High versus Low and Heterospecific treatments) and between presence and absence of interspecifc diversity (Heterospecific and High versus Low and Conspecific) using Tukey's HSD. The estimated marginal means from the model are presented and when necessary, means were back-transformed for consistent reporting. To meet normality assumptions, weed biomass data were log transformed for all crops.

4.3.7.3 Yield stability

To understand the impact of intercrop diversity on yield, stability was assessed in two ways. The first way, the coefficient of variation (CV) was determined by dividing the standard deviation of the yield of a diversity treatment by its mean. The second way, yield stability of crop production was determined by regressing the environmental mean and yield for each treatment in each environment. The environmental mean was calculated as the mean yield of all diversity treatments within each block at each harvest (site, year, cut, crop) (Finlay and Wilkinson 1963, Grover et al. 2009). Calculating environmental mean at the block-level provided greater granularity to diversity treatment responses and more points along the regression. A high intercept indicated a high level of production and steeper slopes indicated a greater yield response to environmental conditions. An analysis of covariance (ANCOVA) was performed separately on each crop with environmental mean and diversity treatment and their interaction as explanatory variables and yield as the response variable. To determine the conditions where diversity treatments differed, the estimated marginal means were compared with Fisher's LSD at the 20^{th}, 50^{th}, and 80^{th} percentiles of the environmental means for each crop.

Stability in cropping mixtures is partially attributed to temporal diversification. In the annual system, this is typically understood as the species richness over the year (Smith et al. 2008) but these did not change across diversity treatments in the experiment. In the perennial system with its multiple harvests and distinguishable crop species, temporal diversification was understood as the expression of different species during the course of the growing season. Intercropping alfalfa with cool season grasses is a common practice to decrease a decline in forage production of cool season grasses during summer months (Williamson 2017). To determine this, the biomass percent of alfalfa and grasses of total biomass for the treatments that had interspecific diversity (Heterospecific and High treatments) were calculated and compared within each site-year in an ANOVA with cut as the fixed effect and block as the random effect. A Tukey HSD test was performed to compare treatment means at $\alpha = 0.05$.

4.4 Results

4.4.1 Weather and soil

The temperatures in the fall of 2016 were generally warmer than average at all sites but on average, rainfall was lower in NH and VT and higher in NY (Table 3). Compared to the long-term average, the 2016-2017 winter was warmer in NY and VT. Spring in 2017 was generally cool and wet at all sites. Temperature and moisture were close to the 30-year average until late summer in NY and NH where conditions became drier. The fall of 2017 was warmer in VT and drier in NY than the average. Compared to the average, precipitation was lower in NH and VT. Winter was colder than the previous year at all sites and drier than average in VT. In 2018, April in NH and VT was colder and wetter than the average, and in NH, May was warmer and drier than the average. Summer in 2018 was warmer at all sites and generally wetter in NH and NY. Fall in 2018 was wetter than average in NY and colder in VT. Winter was generally colder in NY and VT, but milder and wetter in NH. Spring in 2019 was cool at all sites and wetter in VT.

Table 4. 3. Monthly precipitation (mm) and temperature (˚C) in NY, NH, and VT from 2016 to 2019 growing seasons, as well as the 30-yr average.

	New York				New Hampshire				Vermont			
Total monthly precipitation	2016-2017	2017-2018	2018-2019	30-year average	2016-2017	2017-2018	2018-2019	30-year average	2016-2017	2017-2018	2018-2019	30-year average
					------------------- mm -------------------							
Aug.	115.8	37.6	89.7	80.3	42.4	88.9	152.4	89.7	75.7	140.7	75.2	99.3
Sept.	95.5	65.5	93.0	101.9	61.7	94.0	142.0	96.5	62.7	46.7	88.4	92.5
Oct.	204.7	151.6	127.3	86.9	174.8	152.7	115.6	115.6	126.7	83.6	89.7	91.4
Nov.	67.1	62.7	114.0	81.8	88.1	44.5	258.8	110.5	75.9	57.9	114.3	79.2
Dec.	72.9	32.8	74.4	61.5	123.2	81.8	82.8	97.8	39.4	19.8	75.2	60.2
Jan.	59.7	79.2	73.4	48.5	68.1	82.6	188.2	79.2	25.4	20.1	38.9	52.1
Feb.	54.6	40.4	43.2	45.7	105.2	104.4	183.9	83.6	37.3	29.5	43.2	44.7
Mar.	75.7	81.8	27.2	64.0	103.1	106.2	123.7	117.1	40.1	38.4	34.5	56.1
Apr.	156.0	72.1	95.0	82.8	134.6	147.6	137.7	105.9	132.6	112.5	92.7	71.6
May	132.6	51.6	117.3	80.3	164.1	33.8	76.2	102.4	104.9	49.3	124.5	87.6
June	96.8	41.4	N/A*	95.5	93.7	94.2	131.3	99.3	143.3	95.0	N/A	93.7
July	186.2	141.5	N/A	89.4	69.1	151.9	N/A	104.1	124.0	61.7	N/A	105.4
Average monthly temperature					------------------- °C -------------------							
Aug.	22.8	19.5	21.8	21.0	21.3	19.1	21.9	20.0	21.9	19.8	22.6	20.4
Sept.	18.2	17.3	18.3	16.9	17.3	17.9	17.4	15.6	17.6	18.0	17.4	15.9
Oct.	11.5	13.8	10.0	10.5	9.8	13.4	8.3	9.5	10.0	14.1	7.7	9.0

Nov.	5.9	3.3	1.5	5.0	5.0	3.5	1.6	4.2	4.5	1.8	0.1	3.4
Dec.	-1.5	-3.4	-0.4	-1.0	-2.1	-4.5	-1.0	-1.6	-2.9	-7.5	-3.7	-3.4
Jan.	-0.5	-6.1	-5.8	-4.1	-1.3	-4.8	-4.9	-5.2	-2.8	-8.3	-9.4	-7.3
Feb.	1.6	-0.3	-3.3	-3.2	-0.9	0.1	-3.3	-3.5	-2.8	-2.6	-7.3	-5.8
Mar.	-0.8	-1.1	-0.8	1.0	-1.5	1.1	0.0	1.0	-3.9	-0.9	-2.0	-0.5
Apr.	9.9	3.8	7.3	7.9	9.0	5.3	7.5	7.1	8.4	4.0	5.9	7.1
May	12.9	16.7	13.0	14.2	11.7	14.7	11.9	12.8	13.1	15.3	11.8	13.6
June	18.7	18.6	N/A	19.4	18.3	17.2	17.5	18.0	18.6	18.0	N/A	18.8
July	20.9	22.4	N/A	21.7	20.4	21.7	N/A	20.8	20.4	23.4	N/A	21.4

*Experiment was completed in May 2019 in NY and VT and June 2019 in NH.

Soil characteristics primarily varied as a function of whether the crop system was annual or perennial (Tables 4 and B.6). Diversity treatments in place after two years had almost no effect on soil characteristics. An interaction between diversity treatment and system ($P < 0.05$) in VT was observed for soil organic matter (SOM) where the Heterospecific and Low treatments had greater SOM than the Conspecific treatment in the perennials, but not the annuals. Phosphorous levels were greater in annual soils than perennial soils at all sites. pH, gravimetric moisture, and Zn were greater in annual soils than perennial soils in two of the three sites. Potassium also differed in two of the three sites but was higher in perennial soils. The differences in P and K were likely caused by differences in the fertilizer application, which then affected soil pH. Total N application was 81 to 100% greater and total P application was 77 to 100 % greater in the annuals than the perennials, whereas total K application tended to be greater in the perennials than the annuals (Table B.2-B.4). Gravimetric moisture was greater in annual soils than perennial soils in NY and VT. This was likely driven from a reduction bulk density; however this difference was only significant in NY. The tillage performed on the annual soils likely aerated the soils and was captured by the 20 cm soil sampling depth (Gesch et al. 2007). Soil organic matter was higher in the perennial system in NH, the same between the systems in NY, and higher in the annual system in VT.

Table 4. 4. Differences of soil characteristics between the annual and perennial cropping systems by site. Untransformed or back-transformed means from the models are reported. Letters indicate significant differences between annual and perennial cropping systems for the soil characteristic at each site at P < 0.05 and no letters indicate no significant differences.

Soil characteristics	NY					NH					VT				
	P	Annual		Perennial		P	Annual		Perennial		P	Annual		Perennial	
pH	**<0.01**	7.92	a	7.83	b	**<0.01**	6.34	a	6.21	b	0.31	6.67		6.97	
Aggregate stability (%)	0.78	20.83		21.47		0.97	53.24		53.18		**<0.01**	37.92	a	45.91	b
Bulk density (g cm^{-3})	**<0.01**	1.29	a	1.32	b	0.21	0.33		0.28		0.11	1.45		1.43	
Gravimetric moisture (%)	**0.01**	0.17	a	0.16	b	0.18	0.21		0.21		**0.04**	0.16	a	0.13	b
Soil organic matter (%)	0.97	3.81		3.80		**0.05**	3.54		3.97		**<0.01***	4.74	a	4.22	b
K (ppm)	**<0.01**	43.06	a	66.78	b	**0.02**	105.73	a	128.00	b	0.49	47.11		48.57	
P (ppm)	**<0.01**	14.44	a	3.50	b	**0.01**	6.25	a	5.54	b	**<0.01**	5.76	a	4.33	b

*SOM was affected by a diversity*system interaction

4.4.2 Winter annuals

4.4.2.1 Crop production

An interaction between diversity treatment, site, and year was observed for winter annual crop yields ($P < 0.01$, Table 5). Pooled over diversity treatments, NY and NH both had similar yields of the winter annuals in 2017 and 2019, whereas VT had greater yields in 2017 than 2019 (7211 and 4063 kg ha^{-1}, respectively; $P < 0.01$, Table B.7). The winter annuals had the lowest levels of production in all sites in 2018 ($P < 0.01$, Table B.7). In VT, 2017 had 78% more biomass than in 2018.

Pooled over sites and years, the Heterospecific treatment produced 12% more biomass than both the Low and Conspecific treatments ($P < 0.01$, Table B.7). Yield per cost differed by diversity levels ($P < 0.01$, Table B.7). The Heterospecific treatment was more productive and produced 5.7 kg ha^{-1} more per dollar than the Low treatment. The High treatment was as productive as the Heterospecific treatment but had more expensive seed costs and thus produced 4.3 kg ha^{-1} less per dollar than the Heterospecific treatment (Table B.7). Winter annual legumes accounted for less than 1% of the yield in the Heterospecific and High treatments (Figure B.1) and were more expensive, contributing to seed costs without increasing yield.

Table 4. 5. Site, year, and diversity treatment interaction results from the ANOVA of the winter annuals on yield, yield per cost, weed biomass, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Within each site-year, a comparison of treatments with the presence or absence of intra- and interspecific diversity is also presented. Intra – absence consists of the Low and Heterospecific treatments, Intra – presence consists of the Conspecific and High treatments, Inter – absence consists of the Low and Conspecific treatments, and Inter – presence consists of the Heterospecific and High treatments. Untransformed or back-transformed means from the model are reported. The same letters within an effect term indicates no significant pairwise differences at P < 0.05. Letter absence indicates no significant differences across all pairwise comparisons of the effect term.

	Yield	Yield per cost	Weed biomass	CP	NDF		ADF	
			--------------------------------*P*--------------------------------					
Diversity	**<0.01**	**<0.01**	0.85	0.1	**<0.01**		**<0.01**	
Site	0.12	0.13	**<0.01**	**<0.01**	**<0.01**		**<0.01**	
Year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**		**<0.01**	
Diversity × site	0.63	0.71	0.29	**<0.01**	**<0.01**		**<0.01**	
Diversity × year	0.49	0.09	0.05	**<0.01**	**<0.01**		**<0.01**	
Site × year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**		**0.0**	
Diversity × site × year	0.71	0.49	**<0.01**	0.6	**0.0**		**<0.01**	
	(kg ha^{-1})	(kg ha^{-1} \$$^{-1}$)	(kg ha^{-1})		(% of DM)			
Diversity × site × year								
NY 2017								
Low	4205	16.74	9	11.4	59.6	b	35.0	bc
Conspecific	5321	25.69	3	11.6	59.5	b	34.7	c
Heterospecific	5226	24.47	10	11.0	62.8	ab	38.0	ab
High	5021	19.55	3	10.7	65.3	a	39.5	a

	Intra – absence	4716	20.605	10		11.2	61.2		36.5	
	Intra – presence	5171	22.62	3		11.2	62.4		37.1	
	Inter – absence	4763	21.215	6		11.5	59.6	b	34.9	b
	Inter – presence	5124	22.01	7		10.9	64.1	a	38.8	a
	2018									
	Low	2989	11.9	24	b	10.4	59.4		34.0	
	Conspecific	2429	11.73	38	ab	10.7	58.2		33.3	
	Heterospecific	2831	13.25	164	a	12.2	60.6		36.1	
	High	3288	12.8	70	ab	11.0	61.7		35.9	
	Intra – absence	2910	12.575	94		11.3	60.0		35.1	
	Intra – presence	2859	12.265	54		10.9	60.0		34.6	
	Inter – absence	2709	11.815	31	b	10.6	58.8		33.7	b
	Inter – presence	3060	13.025	117	a	11.6	61.2		36.0	a
	2019									
	Low	3995	15.9	192		11.1	61.7		37.0	ab
	Conspecific	4878	23.56	275		11.0	59.6		35.0	b
	Heterospecific	5416	25.36	237		11.6	63.1		38.8	a
	High	4883	19.01	361		11.0	60.5		36.1	ab
	Intra – absence	4706	20.63	215		11.4	62.4	a	37.9	a
	Intra – presence	4881	21.285	318		11.0	60.1	b	35.6	b
	Inter – absence	4437	19.73	234		11.1	60.7		36.0	
	Inter – presence	5150	22.185	299		11.3	61.8		37.5	
NH	2017									

Low	5471		21.78	0	10.9		67.6	b	40.2	b
Conspecific	4646		22.44	0	11.3		66.7	b	39.7	b
Heterospecific	5973		27.97	0	10.5		71.6	a	43.9	a
High	5710		22.23	0	10.6		72.0	a	44.0	a
Intra – absence	5722		24.875	0	10.7		69.6		42.1	
Intra – presence	5178		22.335	0	11.0		69.4		41.9	
Inter – absence	5059	b	22.11	0	11.1		67.2	b	40.0	b
Inter – presence	5842	a	25.1	0	10.6		71.8	a	44.0	a
2018										
Low	4536		18.06	3	6.8		67.2	a	41.4	a
Conspecific	4114		19.86	1	7.5		67.8	a	42.9	a
Heterospecific	4536		21.24	0	7.8		63.3	b	38.1	b
High	4316		16.8	1	8.4		61.9	b	36.4	b
Intra – absence	4536		19.65	2	7.3		65.3		39.8	
Intra – presence	4215		18.33	1	8.0		64.9		39.7	
Inter – absence	4325		18.96	2	7.2	b	67.5	a	42.2	a
Inter – presence	4426		19.02	1	8.1	a	62.6	b	37.3	b
2019										
Low	5469		21.77	39	11.3		69.3	a	41.5	a
Conspecific	5325		25.71	12	11.2		67.0	ab	41.5	a
Heterospecific	6403		29.99	14	10.5		62.7	c	35.8	b
High	6228		24.25	6	11.2		64.7	bc	38.8	a
Intra – absence	5936		25.88	27	10.9		66.0		38.7	

	Intra – presence	5777		24.98		9		11.2		65.9		40.2	
	Inter – absence	5397	b	23.74	b	26		11.3		68.2	a	41.5	a
	Inter – presence	6316	a	27.12	a	10		10.9		63.7	b	37.3	b
VT	2017												
	Low	6592		26.25		32	a	17.5		43.6	b	28.5	c
	Conspecific	6852		33.09		0	b	17.0		46.7	b	29.5	c
	Heterospecific	7801		36.53		43	a	15.9		51.0	a	32.7	b
	High	7601		29.59		57	a	14.7		54.3	a	36.1	a
	Intra – absence	7197		31.39		38		16.7	a	47.3	b	30.6	b
	Intra – presence	7227		31.34		29		15.9	b	50.5	a	32.8	a
	Inter – absence	6722	b	29.67		16	b	17.3	a	45.2	b	29.0	b
	Inter – presence	7701	a	33.06		50	a	15.3	b	52.7	a	34.4	a
	2018												
	Low	1689		6.72		69		13.8		50.8	b	27.5	b
	Conspecific	1278		6.17		97		13.7		50.2	b	27.6	b
	Heterospecific	1878		8.79		23		13.5		53.6	ab	30.7	a
	High	1373		5.35		37		13.4		55.3	a	31.9	a
	Intra – absence	1784		7.755		46		13.7		52.2		29.1	
	Intra – presence	1326		5.76		67		13.6		52.8		29.8	
	Inter – absence	1484		6.445		83	a	13.8		50.5	b	27.6	b
	Inter – presence	1626		7.07		30	b	13.5		54.5	a	31.3	a
	2019												

Low	3922	15.61	73	ab	18.8		52.9	b	30.2	b
Conspecific	3956	19.1	130	a	16.6		55.1	ab	30.9	ab
Heterospecific	3882	18.18	35	ab	18.1		54.9	ab	29.2	b
High	4494	17.5	27	b	16.8		58.5	a	33.3	a
Intra – absence	3902	16.895	54		18.5	a	53.9	b	29.7	b
Intra – presence	4225	18.3	79		16.7	b	56.8	a	32.1	a
Inter – absence	3939	17.355	102	a	17.7		54.0	b	30.6	
Inter – presence	4188	17.84	31	b	17.5		56.7	a	31.3	

4.4.2.2 Weed biomass

Weed biomass was affected by diversity treatments in particular sites and years but with no consistent trends in the three-way interaction ($P < 0.01$, Table 5). Weed biomass was generally low in the winter annuals and ranged from 24 to 30 kg ha^{-1} in the Conspecific and Low treatments, respectively ($P = 0.85$, Table B.7). Weed biomass tended to increase over time, driven in part by NY, where weed biomass increased each year and had a 98% increase from 2017 to 2019 ($P < 0.01$, Table B.7). No differences were seen in 2017 or 2019 in NY, but in 2018, the Low treatment had an order of magnitude less weeds than the Heterospecific treatment ($P < 0.01$, Table 5). No differences were seen in weed biomass across diversity treatments in NH in any year. In 2017 VT, the Conspecific treatment had no reported weeds, likely due to sampling error. In 2019 in VT, the High treatment had an order of magnitude fewer weeds than the Conspecific treatment. No differences were seen between the presence and absence of intraspecific diversity, and the differences of the presence and absence of interspecific diversity were mixed. In the winter annuals, the most common weeds were *Veronica peregrina* L., *Stellaria media* (L.) Vill., and *Silene latifolia* Poir. for NH, NY, and VT, respectively (Table B.8).

4.4.2.3 Forage quality

Site and year had greater effects on forage quality than the diversity treatments in the winter annuals (Tables 5 and B.7). Pooled over sites and years, crude protein levels did not differ by diversity treatment ($P = 0.14$) and ranged from 12 % of dry matter in the High treatment to 12.4 % of dry matter in the Low and Heterospecific treatments

(Table B.7). In five out of the nine site-years, the High treatment had greater NDF and ADF content than the Low treatment ($P < 0.01$, Table 5). Neutral detergent fiber ranged from 59 % of dry matter in the Conspecific treatment to the 61.6 % of dry matter in the High treatment ($P < 0.01$, Table B.7). The High treatment also had 1.9 % of dry matter more ADF than both the Low and Conspecific treatments ($P < 0.01$, Table B.7).

4.4.3 Summer annuals

4.4.3.1 Crop production

An interaction between diversity treatment, site, and year was observed for summer annual crop yields ($P < 0.01$, Table 6). In 2017, in NY and NH a wet spring delayed growth and then drier conditions stunted growth in late summer. When pooled over sites and diversity treatments, crop production was 59% greater in 2018 than 2017 ($P < 0.01$, Table B.9). Pooled over years and diversity treatments, NY (6492 kg ha^{-1}) and VT (5974 kg ha^{-1}) had greater yields than NH (4573 kg ha^{-1}). Across all sites and years, yield of the summer annuals ranged from 5295 kg ha^{-1} in the Low treatment to 5838 kg ha^{-1} in the High treatment ($P = 0.45$, Table B.9). In NY in 2018, the Conspecific treatment was 16% more productive than the High treatment, and the treatments that did not have interspecific diversity were more productive than those that did (Table 6). No differences were seen in diversity treatments in either year in NH (Table 6). In VT in 2017, the Heterospecific and High treatments were more productive than the Low and Conspecific treatments. The High treatment was 53% more productive than the Low treatment (Table 6).

The yield of summer annuals was dominated by sudangrass and sorghum sudangrass (Figure B.2). The annual ryegrass was often outcompeted due to its smaller stature. Observationally, it appeared more frequently along plot edges, likely where light competition was reduced. Pearl millet was less productive than the sudangrass and sorghum sudangrass in NY and VT but produced similar amounts of biomass to the sudangrass and sorghum sudangrass in NH (Figure B.2).

The diversity treatments that only contained sudangrass were less cost efficient than the treatments which contained other species that had lower seed costs ($P < 0.01$, Table B.9). Pooled over sites and years, the Heterospecific treatment produced 22 kg ha^{-1} more biomass per dollar than the Low treatment. In four out of six site-years, the Heterospecific and High treatments were more economical than the Low treatment ($P < 0.01$, Table 6). This trend was partially attributed to the Hayking cultivar used in the Low treatment which may have been more expensive because it was a brown midrib variety (Table B.1). In four of the nine site-years, yield per cost was greater in treatments that contained interspecific diversity than those that only contained sudangrass.

Table 4. 6. Site, year, and diversity treatment interaction results from the ANOVA of the summer annuals on yield, yield per cost, weed biomass, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Within each site-year, a comparison of treatments with the presence or absence of intra- and interspecific diversity is also presented. Intra – absence consists of the Low and Heterospecific treatments, Intra – presence consists of the Conspecific and High treatments, Inter – absence consists of the Low and Conspecific treatments, and Inter – presence consists of the Heterospecific and High treatments. Untransformed or back-transformed means from the model are reported. The same letters within an effect term indicates no significant pairwise differences at P < 0.05. Letter absence indicates no significant differences between all pairwise comparison within an effect term.

	Yield	Yield per cost	Weed biomass	CP	NDF		ADF
			---------------------------------*P*---------------------------------				
Diversity	0.45	**<0.01**	**0.01**	0.50	**<0.01**		0.06
Site	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**		**<0.01**
Year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	0.06		**<0.01**
Diversity × site	**<0.01**	**<0.01**	0.06	0.10	**<0.01**		0.14
Diversity × year	**0.04**	**<0.01**	0.08	**<0.01**	0.64		0.23
Site × year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**		**<0.01**
Diversity × site × year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**		**<0.01**
	($kg\ ha^{-1}$)	($kg\ ha^{-1}\ \$^{-1}$)	($kg\ ha^{-1}$)		(% of DM)		
Diversity × site × year							
NY 2017							
Low	1713	6.97	747	9.6	61.2	ab	40.8
Conspecific	1987	9.26	587	9.7	63.5	a	41.2
Heterospecific	1228	9.15	682	10.1	58.7	b	38.9
High	1559	9.64	623	9.0	63.1	a	41.9

	Intra – absence	1470		8.06		714		9.8		60.0	b	39.8	b
	Intra – presence	1773		9.45		605		9.4		63.3	a	41.6	a
	Inter – absence	1850		8.12		667		9.7		62.3		41.0	
	Inter – presence	1393		9.40		652		9.5		60.9		40.4	
	2018												
	Low	11586	ab	47.11	c	694	ab	14.5		64.4		38.5	
	Conspecific	12412	a	57.86	b	370	bc	14.3		63.6		37.0	
	Heterospecific	11080	ab	82.61	a	752	a	13.9		64.3		37.8	
	High	10368	b	64.13	b	267	c	13.7		65.5		38.2	
	Intra – absence	11333		64.86		723	a	14.2		64.3		38.1	
	Intra – presence	11390		61.00		319	b	14.0		64.5		37.6	
	Inter – absence	11999	a	52.49	b	532		14.4	a	64.0		37.8	
	Inter – presence	10724	b	73.37	a	510		13.8	b	64.9		38.0	
NH	2017												
	Low	3093		12.58		2503		11.7		61.7	a	40.6	
	Conspecific	3271		15.25		1957		12.2		63.0	a	40.7	
	Heterospecific	2850		21.25		2303		11.8		60.5	ab	39.9	
	High	2258		13.97		2501		12.6		57.7	b	38.3	
	Intra – absence	2972		16.91		2403		11.8	b	61.1		40.3	
	Intra – presence	2765		14.61		2229		12.4	a	60.3		39.5	
	Inter – absence	3182		13.91		2230		12.0		62.3	a	40.7	a
	Inter – presence	2554		17.61		2402		12.2		59.1	b	39.1	b
	2018												

		Low	5812		23.63	c	1295		16.3	b	56.5	a	33.4	a
		Conspecific	6615		30.84	bc	998		16.4	b	55.2	a	31.4	ab
		Heterospecific	6581		49.07	a	913		17.8	a	51.8	b	29.0	c
		High	6103		37.75	b	1121		16.5	b	51.8	b	30.4	bc
		Intra – absence	6197		36.35		1104		17.0	a	54.2		31.2	
		Intra – presence	6359		34.29		1059		16.4	b	53.5		30.9	
		Inter – absence	6213		27.23	b	1146		16.3	b	55.8	a	32.4	a
		Inter – presence	6342		43.41	a	1017		17.1	a	51.8	b	29.7	b
VT	2017													
		Low	3535	b	14.37	b	958	a	16.1		53.8		29.9	
		Conspecific	4143	b	19.31	b	532	ab	16.1		53.5		29.9	
		Heterospecific	6332	a	47.21	a	258	c	16.0		53.7		30.2	
		High	7544	a	46.66	a	337	bc	16.0		53.8		30.3	
		Intra – absence	4933		30.79		608		16.0		53.7		30.0	
		Intra – presence	5843		32.99		434		16.1		53.6		30.1	
		Inter – absence	3839	b	16.84	b	745	a	16.1		53.6		29.9	
		Inter – presence	6938	a	46.93	a	298	b	16.0		53.7		30.2	
	2018													
		Low	6033		24.53	b	375		15.7	a	55.7		32.5	
		Conspecific	6326		29.49	b	360		14.4	b	57.5		33.7	
		Heterospecific	6682		49.82	a	294		15.5	ab	55.2		31.9	
		High	7196		44.51	a	252		15.9	a	55.4		32.2	
		Intra – absence	6326		29.49		360		14.4		57.5		33.7	

Intra – presence	6357	37.17		334	15.6		55.4	32.2
Inter – absence	6033	24.53	b	375	15.7	a	55.7	32.5
Inter – presence	6504	39.66	a	327	14.9	b	56.4	32.8

4.4.3.2 Weed biomass

Weed biomass differed by diversity treatments specific to site and year (P < 0.01, Table 6). In four out of six site-years no differences were seen in weed biomass by diversity treatment (Table 6). In NY in 2018, the Low and Heterospecific treatments produced more weeds than the Conspecific and High treatments (P < 0.01, Table 6). In 2017 in VT, the Heterospecific and High treatments produced more weeds than the Low and Conspecific treatments (P < 0.01, Table 6). Pooled over years and diversity treatments, NH had about three and four times more weeds than NY and VT, respectively (P < 0.01, Table B.9). Weed biomass in the summer annuals was greater in 2017 than 2018, likely due to slower canopy closure because of less favorable growing conditions (P < 0.01, Table B.9) with 38 % more weeds in 2017 than 2018. In the summer annuals, the most common weeds were *Chenopodium album* L., *Ambrosia artemisiifolia* L. and *Galinsoga quadriradiata* Cav. for NH, NY, and VT, respectively (Table B.8).

4.4.3.3 Forage quality

Growing conditions, represented by site and year, had greater effects on CP and ADF than diversity treatments in the summer annuals likely due to sudangrass, sorghum sudangrass, and pearl millet being at similar vegetative growth stages when harvested (Table 6). Pooled over sites and years, CP ranged from 13.8 % of dry matter in the Conspecific treatment and 14.2 % of dry matter in the Heterospecific treatment (P = 0.50, Table B9). No differences in CP concentration were observed in four of the six site-years (P < 0.01, Table 6). No differences in NDF concentration were seen in three of the six site-years (P < 0.01, Table 6). Pooled over sites and years, the Conspecific treatment had greater NDF than the Heterospecific and High treatments and the Low treatment had greater NDF than the Heterospecific treatment and ranged from 57.4 % of dry matter in the Heterospecific treatment to 59.4 % of the dry matter in the Conspecific treatment (P < 0.01, Table 6). Pooled over sites and years, no differences were seen in ADF levels by diversity treatments in summer annuals and ranged from 34.6 % of dry matter in the Heterospecific treatment to 35.9 % of dry matter in the Low treatment (P = 0.06, Table B9). In NH in both years, treatments that contained interspecific diversity had lower ADF than those that did not (Table 6). In 2018 in NH, however, the Low and the Conspecific had higher ADF than the Heterospecific treatment and the Low treatment had more ADF than the High treatment (P < 0.01, Table 6).

4.4.4 Perennials

In the establishment year, growing conditions in the perennial system were challenging. A mild winter and a wet spring reduced the growth of alfalfa, increased the incidences of common leaf spot (*Pseudopeziza medicaginis*), and made the alfalfa especially vulnerable to potato leaf hopper (*Empoasca fabae*) in all sites (Table 3). Consequently, in 2017, the first perennial cut had alfalfa with small leaves and tough stems and the second cut of alfalfa was also stressed with small growth and visibly damaged leaves. To ensure the stand would survive the winter, all sites opted not to take a third cut in the fall of 2017 (Table 2). In 2018, four cuts were taken in NH and NY, and three cuts were taken in VT which faced drier conditions.

4.4.4.1 Crop production

The perennial yield consisted mostly of alfalfa and orchardgrass (Figure 2). Generally, alfalfa productivity declined but overall productivity increased with the addition of other species in the Heterospecific and High diversity treatments. In the first year, timothy comprised approximately 33 % of perennial yield in 2017, but this fell to about 1 % in subsequent years. The harvest threshold was based on alfalfa, leading to the harvest of timothy during stem elongation when it is in a vulnerable period of growth (Barnes et al., 2003).

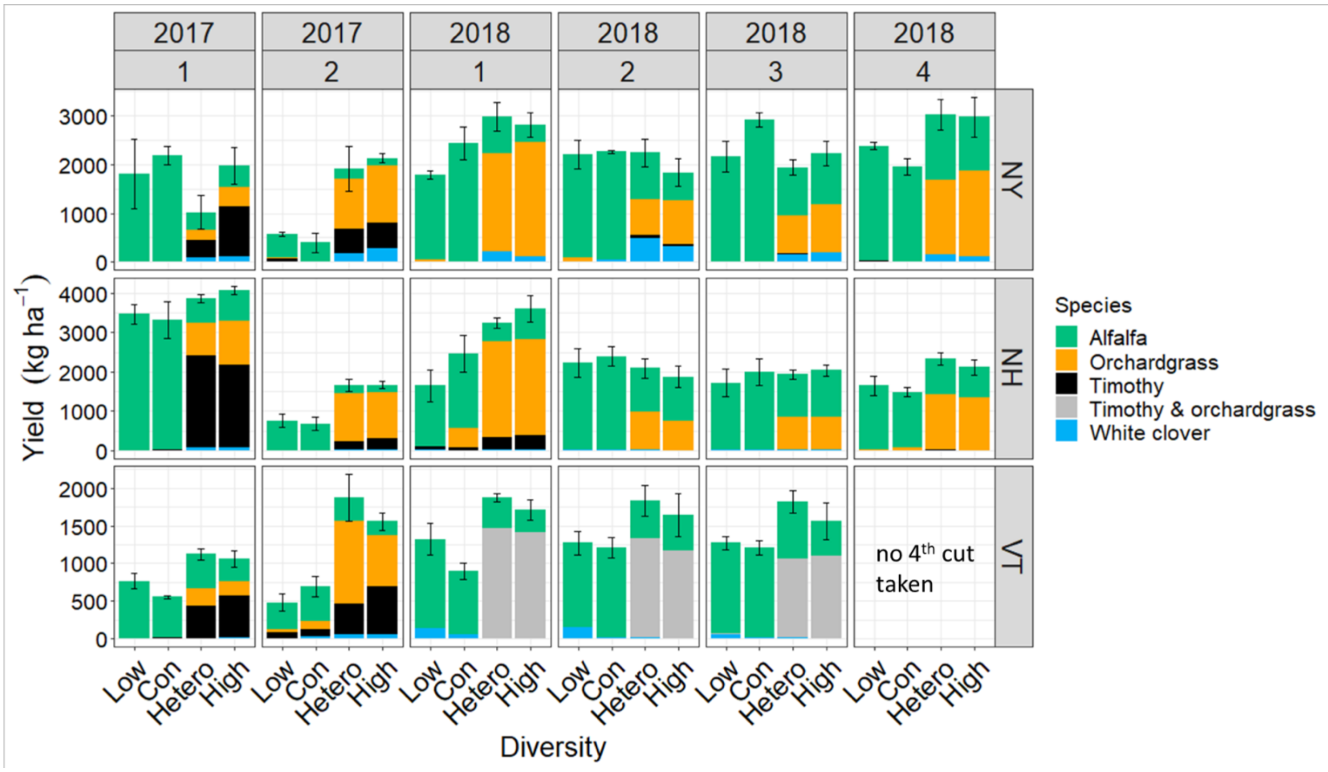

Figure 4. 2. Stacked bar charts of yield by species for each harvest of the perennials. Numbers in the panel beneath the year refer to the number of cuts. Standard error bars reflect the variability of total yield in each diversity level. Con and Hetero refer to Conspecific and Heterospecific diversity treatments..

An interaction between diversity treatment, site, and year was observed for perennial crop yields ($P < 0.01$, Table 7). Crop production of the perennials was greater in diversity treatments that had interspecific diversity in all six site-years (Table 7). No differences were seen between presence and absence of intraspecific diversity (Table 7). In NY in 2017, the High treatment was 41 % more productive than the Low treatment ($P < 0.01$, Table 7). In NY in 2018, differences amongst diversity treatments were less stark. The Heterospecific treatment was 16 % more productive than the Low treatment. In NH in 2017, the Heterospecific and High treatments were more productive than the Conspecific treatment ($P < 0.01$, Table 7) and the High treatment was 26 and 31 % more productive than the Low and Conspecific treatments, respectively ($P < 0.01$, Table 7). In NH in 2018, the Heterospecific and High treatments were both 25 % more productive than the Low treatment. In VT in 2017, the Heterospecific treatment was 58 % more productive than both the Low and Conspecific treatments ($P < 0.01$, Table 7). In VT in 2018, the High treatment was 32 % more productive than the Conspecific treatment and the Heterospecific treatment was 30 and 40 % more productive than the Low and the Conspecific treatments, respectively ($P < 0.01$, Table 7). Pooled across diversity treatments and years, NY and NH were about twice as productive as VT ($P < 0.01$, Table B.10). Pooled across diversity treatments and sites, production of perennials was 56 % greater in 2018 than 2017 ($P < 0.01$, Table B.10). Pooled across sites and years, the Heterospecific and High treatments were more productive than the Low and Conspecific treatments ($P < 0.01$, Table B.10). When pooled over sites and years, the High treatment was 25 % more productive than the Low treatment (P =0.45, Table B.10).

Apart from NY in 2017, treatments than contained interspecific diversity (i.e., grasses) were more economical than those that only contained alfalfa (Table B.10). In all site-years, the High treatment was more economical than the Low treatment and produced about 30 kg ha^{-1} more biomass per dollar ($P < 0.01$, Table 7). In both years in NY and NH, the High treatment was more economical than the Heterospecific treatment.

Table 4. 7. Site, year, and diversity treatment interaction results from the ANOVA of the perennials on yield, yield per cost, weed biomass, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Within each site-year, a comparison of treatments with the presence or absence of intra- and interspecific diversity is also presented. Intra – absence consists of the Low and Heterospecific treatments, Intra – presence consists of the Conspecific and High treatments, Inter – absence consists of the Low and Conspecific treatments, and Inter – presence consists of the Heterospecific and High treatments. Untransformed or back-transformed means from the model are reported. The same letters within an effect term indicates no significant pairwise differences at P < 0.05. Letter absence indicates no significant differences between all pairwise comparison within an effect term.

	Yield		Yield per cost		Weed biomass		CP		NDF		ADF	
	---------------------------------*P*---------------------------------											
Diversity	**<0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**	
Site	**<0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**	
Year	**<0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**	
Diversity × site	0.70		**<0.01**		**<0.01**		**0.02**		**<0.01**		**<0.01**	
Diversity × year	**0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**	
Site × year	**<0.01**		**<0.01**		0.37		**<0.01**		**<0.01**		**<0.01**	
Diversity × site × year	**0.02**		**<0.01**		**<0.01**		**<0.01**		**<0.01**		**<0.01**	
	($kg\ ha^{-1}$)		($kg\ ha^{-1}\ \$^{-1}$)		($kg\ ha^{-1}$)				(% of DM)			
Diversity × site × year												
NY 2017												
Low	2384	b	7.57	c	1751	a	12.4	b	56.1	b	41.7	ab
Conspecific	2345	ab	11.35	bc	2154	a	14.9	a	50.9	c	39.4	b
Heterospecific	2933	ab	16.25	b	658	b	11.5	b	57.6	b	41.0	ab
High	4103	a	29.95	a	1049	ab	11.2	b	61.5	a	42.9	a

	Intra – absence	2658		11.91	b	1204		11.9	b	56.9		41.3	
	Intra – presence	3224		20.65	a	1601		13.0	a	56.2		41.1	
	Inter – absence	2364	b	9.46	b	1953	a	13.6	a	53.5	b	40.6	b
	Inter – presence	3518	a	23.10	a	853	b	11.3	b	59.6	a	41.9	a
	2018												
	Low	8531	b	27.08	d	1658	a	12.1	a	20.3		14.7	ab
	Conspecific	9335	ab	44.99	c	1608	a	13.1	a	20.9		15.8	a
	Heterospecific	10193	a	56.48	b	305	b	9.5	b	19.9		13.2	b
	High	9860	ab	71.96	a	388	b	8.8	b	21.7		13.5	ab
	Intra – absence	9362		41.78	b	981		10.8		20.1		13.9	
	Intra – presence	9597		58.48	a	998		11.0		21.3		14.7	
	Inter – absence	8933	b	36.04	b	1633	a	12.6	a	20.6		15.2	a
	Inter – presence	10026	a	64.22	a	347	b	9.2	b	20.8		13.3	b
NH	2017												
	Low	4230	bc	13.43	c	1284	a	15.9	a	52.8	b	39.5	ab
	Conspecific	3985	c	19.18	c	1242	a	15.2	a	51.7	b	38.9	b
	Heterospecific	5522	ab	30.60	b	139	b	10.5	b	61.5	a	39.9	ab
	High	5743	a	41.91	a	51	c	9.9	b	63.7	a	41.5	a
	Intra – absence	4876		22.01	b	712	a	13.2		57.1		39.7	
	Intra – presence	4864		30.55	a	647	b	12.6		57.7		40.2	
	Inter – absence	4107	b	16.30	b	1263	a	15.5	a	52.3	b	39.2	b
	Inter – presence	5632	a	36.26	a	95	b	10.2	b	62.6	a	40.7	a

	2018													
	Low	7240	b	22.98	d	1190	a	15.5		60.8	a	34.9		
	Conspecific	8327	ab	40.07	c	1215	a	15.6		60.9	a	35.0		
	Heterospecific	9611	a	53.25	b	46	b	16.0		56.0	b	35.0		
	High	9624	a	70.24	a	19	b	16.9		55.0	b	34.2		
	Intra – absence	8425		38.12	b	618		15.7		58.4		34.9		
	Intra – presence	8975		55.16	a	617		16.3		57.9		34.6		
	Inter – absence	7783	b	31.53	b	1202	a	15.6	b	60.8	a	34.9		
	Inter – presence	9617	a	61.74	a	32	b	16.4	a	55.5	b	34.6		
VT	2017													
	Low	1250	b	3.97	b	1019	ab	19.2	a	42.9	c	33.1	bc	
	Conspecific	1248	b	6.01	b	1215	a	19.0	a	43.2	c	33.0	c	
	Heterospecific	2995	a	16.59	a	346	c	15.6	b	54.2	b	35.5	ab	
	High	2614	ab	19.08	a	437	bc	13.9	b	58.0	a	37.7	a	
	Intra – absence	2122		10.28		682		17.4	a	48.6	b	34.3		
	Intra – presence	1931		12.54		826		16.4	b	50.6	a	35.4		
	Inter – absence	1249	b	4.99	b	1117	a	19.1	a	43.1	b	33.1	b	
	Inter – presence	2805	a	17.84	a	392	b	14.8	b	56.1	a	36.6	a	
	2018													
	Low	3865	bc	12.27	b	1939	a	20.5	a	31.1	c	22.9	c	
	Conspecific	3321	c	15.99	b	2423	a	21.5	a	36.3	b	25.9	b	
	Heterospecific	5527	a	30.63	a	43	b	17.8	b	48.8	a	30.5	a	
	High	4905	ab	35.80	a	59	b	17.3	b	49.9	a	30.9	a	

Intra – absence	4696		21.45	b	991		19.1		40.0	b	26.7	b
Intra – presence	4113		25.89	a	1241		19.4		43.1	a	28.4	a
Inter – absence	3593	b	14.13	b	2181	a	21.0	a	33.7	b	24.4	b
Inter – presence	5216	a	33.21	a	51	b	17.5	b	49.4	a	30.7	a

4.4.4.2 Weed biomass

Weed biomass differed by diversity treatment within sites and years ($P < 0.01$, Table 7). In five of the six site-years, the Heterospecific and High treatments had less weeds than the Low and Conspecific treatments in the perennials ($P < 0.01$, Table 7). In all six site-years, treatments that contained interspecific diversity had less weeds than those that did not, whereas, lower weed biomass was seen in the presence of intraspecific diversity only in NH 2017 (Table 7). In 2017 in NY, weed biomass of the Low and the Conspecific treatments was 2.7 and 3.3 times greater than in the Heterospecific treatment, respectively. In 2017 in NH, Heterospecific and the High treatments produced less weeds than the Low and the Conspecific treatments and the Heterospecific treatment produced 2.7 times greater weed biomass than the High treatment ($P < 0.01$, Table 7). In 2017 in VT, weed biomass of the Low and Conspecific treatments was 2.9 and 2.8 times greater than the Heterospecific treatment, respectively ($P < 0.01$, Table 7). Greater differences in weed biomass amongst diversity treatments were seen over time, suggesting that the weed abundance was affected by crop management as the experiment progressed. In the perennials, the most common weeds were *Digitaria ischaemum* (Schreb.) Schreb. ex Muhl., *Taraxacum officinale* F. H. Wigg, and *Silene latifolia* Poir. in NH, NY, and VT, respectively (Table B.8). To summarize, when pooled across sites and years, the Low and Conspecific treatments in the perennials had an order of magnitude more weed biomass than the Heterospecific and High treatments ($P < 0.01$, Table B.10). Pooled across diversity treatments and years, New York had 73 and 51 % more weeds than

NH and VT, respectively (P < 0.01) and the perennials had 42 % more weeds in 2017 than 2018 (P < 0.01, Table B.10).

4.4.4.3 Forage quality

Differences in forage quality were largely driven by growing conditions but addition of grasses in the Heterospecific and High treatments significantly affected forage quality (Table 7). In four of six site-years, CP concentration was greater in the Low and Conspecific than the Heterospecific and High treatments (P < 0.01, Table 7). Pooled across sites and years, the Low and Conspecific treatments had higher CP than the Heterospecific and High diversity treatments and ranged from 13 % in the High treatment to 16.5 % in the Conspecific treatment (P < 0.01, Table B.10). Neutral detergent fiber was lower in the Low and Conspecific treatments than the High treatment in four of the six site-years (P < 0.01, Table 7). In 2018 NY, no differences were seen amongst diversity treatments but NDF was quite low because the first and fourth harvests were not included in the forage quality analysis due to mold. These cuts typically had higher grass content likely contributed to higher NDF (Figure 2) as grasses typically have higher fiber concentrations compared to legumes (Buxton and Redfearn 1997). Pooled over sites and years, NDF was lowest in the Low and Conspecific treatments (both 44% of dry matter) and greatest at 51.7% in the High treatment (P < 0.01, Table B.10). Pooled over sites and years, ADF ranged from 31.1 % in the Low treatment to 33.4 % in the High treatment (P < 0.01, Table B.10). Four of the six site-years, ADF was greater in treatments that contained interspecifc diversity (Table 7).

4.4.5 Yield variability and temporal diversification

Yield stability of diversity treatments was evaluated using coefficient of variation and results show that diversity treatment ranking varied by crop type. Crop production varied the least in the winter annuals across all diversity treatments. The CV for the winter annuals were 0.21, 0.20, 0.18, and 0.21 for the Low, Conspecific, and Heterospecific, and High treatments, respectively. For the summer annuals, the CVs were 0.27, 0.35, 0.25, and 0.25 for the Low, Conspecific, and Heterospecific, and High treatments, respectively. The Conspecific treatment in the summer annuals had the greatest variability across all crops. The perennials had the greatest difference in variability between the treatments with or without interspecific diversity. The CV for the perennials were 0.31, 0.28, 0.22, and 0.22 for the Low, Conspecific, and Heterospecific, and High treatments, respectively.

Yield stability of diversity treatments was also evaluated across the variety of growing conditions. Here, growing conditions were proxied by the environmental mean effect term (Table 8, Figure 3). For the winter annuals, the Heterospecific treatment produced greater biomass than the Conspecific treatment in sub-optimal conditions (20^{th} percentile of the environmental mean) (Table 8, Figure 3a). In average (50^{th} percentile) and optimal (80^{th} percentile) conditions, the Heterospecific and High treatments outperformed the Low and Conspecific treatments. In the summer annuals, low-yielding environments, the Low diversity treatment did worse than treatments that had intra-or interspecific diversity (Table 8, Figure 3b). This was likely driven by the sampling effect, that diversity increased the likelihood of including a cultivar or species that could better respond to the environment. No differences were seen across diversity treatments in optimal or high-yielding environments. In the perennials, the Heterospecific and High treatments outperformed the Low and Conspecific treatments across all environments (Table 8, Figure 3c).

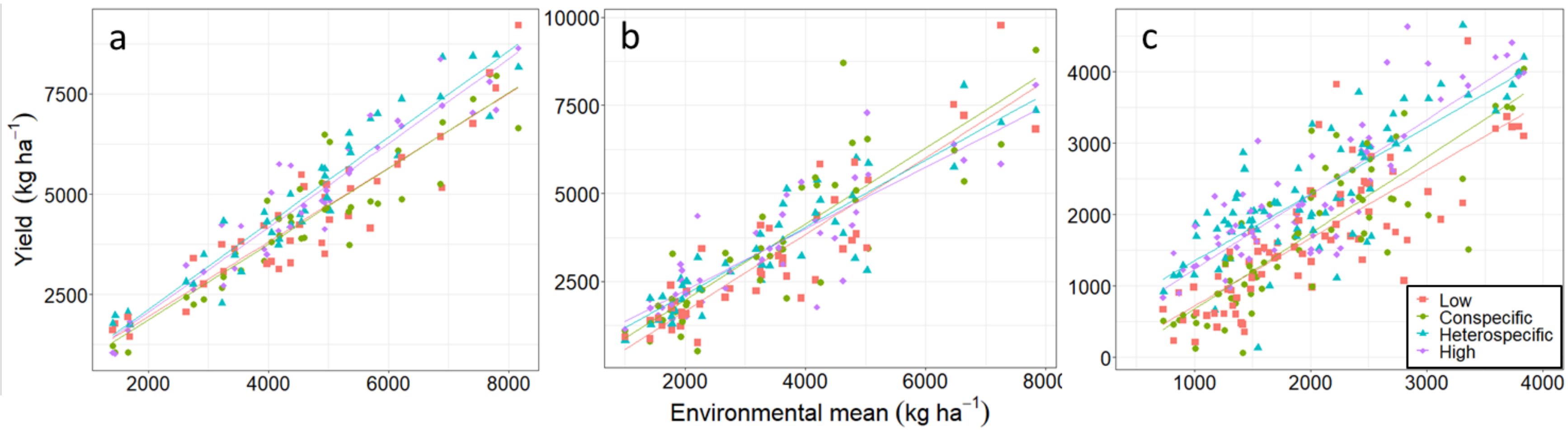

Figure 4. 3. Environmental stability regressions between the environmental mean and the yield of the diversity treatment for each block-harvest of (a) winter annuals, (b) summer annuals, and (c) perennials.

Table 4. 8. The environmental stability regressions by diversity treatments for each crop that correspond to Figure 5. Regressions of diversity treatments are compared at the 20th, 50th, and 80th percentiles of each crop's environmental mean. Same letters indicate no significant differences between diversity treatments for each environmental mean percentile at P < 0.05, and no letters indicate no significant differences among diversity treatments within an environmental mean percentile. R^2 presented is the adjusted R^2.

Crop	Diversity	P	R^2	Slope	Intercept	Predicted biomass (kg ha^{-1}) based on growing conditions		
						20th	50th	80th
Winter annuals	Low	<0.01	0.86	9.3	101.1	3092 ab	4319 b	5803 b
	Conspecific	<0.01	0.85	9.5	-26.8	3024 b	4275 b	5788 b
	Heterospecific	<0.01	0.91	10.7	-23.0	3444 a	4867 a	6587 a
	High	<0.01	0.9	10.5	-51.3	3350 ab	4745 a	6433 a
Summer annuals	Low	<0.01	0.8	10.9	-528.0	1485 b	3030 a	4686 a
	Conspecific	<0.01	0.73	10.8	-193.0	1801 ab	3332 a	4972 a
	Heterospecific	<0.01	0.81	9.5	231.0	1988 ab	3337 a	4782 a
	High	<0.01	0.73	8.8	489.9	2106 a	3347 a	4676 a
Perennials	Low	<0.01	0.65	9.5	-232.5	1011 b	1559 b	2167 b
	Conspecific	<0.01	0.72	10.6	-388.6	1003 b	1615 b	2295 b
	Heterospecific	<0.01	0.64	9.4	410.0	1637 a	2177 a	2777 a
	High	<0.01	0.73	10.5	183.1	1554 a	2159 a	2828 a

In the perennial system, temporal diversification occurred over harvests within a growing season as evidenced by the change in percent alfalfa and grasses in the Heterospecific and High diversity treatments (Table 9). In 2017, which had fewer harvests, percent alfalfa generally decreased between the 1st and 2nd cuts as the cool, wet spring delayed growth and the infestation of potato leaf hopper decreased biomass. No differences in percent grass was across cuts in NY and NH in 2017. In VT in 2017, percent grass was lower in the first cut than the second. After the establishment year, the percent alfalfa increased after the first cut. New Hampshire had the most pronounced differences across cuts ($P < 0.01$, Table 9), but numerically percent alfalfa was lower in the 4th cut for NH and NY than in the 2nd and 3rd cuts. In 2018, percent grass biomass was highest in the first cut at all three sites and generally was lower in the middle cuts (Table 9). White clover which made up the difference between alfalfa and perennial grasses generally ranged between 0.38 and 11.7 % but did reach 20 % in the second cut of NY in 2018 (data not shown).

Table 4. 9. Percent of alfalfa and grasses in the perennial biomass of Heterospecific and High diversity treatments differed by cut. Same letters indicate no significant differences of percent alfalfa between cuts for each site at $P < 0.05$, and no letters indicate no significant differences of percent alfalfa and grasses.

Year	Location	P	Percent (%) by cut							
						Alfalfa				
			1st		2nd		3rd		4th	
2017	NY	0.02	27.1	a	11	b				
	NH	0.11	15.4		12.7					
	VT	0.01	39.9	a	15.6	b				
2018	NY	<0.01	19.2	b	35.8	ab	48	a	39	a
	NH	<0.01	18.4	c	55.3	a	55.9	a	36.5	b
	VT	0.02	19.5	b	26.9	ab	33.7	a		
						Grasses				
2017	NY	0.11	66.1		77.3					

	NH	0.20	85.5		83.1					
	VT	0.01	80.6	a	63.9	b				
2018	NY	<0.01	74.9	a	44.2	b	43.3	b	56.8	ab
	NH	<0.01	81.2	a	44.3	c	43.3	c	63.2	b
	VT	0.02	80.1	a	72.6	ab	65.8	b		

4.5 Discussion

We implemented three diversification strategies that dairy farmers in the Northeast could quickly adopt using species and cultivars commonly grown for forage production in the region. Many of the benefits of crop diversity seen in our results can likely be attributed to the sampling effect, which is the increased likelihood of including a species/cultivar that has a high impact on the ecosystem functioning as the selection pool expands (e.g. orchardgrass is known to be more productive and have less expensive seed than alfalfa) (Huston 1997, Tilman et al. 2013, Barot et al. 2017). Instead of endeavoring to quantify the sampling effect by growing each species separately (Loreau and Hector 2001), we leveraged the sampling effect by selecting particular species and cultivars for mixtures that had potentially useful traits and compared them to an agronomically justifiable single cultivar monoculture. We found partial support for our hypothesis that strategies with greater crop diversity would have higher and more stable yields, lower weed biomass, improved forage quality and greater economic performance than treatments with lower diversity. In the summer annuals and perennials, the implemented diversification strategies resulted in improvements in many of measured variables, whereas in the winter annuals the diversification strategy applied did not result in the expected benefits.

4.5.1 Diversification strategy of multiple species complicated forage production of winter annuals

Our approach in the winter annuals had mixed success with greater yields when triticale was grown with other species, but no difference in weed biomass and lower forage quality. The legumes did not perform well and limited our ability to draw conclusions about our intended diversity strategy. We attribute this to dominance of the grasses due to planting dates, seeding rates, and fertility, but potentially difficulties of winter survival. Winter annual legumes generally establish better when planted in late summer (Schipanski and Drinkwater 2011) and three of the nine planting dates fell in the second half of September. The replacement seeding rates likely contributed to the competitive advantage of the grasses, and greater diversity might have been expressed if lower grass seeding rates and greater legume seeding rates were used (White et al. 2015). Our triticale-based fertility management also likely conditioned the legumes to be outcompeted, as legumes are more competitive with grasses in low fertility soils (Brainard et al. 2011). Management aside, efforts are underway to breed more cold-tolerant winter annual legumes to improve winter survival (Kucek et al. 2019).

As a result of poor performance of the legumes, triticale and cereal rye dominated. Under poor growing conditions triticale and cereal rye performed similarly, but under more favorable conditions, the productivity of cereal rye outperformed triticale. Cereal rye was often a larger plant that matured earlier than the triticale and was less expensive, thus, the Heterospecific diversity treatment was the most economical. Yet, weed biomass was not lower in higher diversity treatments and was generally low for all diversity treatments. The staggered maturity in treatments containing triticale and cereal rye resulted in lower quality feed and potentially more difficult harvest decisions by the farmer.

4.5.2 Diversification strategy of multiple species in summer annuals reduced weed biomass and provided yield advantage

In the summer annuals, additional species to sudangrass resulted in greater yields in poor growing conditions, increased yield stability, reduced weed biomass, and increased the economic performance. Increasing diversity did not affect crop productivity or forage quality generally. Likely, the inclusion of different species allowed for adaption to the growing conditions (Lin 2011). Sudangrass has fine stems and narrow leaves likely had later canopy closure than in a mixture containing sorghum sudangrass and pearl millet. Pearl millet has a shorter-stature and high level of plasticity (Bybee-Finley et al., in review), likely had greater light capture in the canopy gaps of the taller grass species and outcompeted the weeds for other resources. Reducing weed-crop competition for light is essential for reducing weed pressure (Holt 1995). Furthermore, previous research has shown that pearl millet had a faster crop growth rate than sorghum sudangrass in sandier soil (Bybee-Finley et al., 2016), as seen in the greater percentage of pearl millet in NH.

Forage quality did not vary greatly across the diversity treatments as the predominant species (sudangrass, sorghum sudangrass) had similar maturation, a potential explanation for similar results in CP and ADF. The Conspecific diversity treatment had the greatest NDF content and was a lower quality feed, although this may have been somewhat ameliorated by BMR traits in the included cultivars.

4.5.3 Diversifiction strategy of multiple species and cultivars in perennials resulted in greater yields, yield stability, improved economic performance, lower weed biomass, and lower forage quality

Of all the crops, we saw the greatest differences across diversification strategies in the perennial system. When alfalfa was grown with other species, yields were greater and weed biomass was lower, although this resulted in forage quality with a higher fiber content. This was driven primarily by the addition of orchardgrass to the alfalfa, as timothy did not persist well after the first year. Grasses tend to have a faster growth rate and were planted at a higher density thus were better able to outcompete weeds for resources, as compared to the more upright growth from the monoculture alfalfa that took more time to fill into empty spaces. The higher fiber content of the grasses resulted in lower forage quality.

Within a growing season, the grasses generally had a higher percentage of biomass in the first and final cuts, whereas alfalfa generally had a higher percentage in the middle cuts. Alfalfa growth is driven by heat units and orchardgrass growth is driven by day-length likely explains the differences in species expression across cuts (Cherney et al. 2020). The heat of mid-summer likely triggered dormancy of the cool season grasses and we speculate that the selected alfalfa varieties, which had semi-dormant traits with larger taproots and crowns, may have been less affected to increased humidity and high night temperatures in mid-summer (Ottman and Mostafa 2014). Barot et al., (2017) attributes the asynchrony of growth in species as a response to environmental variability due to temporal niche differentiation, a kind of temporal complementarity effect and a sampling effect, which decreased the temporal variability in production. Farmers simply refer to this phenomenon of decreasing grass production mid-season as the ‘summer slump’ (Williamson 2017).

Computationally, Louarn et al. (2020) modelled grass-legume mixtures and showed how non-random selection of functional cultivar traits that fit the expected conditions provided increased yield stability. However, we were unable to detect increased yield stability in the species mixtures with multiple cultivars. Theoretically, the variety of traits would enable increased responsiveness to growing conditions. For example, in the difficult growing conditions of 2017, two of the cultivars claimed to have good disease resistance which likely helped the alfalfa overcome leaf spot disease. One cultivar was resistant to potato leaf hopper and observationally appeared to be less affected by the pest and another cultivar was ascribed ‘good persistence’. Ability to detect effects of response diversity is constrained by the response variable measured, supporting a holistic approach to understanding diversity in cropping systems.

4.5.5 Resilience

In addition to in-field diversification strategies, having multiple approaches to forage production (e.g., having annuals, perennials, pasture, etc.) on farm can enhance social-ecological resilience. Increasing crop diversity on-farm generally increases the diversity of practice, meaning that farmers have a variety of avenues to manage ecosystem services and a greater capacity to adapt to stress events (Colding 2000), including weather or market volatility. A diversity of crops requires different equipment and agronomic management throughout the growing season. While access to equipment may be a barrier for some types of farmers, dairy farms often grow annual and perennial crops. Spreading labor demands more evenly can reduce bottlenecks during peak times, result in higher quality crop management, and utilize available labor resources more thoroughly (Hoagland et al. 2010). Within our management scenarios, we show how the different crops staggered the timing of labor to plant, fertilize, and harvest (Figure 1). Additionally, the summer annuals and perennial crops provide an opportunity to spread manure throughout the summer. In the double-cropped annual system, labor requirements are reduced during the typically busy periods in spring and fall. Farmers can opt to use winter annuals as a cover crop or as a forage crop if feedstocks are limited. Short season summer annuals, like the ones used in this experiment, can serve as 'emergency forage crops' if a corn silage crop fails and there is insufficient time to replant. Crop diversity and a diversity of practice further enables farmers the flexibility to select crops based on the biophysical characteristics of the field. For example, crop production in a low-lying field could be increased with the use of a species more tolerant to waterlogged soil (e.g. meadow fescue (*Schedonorus pratensis*); syn. *Festuca pratensis*; syn. *Lolium pratense*) (Cherney and Cherney, 2020).

This experiment took place under organic management and organic operations engage in more ecological management (Milestad and Darnhofer 2003), making them more likely to incorporate the intercropping diversification strategies used in this experiment. However, intercropping can be practiced by all farm types. Managing weeds without synthetic pesticides requires early crop canopy closure (Bàrberi 2002) which we saw in the interspecific mixtures of the summer annuals and perennials. Additionally, rotating annual and perennial crops is a useful weed management strategy that depletes the weed seedbank and reduces soil disturbance (Liebman and Nichols 2020). Organic certification for dairies also requires 30% of feed come from grazing, an additional diversity of practice (Northeast Organic Farming Association of Vermont 2014).

Evidence suggests crop diversification practices can also mitigate the effects of extreme weather events in addition to adaptation during extreme weather events. In the duration of our experiment, we attribute the differences in soil metrics to tillage and fertility management, but more differences between the systems and diversity treatments would likely be seen with a longer duration (McDaniel et al. 2014). Cong et al. (2015) in a seven-year field experiment showed that intercrops of different species sequestered more soil organic carbon, a key indicator to soil health, at a faster rate than monocultures. Long-term agricultural research experiments have shown that crop rotations, as seen in the annual system, and perenniality, seen in the perennial system are characteristics of cropping systems that improve yield and yield stability over time (Bowles et al. 2020, Sanford et al. 2021).

4.5.4 Future work

More work is needed to further manipulate the sampling effect for more favorable outcomes in mixtures. Developing strategies for selection of crop mixtures for particular traits or performance of specific functions could begin with known traits (e.g., disease resistance or seed costs) and advance to using functional trait databases like Encyclopedia of Life (Rees 2019). Using trait-based information (Louarn et al. 2020) and prioritizing farmer criteria (e.g. seed costs) could garner more favorable outcomes of mixtures and greater adoption, respectively. Seeding rates of crop mixtures could be based on the competitive traits of the species in a given environment (Bybee-Finley et al., in review). This could result in an improved cost-benefit ratio, also increasing the likelihood of adoption.

4.6 Conclusion

Four strategies of crop diversity were implemented in annual and perennial systems using commonly grown species and cultivars to test the effects of intercropping on crop production, profits, weed suppression, forage quality, and yield stability. Treatments that contained multiple species enhanced the resilience of crops more than treatments that did not. Intercropping multiple species increased yield stability across different environmental conditions. In winter annuals, greater crop production with multiple species in favorable growing conditions, whereas in summer annuals this occurred in poorer growing conditions. Weed biomass was reduced in summer annuals and perennials in mixtures with interspecific diversity. Evidence in support of diversity was clearest in the perennial system that contained grass and legume species that had divergent characteristics and persisted for multiple years. A mixture that grew well under a variety of conditions contained species with different physiologies that were able to absorb the stress of a specific condition. The potential to maintain or increase crop production and yield stability while reducing costs of production by selecting species with lower seed costs for mixtures will help dairy farmers enhance the resilience of their cropping systems in the face of a variety of growing conditions.

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CHAPTER 5

FINDING THE RIGHT MIX: A FRAMEWORK FOR SELECTING SEEDING RATES FOR COVER CROP MIXTURES

5.1 Abstract

Cover crop mixtures have the potential to provide more ecosystem services than cover crop monocultures. However, seeding rates that are typically recommended (i.e. seeding rate of monoculture divided by the number of species in the mixture) are non-optimized and often result in one or two competitive species dominating the mixture, and thus limiting the amount of ecosystem services that are provided. We created an analytical framework for selecting seeding rates for cover crop mixtures that maximize multifunctionality while minimizing seed costs. The framework was developed using data from a field experiment, which included six response surface designs of two-species mixtures, as well as a factorial replacement design of three- and four-species mixtures. We quantified intra- and interspecific competition among two grasses and two legume cover crop species with grass and legume representing two functional groups: pearl millet [*Pennisetum glaucum* (L.) R. Br.], sorghum sudangrass [*Sorghum bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf], sunn hemp (*Crotalaria juncea* L.), and cowpea [*Vigna unguiculata* (L.) Walp]. Yield-density models were fit to estimate intra- and interspecific competition coefficients for each species in biculture. The hierarchy from most to least competitive was sorghum sudangrass > sunn hemp > pearl millet > cowpea. Intraspecific competition of a less competitive species was the greatest when the biculture was composed of two species in the same functional group. Competition coefficients were used to build models that

estimated the biomass of each cover crop species in three- and four-species mixtures. The competition coefficients and models were validated with an additional nine site-years testing the same cover crop mixtures. The biomass of a species in a site-year was accurately predicted 69% of the time (low root mean square error, correlation > 0.5, not biased, $r^2 > 0.5$). Applying the framework, we designed three- and four-species mixtures by identifying relative seeding rates that produced high biomass with high species evenness (i.e. high multifunctionality) at low seed costs based on a Pareto front analysis of 10,418 mixtures. Accounting for competition when constructing cover crop mixtures can improve the ecosystem services provided, and such an advancement would likely lead to greater farmer adoption.

5.2 Introduction

Cover crops can protect environmental quality, replace agricultural inputs with biological processes, and regenerate soil health (Teasdale 1996, Dabney et al. 2001, McDaniel et al. 2014, Petit et al. 2018). Cover crops are not harvested but rather their inclusion is a step toward a more sustainable and multifunctional agro-ecosystem, as multifunctionality of ecosystems has been linked with an increasing presence of species (Lin et al. 2011, Davis et al. 2012, Gaudin et al. 2015, Bowles et al. 2020). Cover crops included in a crop rotation provide temporal diversification so that the agro-ecosystem contains more species over time. Mixtures of cover crops can also provide spatial diversification. Temporal and spatial diversification reduce pest pressure of weeds (Liebman and Dyck 1993, Verret et al. 2017), insects (Tonhasca and Byrne 1994, Langellotto and Denno 2004), diseases (Boudreau 2013), and improve soil health (Vukicevich et al. 2016). The multifunctionality of cover crops are increased in mixtures as species perform different functions and can enhance the functions of other species. For example, legumes in mixture with grasses tend to fix nitrogen more efficiently (Brainard et al. 2011, Schipanski and Drinkwater 2012), results in lower carbon to nitrogen ratio of the total biomass (Butler et al. 2012, Cong et al. 2015), and leads to faster N mineralization which could provide N to the subsequent crop or increase leaching potential.

Successfully establishing multiple species together at the same time can be difficult due to competition amongst plants for resources (Hall 1974). Competition within mixtures, as well as the ecosystem services they may deliver, is dependent on the growing conditions, management, and included species (Reiss and Drinkwater 2020). Most commonly, asymmetric competition occurs when one or more species suppresses the growth of other species. This can lead to one species dominating in the mixture due to particular traits that confer a fitness advantage (Funk and Wolf 2016). Poorly constructed mixtures will not deliver the intended ecosystem services. Furthermore, poorly constructed mixtures likely impede adoption because the seed costs of mixtures may be difficult to justify (Wayman et al. 2017, Roesch-McNally et al. 2018, Bergtold et al. 2019).

For this reason, we propose a framework to increase multifunctionality of mixtures while considering seed costs (Figure 1). In it, crop biomass and species evenness of a cover crop mixture serve as coarse proxies for multifunctionality. Greater cover crop biomass tends to provide more ecosystem services, particularly weed suppression and reduced nitrate leaching (Schipanski et al. 2014). However, biomass alone is insufficient to provide multifunctionality (Smith et al. 2014). Finney et al. (2016, 2017) have shown that increasing functional diversity of cover crop mixtures is important for providing multiple ecosystem services. A high level of evenness means that each species present in a mixture produces a similar amount of biomass, indicating reduced asymmetric competition amongst species (Bybee-Finley et al. 2016). Computing biomass-based evenness ensures species of different sizes can perform their affiliated ecosystem service to a sufficient degree. By leveraging the seeding rates of each species in the mixture, competition can be managed and potential tradeoffs with overall biomass production and seed costs can be accounted for (i.e. generating mixtures that produce high biomass with a high level of species evenness at low seed costs). Typically, practitioners use two approaches when constructing mixtures: additive or replacement seeding rates. The additive approach often uses monoculture seeding rates for each species in the mixture, resulting in a greater total density of plants and higher seed costs. The replacement approach often uses a proportion of the monoculture rate for each species, usually divided by the number of species in the mixture.

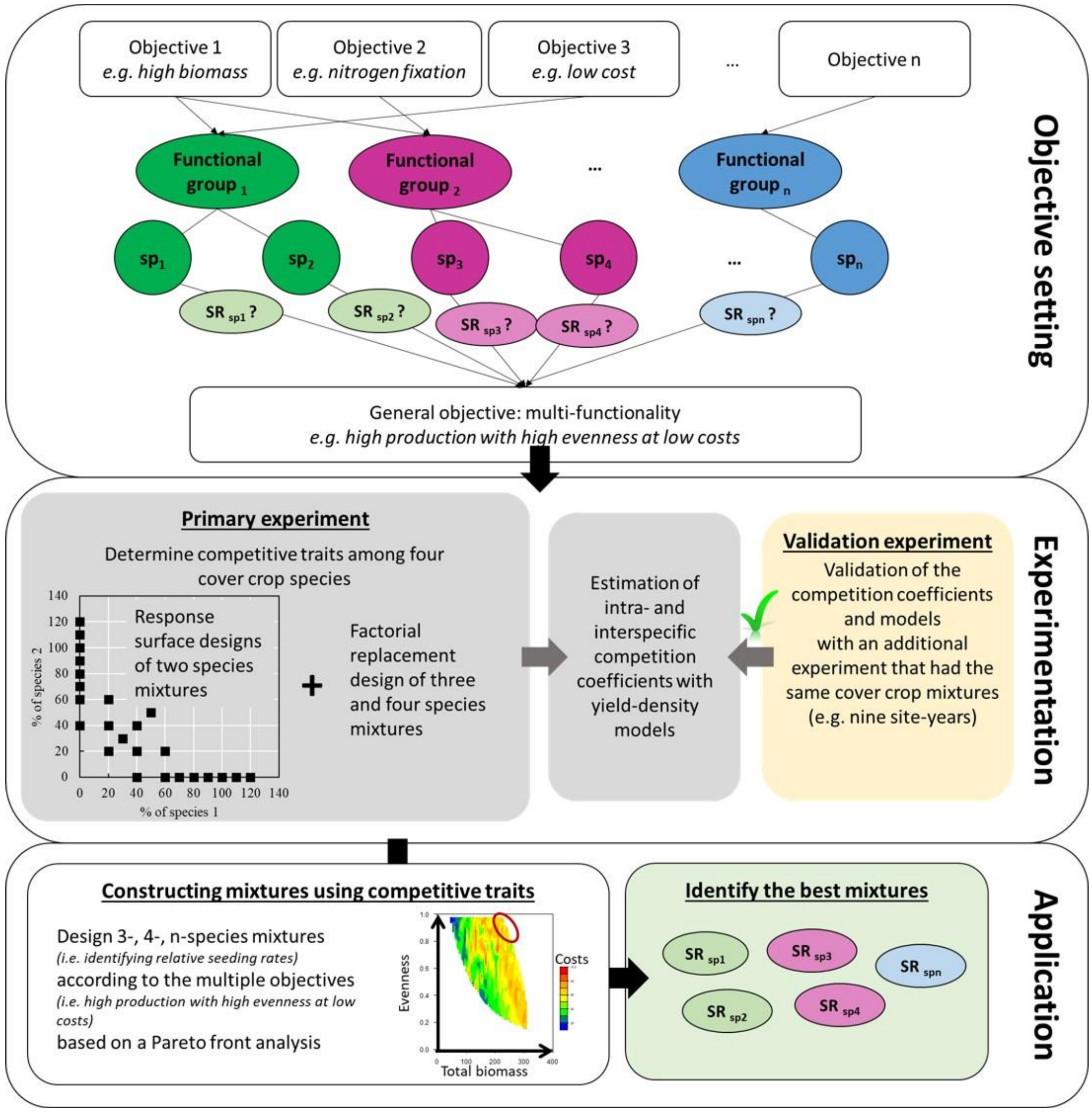

Figure 5. 1. Framework for selecting cover crop mixtures for multifunctionality.

However, using replacement rates in intercropping research leads to findings that are highly conditional on the initial monoculture seeding rates of each species in the mixture (e.g., Creamer and Baldwin 2000, Kadziulienė et al. 2011, Hayden et al. 2014) and confounds intra- and interspecific competition because the seeding rates of the species are not changed independently. Intraspecific competition is when individuals of the same species compete with each other, and interspecific competition is when individuals of different species compete with each other. The performance of an individual plant depends on the degree of intra- and interspecific competition it faces.

An alternative approach for intercropping research is a response surface design, which varies the densities of the two species separately. These designs entail that the monocultures of each species are planted at multiple densities and the bicultures are planted in multiple proportions, thus response surface designs do not have the confounding effects that replacement rate designs do. By applying a yield-density model to a response surface design the traits for intra- and interspecific competition can be quantitatively determined (Spitters 1983).

Complementarity, the combined effects of resource-partitioning (i.e., niche differentiation) and facilitation, is derived from combining species with different functional traits to access and use available resources more completely (Cardinale et al. 2011), better adapt to environmental conditions (Elmqvist et al. 2003), and provide a greater diversity of services relative to a monoculture (Smith et al. 2014). The niche differentiation index (NDI) is the predominant measure of complementarity and is a ratio of overall intra- and interspecific competition in a biculture (Spitters 1983). An NDI above one indicates complementarity between two species, meaning that the net intraspecific competition is greater than the net interspecific competition (i.e. a species is less competitive with another species than with itself). Niche differentiation between species in mixtures has been found in several experiments that use the Spitter's yield-density model and response surface designs: oat (*Avena sativa* L.) and faba bean (*Vicia faba* L.) bicultures (Helenius and Jokinen 1994), field pea (*Pisum* *sativum* L.) and oat bicultures (Neumann et al. 2009), and all biculture combinations of mustard (*Brassica juncea* (L.) Czern.), field pea, black oat (*Avena strigosa* Schreb.) and phacelia (*Phacelia tanacetifolia* Benth.) (Wendling et al. 2017).

In this paper, we describe how our data-driven approach can be applied to advance the multifunctionality of cover crop mixtures and contribute to the precision of sustainable agriculture (Figure 1). Our framework was developed using data from field research in the northeastern United States of four warm-season cover crop species representing two functional groups: grass and legume. Each species was grown in monoculture and with every other species in biculture using a series of response surface designs, as well as in three- and four-species polycultures using a replacement rate design. The relationship between seeding rate and crop performance was determined by using a yield-density model to quantify intraspecific competition of each species in monoculture. An expanded yield-density model was used to quantify interspecific competition between species in each biculture. Competition coefficients from the biculture yield-density models were used to predict the biomass of each component species in three- and four-species polycultures. Predicted biomass was compared to actual biomass using data from the three- and four-species polycultures, and the approach was evaluated further using a separate dataset with nine site-years. Generating 10,418 three-and four-species cover crop mixtures within the density limits of the experiment, the prediction equation simulated the biomass for each species and the mixtures that best fit the multifunctional criteria were determined.

We hypothesized that 1) functionally diverse bicultures (i.e., grass-legume) will produce greater biomass and have greater niche differentiation compared with functionally similar bicultures (i.e. grass-grass and legume-legume), and 2) competition coefficients generated from bicultures can be used to accurately predict the biomass of three- and four-species mixtures.

5.3 Materials and methods

The primary field experiment contained monocultures, bicultures, and three- and four-species polycultures. It was conducted in 2014 at the Cornell Musgrave Research Farm in Aurora, NY (42º45'N, 76 º35'W) on a Honeoye (fine-loamy, mixed, semiactive, mesic Glossic Hapludalf) and Lima (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalf) silt loam, USDA plant hardiness zone 5b (minimum average temperature of -26.1 to -23.3°C).

5.3.1 Restricted response surface design using monoculture and biculture treatments

A series of restricted response surfaces was used to determine the effects of seeding rates on biomass production of four warm-season annual cover crops grown in monocultures and each possible biculture combination (Table 1). Both the monocultures and the bicultures had eight different seeding rates. Two of the monoculture rates were greater than the recommended monoculture seeding rates to ensure that the intraspecific treatments measured maximum yield (i.e., asymptotic yield) for each species (Weiner and Freckleton 2010). Following this law of constant final yield (Weiner and Freckleton 2010), biculture seeding rate combinations were at or below replacement rate levels. Priority was given to the number of seeding rate treatments rather than replicates at a reduced number of rates to have a greater range of plant densities to better fill out the non-linear regression model (Inouye 2001).

Table 5. 1. Target seeding rates as a function of the recommended monoculture rates. The four monocultures and six biculture combinations were each planted at eight rates. The five polyculture combinations were planted at one rate.

Number of species in mixture	Species 1	Species 2	Species 3	Species 4
	(Proportion of each species by its standard monoculture seeding rate)			
1	0.4			
1	0.6			
1	0.7			
1	0.8			
1	0.9			
1	1			
1	1.1			
1	1.2			
2	0.2	0.2		
2	0.2	0.4		
2	0.2	0.6		
2	0.3	0.3		
2	0.4	0.2		
2	0.4	0.4		
2	0.5	0.5		
2	0.6	0.2		
3	0.33	0.33	0.33	
4	0.25	0.25	0.25	0.25

The four warm-season annual crops tested were obtained from King's Agriseeds (Ronks, PA) and included: pearl millet [*Pennisetum glaucum* (L.) R. Br.] (cv. 'Wonderleaf'), sorghum sudangrass [*Sorghum bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf], (cv. 'AS6401'), sunn hemp (*Crotalaria juncea* L.) (VNS), and cowpea [*Vigna unguiculata* (L.) Walp] (cv. 'Iron and Clay'). These species used as cover crops can produce large amounts of biomass, are drought-tolerant, and can be used as a forage crop, or in small grains or vegetable production systems after a spring crop is harvested and before a fall crop. Both grasses are C_4 and native to northeastern Africa (Andrews et al. 1993). Pearl millet is a deep-rooted cereal grain with a high tillering ability and can reach 1 to 2.5 m (Newman et al. 2010, Lee et al. 2012, Sheahan 2014). Pearl millet matures earlier than sorghum (*Sorghum bicolor* (L.) Moench) and is more drought-tolerant (Jefferson Institute 2002). Sorghum sudangrass is a cross between sorghum and sudangrass (*Sorghum sudanense* (Piper) Stapf) that provides the yield advantage of sorghum with the finer stem of sudangrass and can reach 1.2 to 4 m tall. It also has the ability to tiller. The sorghum sudangrass variety used in our research had a brown-midrib mutation that reduces the lignin content and provides higher forage quality (Miller and Stroup 2003). Sunn hemp is a fibrous legume native to India (Cook and White 1996). Sunn hemp can grow 1 to 3 m and has leaves radiating around the stem (NRCS 1999, Sarkar et al. 2015). Cowpea is an herbaceous, tap-rooted legume native to western Africa (Davis et al. 1991). It does not grow well in alkaline or poorly drained soils (SARE 2012), but is shade-tolerant (Blade et al. 1997). Iron and Clay is a blend of two cultivars: one with a upright bushy growth habit, while the other has a vining, prostrate growth habit.

The recommended seeding rates for each cover crop species (and abbreviations used henceforth) in monoculture were: pearl millet (M) 2.1 g seed m^{-2} (292 seeds m^{-2}), sorghum sudangrass (S) 6.6 g seed m^{-2} (218 seeds m^{-2}), sunn hemp (H) 5.6 g seed m^{-2} (146 seeds m^{-2}), cowpea (C) 7.0 g seed m^{-2} (72 seeds m^{-2}). The rates used as a basis (100% recommended seeding rate) were within the recommended range for the species according to the seed supplier. Pearl millet, sunn hemp, and cowpea had germination rates of 80% and sorghum sudangrass had a germination rate of 85% according to the seed label (King's Agriseeds, 2014). To ensure consistent targeted emergence rates among species, seeding rates based on seed weights were adjusted for a live-seed basis. Seed costs per kg were \$3.13, 3.66, 5.69, and 4.52 for M, S, H, and C, respectively. These costs are within range for what would be typical for producers, particularly those who are growing higher value vegetables.

5.3.2 Replicated three- and four-species polycultures

A factorial design of each possible three- and four-species mixture using the same species was replicated five times. To do this, we used replacement seeding rates such that each species included in the polyculture was seeded at the recommended seeding rate of the monoculture divided by the number of species in the polyculture (Table 1). The treatments in the restricted response surface design and the factorial design were randomized in the field to control for spatial heterogeneity.

5.3.3 Management

Preceding this experiment, the field contained conventional corn in 2012, conventional soybeans in 2013, and then planted into conventional winter wheat fall of 2013, which was sprayed with glyphosate in the spring of 2014. Afterwards, the field was chisel-plowed, disked, and cultipacked prior to planting the cover crops. Then, the primary experiment was managed organically. Prior to cover crop planting, 35 kg ha^{-1} of total N was broadcast in the form of poultry manure (5–4–3). Although this is more N than would typically be applied prior to legume crops, it represents less than half of the recommended rate for sorghum sudangrass (Ketterings et al. 2007). The legumes were inoculated with N-Dure rhizobium mixture (Verdesian Life Sciences Cary, NC) suitable for cowpea and sunn hemp prior to planting.

Cover crops were planted on July 7th, 2014 to a depth of approximately 2.5 cm in 18 cm rows with 6 rows using a custom-built cone seeder drill with hydraulic twin disc row openers and packing wheels. Plots were 1.26 m by 6 m with a buffer of 1.5 m between plots maintained by mowing to prevent potential light competition between plots.

5.3.4 Sampling

Crop and weed biomass samples were collected 50 days after planting (DAP; 473 growing degree days, base temperature 10°C). In two 0.5 m^2 quadrats centered in the plot, plants were clipped 10 cm above the soil surface, separated by species, dried at 60°C for at least one week, and then weighed. Within each quadrat, cover crop and weed density were counted by species at the same time as the biomass sampling. Individual plants of grass species were distinguished by tracing stems to the soil to avoid counting tillers as separate plants.

5.3.5 Data analysis

Data were analyzed using R 3.3.2 (R version 3.3.2, Inc., Boston, MA, 2015). Analyses were performed using the observed densities unless otherwise stated, as the seeding densities differed somewhat from the observed densities of emerged plants (Figure C.1).

To summarize the results, three separate Type III analysis of variance tests were used to compare total cover crop biomass among 1) the four monoculture treatments (n = 8 for each of the cover crop monocultures), 2) the six biculture treatments (n = 8 for each of the cover crop bicultures), and 3) the five polyculture treatments (n = 4 for each of the polycultures). As the monoculture and bicultural treatments were not replicated, seeding rate levels were used as replicates for both the monoculture and biculture treatments, assuming no differential responses to seeding rates for the purpose of presenting an initial sense of seed treatment effects. Tukey's honest significance difference test was performed to compare treatment means at $\alpha = 0.05$. Pearl millet had only seven monoculture treatments, as density was not recorded in the 60% seeding rate treatment.

5.3.5.1 Yield-density competition model

Crop biomass and density data were used to quantify intra- and interspecific competition using data from the restricted response surfaces (Willey and Heath 1969). Using the eight seeding rates of a species in monoculture, Y_1 is the biomass of species 1, the focal species, calculated by (Eq. 1):

$$Y_1 = \frac{N_1}{b_{1,0} + b_{1,1}N_1} \qquad \text{(Eq. 1)}$$

The term, N_1 is the density of the species I. The term, $b_{1,0}$ is necessary to ensure that when N_1=0, $b_{1,1}$=0, Y_1=0 and when N_1=1, $b_{1,1}$=0, $Y_1 \neq 0$. The term is a more influential parameter when density is low. The intraspecific competition coefficient, $b_{1,1}$ ($m^2\ g^{-1}$), describes how the per plant weight decreases when additional plants of the same species are added. To determine the intraspecific competition coefficient for each species in monoculture, yield-density models (Eq. 1) were fit using nonlinear regression to the observed density and biomass for each species in monoculture.

The yield-density model is expanded for a biculture to account for interspecific competition with the assumption that additional species hold a similar hyperbolic relationship (Spitters 1983). In which $Y_{1,2}$ is the biomass of species *1* in a biculture of species *1* and *2* and is calculated by (Eq. 2):

$$Y_{1,2} = \frac{N_1}{b_{1,0} + b_{1,1}N_1 + b_{1,2}N_2} \qquad \text{(Eq. 2)}$$

Where N_1 and N_2 are the plant densities of each species. The interspecific competition coefficient, $b_{1,2}$ (m^2 g^{-1}), is a measure of interspecific competition of species *2* on species *1* and describes how the per plant weight of species *1* decreases when plants of species *2* are added. The relationship can be made linear by using the inverse of the per plant weight, as yield (Y_1) equals the weight per plant times the density (N_1) (Eq. C1). As a visual aid to help the reader understand how the shape of the yield-density curve changes under different competition scenarios, examples using various competition coefficients can be found in the appendix (Figure C.2). For the bicultures, intra-and interspecific competition coefficients were determined using the expanded yield-density model (Eq. 2). Models were fit using nonlinear regression to the observed density and biomass of the response surface design (combined monoculture and biculture data) for each species in each biculture.

Initially, weed density was included as a term in the model but resulted in a higher Akaike Index Criterion (AIC) without improving the model fit, so the weed density term was omitted. Briefly, weed biomass was generally low with an average of 16 weeds m^{-2} weighing 6 g m^{-2}. Several plots had no weeds (cowpea seeded at 110%, pearl millet-cowpea seeded at 40% and 20% respectively, and one replicate of the pearl millet-sorghum sudangrass-cowpea mixture). The bicultures of pearl millet-cowpea seeded at 20% and 40%, respectively, and sunn hemp-cowpea each seeded at 40% had the greatest amount of weeds (40 plants m^{-2} with 89 g and 46 plants m^{-2} with 16.1 g, respectively). Weed biomass tended to be lower in plots with high levels of cover crop biomass (data not shown). The most common weed species was Venice mallow (*Hibiscus trionum* L.), a legacy from a previous experiment.

5.3.5.2 Theoretical maximum weight and maximum yield

Previous work on yield-density models has not described the relevance of the reciprocal intercept term, $1/b_{1,0}$ (g $plant^{-1}$). Spitters (1983) described it as the virtual biomass of an isolated plant. The term describes the theoretical maximum weight per plant as a function of the growing conditions and portrays the potential of a plant, garnering an idea of what may be possible if competition is managed in a mixture. Similarly, the reciprocal of the intraspecific competition term, $1/b_{1,1}$ (g m^{-2}), represents the theoretical maximum yield.

5.3.5.3 Assessing competition and complementarity between species

Competition in bicultures was assessed by comparing intra- and interspecific competition coefficients. These were first normalized to control for size bias by dividing the competition coefficients by the intercept ($b_{1,1}/b_{1,0}$ and $b_{1,2}/b_{1,0}$), as an increase in the density of a larger plant results in a greater biomass than that of a smaller species (Neumann et al. 2009). Two indices were used to measure the influence of species interactions on mixture performance. The relative competitive ability (RC) is a ratio of intraspecific competition to interspecific competition independent of the density of either species in the biculture (Eq. 3). Biologically, it is the number of plants of species *1* that can replace plants of species *2* without changing the per plant weight of species *1* (Helenius and Jokinen 1994):

$$RC = \frac{b_{1,1}}{b_{1,2}} \qquad \text{(Eq. 3)}$$

The niche differentiation index (NDI) uses the four competition coefficients of a biculture to assess resource complementarity (Eq. 4). It is the product of both species RCs:

$$NDI = \frac{b_{1,1}}{b_{1,2}} \times \frac{b_{2,2}}{b_{2,1}} \qquad \text{(Eq. 4)}$$

Predicting crop biomass of three-and four-species polycultures

Intercepts and competition coefficients determined with response surface data were used to predict biomass for each species in three- and four-species polycultures (Eq. 5). The model is specific to species composition of the polyculture (e.g. called *1,2,3,…, r*) with yield of a focal species *a* in the polyculture, calculated by:

$$Y_{a\ in\ 1,2,3,\dots,\mathrm{r}} = \frac{N_a}{\bar{b}_{a,0} + \bar{b}_{a,a}N_a + \sum_{i\ in\ \{\mathbb{N}\setminus\{a\}\}}^{r} b_{a,i}N_i} \qquad \text{(Eq. 5)}$$

Where $\bar{b}_{a,0}$ and $\bar{b}_{a,a}$ are means of $b_{a,0}$ intercept coefficients and $b_{a,a}$ intraspecific competition coefficients of species *a* in each *a,i* bicultures of a mixture containing *r* species, where $\{\mathbb{N}\setminus\{a\}\}$ means the *i* term cannot be *a* (i.e, in the MSH polyculture where *a* is pearl millet, M, estimates are based on MS and MH bicultures intercepts and competition coefficients). Here, we continued with the assumption made by Spitters et al. (1983) that indirect competition from additional species (i.e. interactive effects amongst species) is quite small compared to direct competition, and thus we do not account for it.

To determine if the competition model (Eq. 5) fit one species better than another, the observed and predicted biomass were first scaled using Z score normalization ($\mu = 0$ and $\sigma = 1$) by species to account for magnitudes of difference in biomass. Using the scaled predicted and observed data, the fit of the models were assessed with four indicators: i) the root mean square error (RMSE) to describe the difference between the predicted and observed values, ii) the coefficient of correlation (slope) of a simple linear regression between the predicted and observed biomass to describe the strength of the relationship, iii) a test (slope $\neq 1$) to determine if the model exhibited bias, and iv) the coefficient of determination (r^2) to describe the strength of the correlation (Mudrak et al. 2014).

5.3.5.4 Model validation

The results from a two-year summer cover crop experiment using the same polycultures and biomass sampling methods (called hereafter the validation experiment) were used to test the ability of our model to make accurate predictions of crop biomass of three-and four-species polycultures across different growing conditions. The validation experiment was conducted in 2013 and 2014 at (i) the Cornell Musgrave Research Farm (Aur) on the same soil types as the primary experiment; (ii) the Cornell Willsboro Research Farm (Wil) in Willsboro, NY (44°21' N, 73°23' W) on a Stafford fine sandy loam (mixed, mesic Typic Psammaquent), plant hardiness zone 4b (minimum average temperature of -31.7 to -28.9°C); and (iii) the USDA–ARS Beltsville Agricultural Research Center (Bel) in Beltsville, MD (39°02' N, 76°54' W) on an Elkton silt loam (fine-silty, mixed, active, mesic Typic Endoaquult), plant hardiness zone 7a (minimum average temperature of -17.8 to -15°C). The Bel location included two different field sites in 2013, and the Aur and Wil locations included two different field sites in 2014. Different field sites within a location were planted a month apart, as indicated by "E" (for early) and "L" (for late). Thus, the validation experiment had nine site-years. A randomized complete block design was used (except for the BelL13 site-year) with four to five blocks per site-year for a total of 199 plots. Biomass was sampled from 43 to 53 days after planting (DAP) using the same protocol described above. Slight modifications to management practices, planting dates, and plot sizes across sites and years occurred (see Bybee-Finley et al. 2016 for more details).

The competition model (Eq. 5) was run using the observed densities from the experiment to predict the crop biomass of a focal species. Observed and predicted data were scaled using Z score normalization ($\mu = 0$ and $\sigma = 1$) by site-year and species to account for species size and control for the variety of growing conditions. The normalized data were assessed using the same four steps described above.

5.3.5.5 Pareto front to determine optimal three- and four-species polycultures

To find the optimum densities of species for achieving high total biomass and high species evenness in three- and four-species polycultures, the competition models (Eq. 5) were used to compute the biomass for each focal species of a simulated mixture. Simulated mixtures were generated so that they fit within the limits of the model, i.e.

the seeding rates of the simulations ranged from 0 to 120% of the recommended monoculture seeding rates (i.e. from 0 to 350, 262, 176, and 86 seeds m^{-2} for pearl millet, sorghum sudangrass, sunn hemp, and cowpea, respectively). To do this, increments proportional to 5% of the maximum seeding rates of each species (increments of 17, 13, 8, 4 seeds m^{-2} respectively for pearl millet, sorghum sudangrass, sunn hemp and cowpea) were used. To respect the limits of the model, mixtures were excluded when the sum of the proportions of each species exceeded 120%, so that biomass of each species for 10,418 mixtures was computed.

The total biomass was the sum of each species biomass. The species evenness based on biomass was computed using the vegan package (Oksanen et al. 2019) (Eq. 6):

$$Pielou's\ species\ evenness = \frac{-\sum_{i=1}^{S} pi_1 \ln{(pi)}}{ln\ (S)} \qquad \text{(Eq. 6)}$$

where the numerator is the Shannon diversity index, *pi* the proportion of biomass belonging to the i^{th} species, and *S* the number of species in the mix. The denominator is the maximum Shannon diversity, ln(*S*). Species evenness is bounded between 0 and 1, with increasing evenness until the maximum of 1 is reached, meaning equal amount of biomass for each species in the intercrop. Mixture costs, based on the cost of seeds at time of purchase and accounting for germination rate, were also computed. The output was plotted using contour plots with the Akima package (Akima et al. 2016).

To find the best mix, we identified "Pareto-optimal" mixtures following the methodology developed by Lafond et al. (2017). The Pareto front method identifies "efficient" and "non-dominated" solutions that perform at least as well as others for all criteria and strictly better for at least one criterion (Kennedy and Ford 2011). This set of solutions is also called the "Pareto-optimal set" and forms the "Pareto front", on which it is not possible to increase a criterion without reducing at least another one. Here, we identified the Pareto-optimal set of mixtures that optimized total biomass and species evenness, followed by consideration of seed cost for the best mixtures. From the Pareto front, a subset of mixtures was selected that had a species evenness greater than 0.8, threshold selected according to Tracy and Sanderson (2004).

5.4 Results

5.4.1 Cover crop production in primary experiment

5.4.1.1 Monoculture treatments

Sorghum sudangrass produced the greatest amount of biomass in monoculture (Figure 2) with an average of 462 g m^{-2} and a range of 398 to 511 g m^{-2}, which was observed in the 70% and 60% seeding rate treatments, respectively. Pearl millet and sunn hemp monocultures produced similar amounts of biomass with averages of 287 and 312 g m^{-2}, respectively. Pearl millet biomass ranged from 254 to 366 g m^{-2} at the 100% and 90% seeding rates, respectively. Sunn hemp biomass ranged from 263 to 344 g m^{-2} at the 40% and 90% seeding rates, respectively. The cowpea monoculture produced the least amount of biomass, resulting in an average of 203 g m^{-2}, less than half the amount of the sorghum sudangrass monoculture. Cowpea biomass ranged from 171 to 246 g m^{-2} at the 40% and 110% seeding rates, respectively.

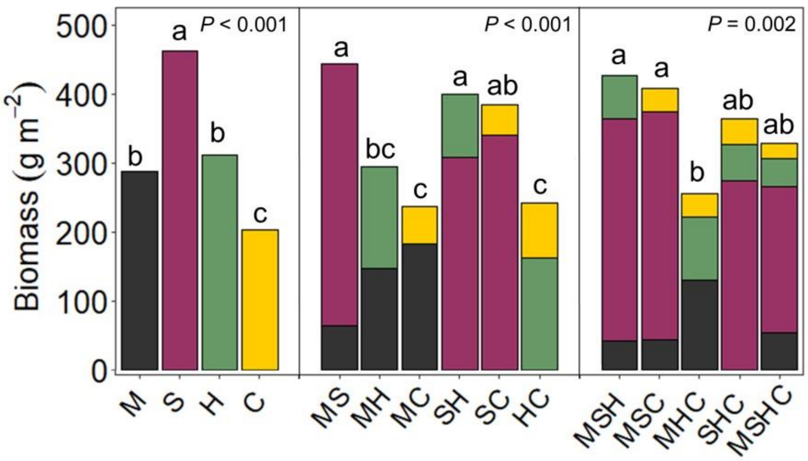

Figure 5. 2. Analysis of variance of average crop biomass across mixture treatments. ANOVAs were performed based on species richness, such that monocultures, bicultures, and polycultures were assessed separately. Similar letters above bars within a panel (e.g., monoculture, biculture, and polyculture) indicate no significant differences between treatments in total crop biomass at $P < 0.05$. M, pearl millet; S, sorghum sudangrass; H, sunn hemp; C, cowpea.

5.4.1.2 Biculture treatments

The treatments that contained sorghum sudangrass were the most productive bicultures (Figure 2). The sorghum sudangrass-cowpea (SC) biculture produced similar amounts of biomass as the pearl millet-sorghum sudangrass (MS) and the sorghum sudangrass-sunn hemp (SH) bicultures but more than the other bicultures containing cowpea. The pearl millet-sunn hemp (MH) biculture produced a similar amount of biomass as the bicultures containing cowpea. Biomass of each species in the bicultures was lower than their biomass in monocultures, which was expected. Higher seeding rates typically resulted in more biomass. However, the extent of the reduction of biomass in biculture compared to monocultures differed by species as a result of asymmetric competition.

5.4.1.3 Polyculture treatments

As with the bicultures, including sorghum sudangrass in a polyculture generally resulted in greater total biomass compared to polycultures without sorghum sudangrass. However, no transgressive overyielding was observed in the polycultures, i.e. no polyculture yielded more than the most productive monoculture. Within the polycultures, sorghum sudangrass constituted the majority of the biomass and suppressed the growth of the other included species. The pearl millet-sunn hemp-cowpea (MHC) polyculture was less productive than the pearl millet-sorghum sudangrass-cowpea (MSC) and the pearl millet-sorghum sudangrass-sunn hemp (MSH) polycultures (Figure 2). The coefficient of variation (CV), found by dividing the standard deviation of a polyculture by its mean biomass, were 0.19, 0.20, 0.18, 0.12, and 0.12 for MSH, MSC, MHC, SHC, and MSHC, respectively. The SHC and MSHC polycultures which contained sorghum sudangrass and the two legumes had the most stable production.

5.4.2 Intraspecific competition and maximum yield of the monocultures

Intraspecific competition was greatest in sorghum sudangrass, followed by cowpea, pearl millet, and sunn hemp (Table 2, raw numbers in Appendix S1: Table S1). The competition coefficient for sunn hemp was less than half of the competition coefficients for sorghum sudangrass and cowpea. Maximum yield ($1/b_{1,1}$) occurs at the asymptote and thus at an infinitely high density. Sorghum sudangrass had the largest maximum yield, followed by sunn hemp, pearl millet, and cowpea (540, 470, 357, and 302 g m^{-2}, respectively).

Table 5. 2. Parameter values and competition indices of the four monocultures and six bicultures determined by the yield-density model. The data used in the expanded yield-density model for the bicultures contained the focal species in monoculture and in biculture to determine intra-and interspecific competition coefficients. The term $b_{1,0}$ is the intercept; $b_{1,1}$, intraspecific competition coefficient; $b_{1,2}$, interspecific competition coefficient; RC, relative competitive ability; NDI, niche differentiation index; r^2 of observed and predicted biomass standardized by species ($\mu = 0$ and $\sigma = 1$); M, pearl millet; S, sorghum sudangrass; H, sunn hemp; C, cowpea.

Treatments	Species	$b_{1,0}$ (plant g^{-1})	$b_{1,1}/b_{1,0}$ (m^2 $plant^{-1}$)	$b_{1,2}/b_{1,0}$ (m^2 $plant^{-1}$)	RC	NDI	r^2
M	M	0.1336	0.0210				0.19
S	S	0.0491	0.0377				0.66
H	H	0.1606	0.0132				0.44
C	C	0.0930	0.0356				0.86
MS	M	0.1319	0.0213	0.0622	0.34	3.62	0.75
MS	S	0.0658	0.0266	0.0025	10.57		0.59
MH	M	0.1646	0.0161	0.0175	0.92	1.35	0.83
MH	H	0.2091	0.0088	0.0060	1.47		0.9
MC	M	0.1920	0.0134	0.0041	3.27	3.2	0.46
MC	C	0.0970	0.0335	0.0342	0.98		0.94
SH	S	0.0839	0.0203	0.0078	2.59	1.31	0.57
SH	H	0.1502	0.0146	0.0289	0.51		0.95
SC	S	0.0644	0.0279	0.0226	1.23	0.95	0.24
SC	C	0.1007	0.0317	0.0412	0.77		0.78
HC	H	0.1548	0.0141	0.0106	1.32	1.27	0.89
HC	C	0.0931	0.0355	0.0369	0.96		0.97

5.4.3 Competitive dynamics of the restricted response surface

5.4.3.1 Intra- and interspecific competition within the response surfaces

Pearl millet had the most variable response to the other species in the biculture. Pearl millet plants faced the highest level of interspecific competition from sorghum sudangrass and the lowest level of interspecific competition from cowpea (0.0622 and 0.0134 m^2 $plant^{-1}$, respectively, Table 2). As such, pearl millet biomass declined sharply with increasing sorghum sudangrass density but only slightly with increasing cowpea density (Figure 3b and d). Sorghum sudangrass produced a large amount of biomass even at low seeding rates. Increasing the densities of pearl millet, sunn hemp, and cowpea had slight negative effects on the sorghum sudangrass biomass (Figure 3a, g, h). More than the other two species, increasing the density of cowpea led to greater decline of sorghum sudangrass biomass (Figure 3h). Sunn hemp faced the highest level of interspecific competition from sorghum sudangrass and the lowest level of interspecific competition from pearl millet (0.0289 and 0.0060 m^2 $plant^{-1}$, respectively, Table 2). For this reason, sunn hemp biomass declined sharply with increasing sorghum sudangrass density but at a slower rate when increasing pearl millet density (Figure 3f and e). Cowpea biomass declined sharply with increasing pearl millet and sorghum sudangrass density (Figure 3i and j), but less so with sunn hemp (Figure 3k). Compared to its other bicultures, cowpea had the lowest intraspecific competition but faced the most interspecific competition when in biculture with sorghum sudangrass (Table 2).

Overall, sunn hemp generally had the lowest level of intraspecific competition and cowpea had the greatest, followed by sorghum sudangrass (Table 2). Cowpea faced the greatest level of intraspecific competition of any species in biculture when it was paired with sunn hemp (0.0355 m^2 $plant^{-1}$, Table 2). The competitive dynamics of pearl millet-sorghum sudangrass (MS) and sunn hemp-cowpea (HC) (Table 2) show that intraspecific competition of a less competitive species (pearl millet and cowpea, respectively) is the greatest when the biculture is composed of two species in the same functional group (i.e., grass-grass, legume-legume).

We observed that competitive properties are intransitive. Of all the bicultures, pearl millet faced the greatest amount of interspecific competition from sorghum sudangrass. Cowpea in all three of its bicultures faced the next greatest levels of interspecific competition. Cowpea affected pearl millet very little, yet cowpea affected sorghum sudangrass more than any other species (interspecific competition coefficient of 0.0041 and 0.0226 m^2 $plant^{-1}$, respectively Table 2).

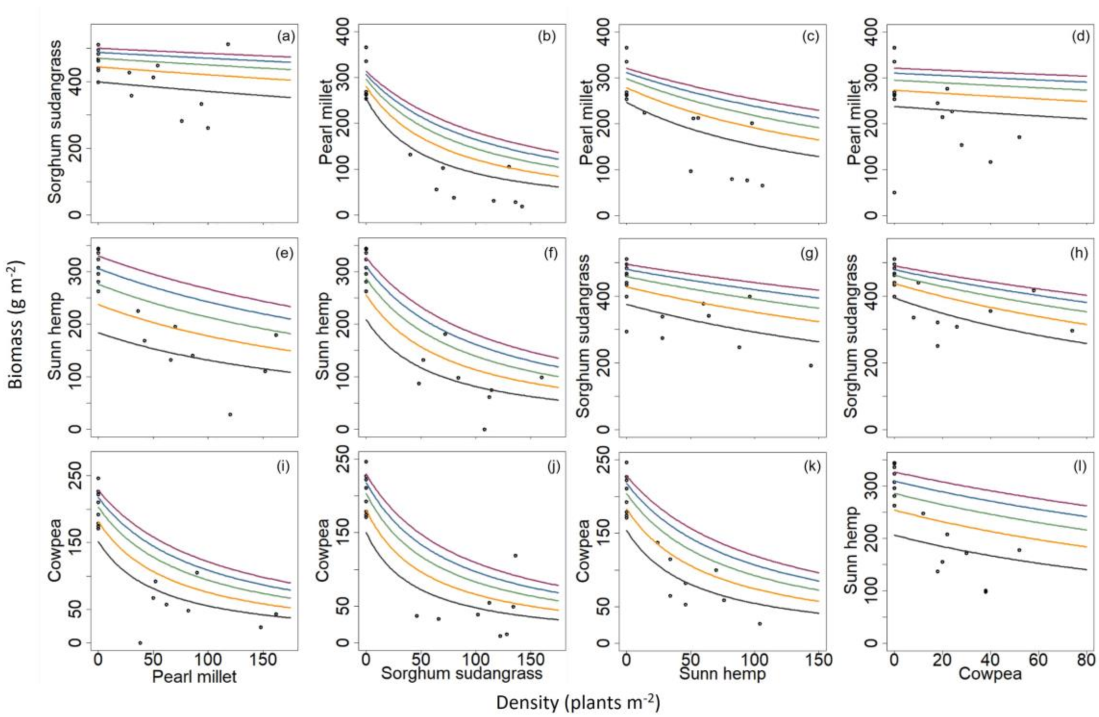

Figure 5. 3. Each panel (a-l) depicts the biomass of the focal species and the density of the other species in the biculture with each row representing a different biculture. The

data used in the expanded yield-density model contained the focal species in monoculture and in biculture to determine intra-and interspecific competition coefficients. The points at zero density of a species represent the biomass of the focal species when planted in monoculture. The different lines represent different proportions of the recommended monoculture seeding rate of the focal species, illustrating the effects of increasing the density of the non-focal species.

5.4.3.2 Relative competitive ability of each species

Despite being functionally similar, the grasses had very different patterns in the ratio of inter- to intraspecific competition. In the bicultures, the intraspecific competition faced by pearl millet was lower than the interspecific competition from sorghum sudangrass and sunn hemp, resulting in RCs less than one. In contrast, sorghum sudangrass had higher levels of intraspecific competition and lower levels of interspecific competition, resulting in RCs consistently above one. All species planted with sorghum sudangrass had RCs less than one, indicating they faced greater interspecific competition than intraspecific competition (Table 2). The biculture of the two grasses, had the greatest difference of RCs. In the pearl millet-sorghum sudangrass (MS) biculture, the RC of pearl millet was 0.34, meaning that the pearl millet plants could sense the presence of one pearl millet plant as strongly as the presence of 0.34 sorghum sudangrass plants (Table 2). In the pearl millet-cowpea (MC) biculture, the intraspecific competition of pearl millet was much higher than interspecific competition from cowpea, resulting in an RC of 3.27 (Table 2). The RCs of pearl millet in the pearl millet-sunn hemp (MH) biculture, cowpea in the pearl millet-cowpea (MC) biculture, and cowpea in the sunn hemp-cowpea (HC) biculture were close to one (Table 2), indicating similar levels of intra-and interspecific competition of species in bicultures. Cowpea had high levels of both intra- and interspecific competition indicating that cowpea performs best when planted at lower seeding rates. By examining whether intra- or interspecific competition was higher for each species in each biculture, the following hierarchy from most to least competitive was established: sorghum sudangrass > sunn hemp > pearl millet > cowpea.

5.4.3.3 Niche differentiation

All bicultures had NDIs greater than one, apart from one, indicating that in most cases species exhibited complementarity. The NDI for pearl millet-sorghum sudangrass was large because of the low intraspecific competition pearl millet had with itself and low level of interspecific competition it gave to the sorghum sudangrass (Table 2). Whereas, the large NDI for pearl millet-cowpea was because the species faced greater overall intraspecific competition than interspecific competition, particularly pearl millet faced low interspecific competition from cowpea. The sorghum sudangrass-cowpea biculture had the only NDI below one because the overall interspecific competition was greater than the intraspecific competition that either species faced.

Like Wendling et al. (2017), a positive correlation was observed between total biomass of the biculture treatments and NDI (Kendall's coefficient of correlation $\tau = 0.20$, $P = 0.04$). The bicultures that contained sorghum sudangrass generally produced more biomass than those that did not, thus more biomass was produced when the most productive species was included. More biomass was produced by bicultures that faced lower overall interspecific competition, but they were not necessarily functionally diverse.

5.4.3.4 Theoretical maximum plant weight

Intercept ($b_{1,0}$) values were variable with larger standard errors (SE) compared to the other model parameters (Table C.1). The theoretical maximum weight of a plant ($1/b_{1,0}$) changed from when species were planted in monoculture or biculture, sometimes increasing which indicates potential benefits of growing species together. In monocultures, the theoretical weights were 20.4, 10.8, 7.5, and 6.2 g plant^{-1} for sorghum sudangrass, cowpea, pearl millet, and respectively.

The theoretical maximum weight of sorghum sudangrass changed the most when it was planted with another species, dropping to 11.9 g plant^{-1} when in biculture with sunn hemp. The theoretical weight of sunn hemp was largest when it was planted with sorghum sudangrass (6.7 g plant^{-1}) and smallest when it was planted with pearl millet (4.8 g plant^{-1}). The theoretical weight of pearl millet was largest with sorghum sudangrass (7.6 g plant^{-1}). In a pearl millet-cowpea biculture, cowpea (10.31 g plant^{-1}) was theoretically a larger plant than pearl millet (5.21 g plant^{-1}), but increasing the seeding rate of pearl millet led to a greater increase in biomass because the pearl millet sowing density was higher and it faced less intraspecific competition than that of cowpea.

5.4.4 Predicting crop biomass in polycultures in primary experiment

As the competition coefficients used were generated under the same growing conditions as the polycultures, we demonstrated the ability of Eq 5 to accurately predict crop biomass in a three- or four-species polycultures (Figure 4). Models fit each species well and the predicted biomass values were similar to the observed biomass of the polycultures. Models fit pearl millet the best and sunn hemp the worst. No bias was detected in the model predictions.

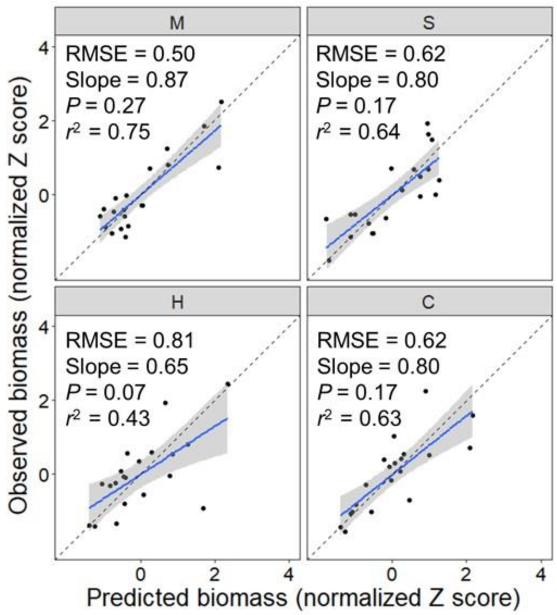

Figure 5. 4. The fit of the predicted biomass from the models that used the competition coefficients from the response surface designs to the observed biomass for each species in the polycultures. The blue line reflects a linear regression between the observed and predicted biomass scaled by species. The dotted line shows Observed = Predicted, reflecting a perfect prediction. The shaded area represents the 95% confidence interval. M, pearl millet; S, sorghum sudangrass; H, sunn hemp; C, cowpea; RMSE, root mean square error; slope, the coefficient of correlation between observed and predicted; *P* value (slope ≠1) describes if the model predictions had bias; r^2, the coefficient of determination describes the strength of the correlation.

5.4.5 Predicting crop biomass in validation experiment

The models successfully predicted the crop biomass in 5, 7, 7, and 6 of the site-years for cowpea, sunn hemp, millet, and sorghum sudangrass, respectively (total, 25/36 = 69%) (Figure 5, Table C.2). In four out of nine site-years, the model successfully predicted biomass of all four species. Across site-years, the model best predicted pearl millet biomass, followed by sunn hemp, sorghum sudangrass, and finally cowpea. This is likely due to the competition coefficients generated in the response surface designs better representing pearl millet across growing conditions than cowpea.

Across the site-years, no species-specific trends in model fitness emerged. The model performed the best in the AurE14, BelE13, and BelL13 site-years. Interestingly, in the one site-year that used synthetic fertilizer (AurL13) instead of poultry manure, the model did not predict crop biomass for any species well (higher RMSEs, lower slopes and r^2 values, and bias in predictions). This is a clear indication of changes in competition dynamics under different management practices. If only site-years with similar fertilizer regimes were included, the model accurately predicted crop biomass 78% of the time. In the WilE14 site-year, the model did not predict the grass species well, and in the WilL14 site-year, the model did not predict the legume species well. The model tended to over-predict biomass production of all species, especially the grasses, but these were within the confidence intervals.

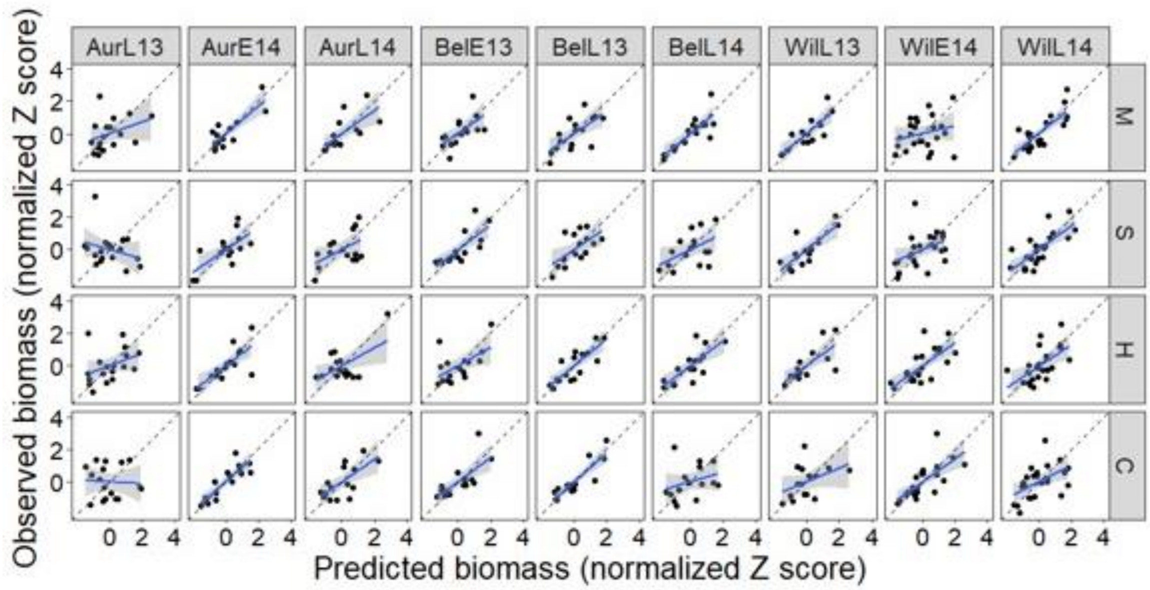

Figure 5. 5. Visualization of model validation using observed biomass from nine site-years of data, which took place in three locations over two years, in which some sites had experiment replicates. Data is standardized for each species within each site ($\mu = 0$ and $\sigma = 1$). The blue line reflects a linear regression and the dotted line shows Observed = Predicted, reflecting a perfect prediction of the validation data. The shaded area represents the 95% confidence interval. Aur, Aurora, NY; Wil, Willsboro, NY; Bel, Beltsville, MD; "E" and "L" correspond to early and late planting date; 13 and 14 correspond to planting date year; M, pearl millet; S, sorghum sudangrass; H, sunn hemp; C, cowpea.

5.4.6 Optimal mixtures

We simulated the biomass production of 10,418 different polycultures using Eq. 5 and plotted their total crop biomass and species evenness (Figure 6). The Pareto front was used to identify the seeding rate and species combinations that optimized these two parameters. On it, a tradeoff between evenness and biomass was observed, where mixtures that had the highest levels of evenness did not produce the most biomass. No four-species polycultures were found on the Pareto front and all polyculture combinations contained pearl millet (MSH, MSC, and MHC). The MSH polyculture was the most common with combinations that ranged from producing 398 g m^{-2} of biomass with an evenness of 1 to combinations producing 498 g m^{-2} of biomass with an evenness of 0.39.

Seeding rates and seed costs were examined for polycultures with an evenness of 0.8 or greater (Table 3). The MSH polyculture combinations that fit this criteria contained pearl millet proportions between 41-64% of its monoculture seeding rate, sorghum sudangrass proportions between 12-36% of its monoculture seeding rate, and sunn hemp proportions between 22-60% of its monoculture seeding rate. On average, these polycultures produced 436 g m^{-2} of biomass with an evenness of 0.92 at a cost of \$279.40 ha^{-1}. Based on these results, some general seeding rate principles emerge. Because sorghum sudangrass is much more competitive than pearl millet, sorghum sudangrass density should be lower than pearl millet to achieve high evenness. Because sunn hemp seed is relatively expensive, sunn hemp should be included at a low proportion if low seed costs are a priority.

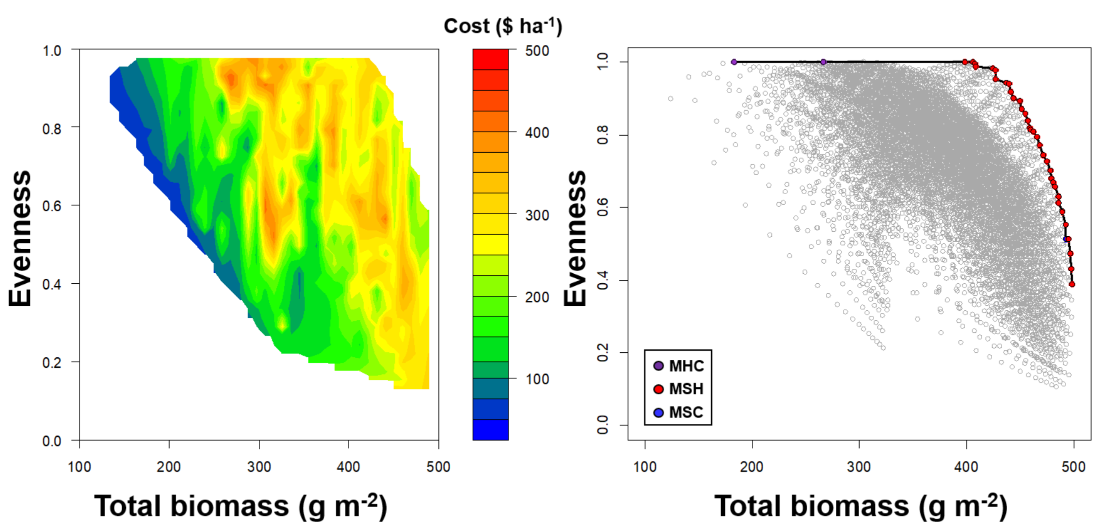

Figure 5. 6. The total biomass and species evenness of three- and four- species mixtures (N=10,418) of pearl millet (M), sorghum sudangrass (S), sunn hemp (H) and cowpea (C) with a heat map overlay of seed costs on the left. On the right is the Pareto front highlighting the mixtures where biomass and evenness are optimized.

Table 5. 3. Polycultures identified on the Pareto front that had a species evenness greater than 0.8. M, pearl millet; S, sorghum sudangrass; H, sunn hemp; C, cowpea.

Mixture	Proportion of monoculture rate (%)				Total proportions	Biomass ($g\ m^{-2}$)				Total biomass ($g\ m^{-2}$)	Evenness	Cost ($\$\ ha^{-1}$)
	M	S	H	C		M	S	H	C			
MSH	0.47	0.36	0.33	--	1.15	104.75	296.05	61.22	--	462.01	0.81	270.95
MSH	0.64	0.30	0.22	--	1.16	145.56	271.96	42.16	--	459.68	0.81	224.72
MSH	0.41	0.36	0.38	--	1.15	93.33	293.34	71.88	--	458.55	0.82	288.00
MSH	0.58	0.30	0.27	--	1.15	134.77	269.22	53.05	--	457.04	0.84	241.77
MSH	0.52	0.30	0.33	--	1.15	123.58	266.53	64.09	--	454.20	0.86	258.82
MSH	0.47	0.30	0.38	--	1.15	111.96	263.90	75.28	--	451.13	0.87	275.87
MSH	0.41	0.30	0.49	--	1.20	97.98	255.91	95.36	--	449.25	0.89	314.76
MSH	0.58	0.24	0.33	--	1.15	144.34	231.85	67.25	--	443.45	0.90	246.68
MSH	0.52	0.24	0.38	--	1.15	132.53	229.37	79.02	--	440.91	0.92	263.73
MSH	0.47	0.24	0.49	--	1.20	117.83	221.84	100.02	--	439.69	0.94	302.62
MSH	0.41	0.24	0.55	--	1.19	105.22	219.56	111.92	--	436.70	0.94	319.67
MSH	0.58	0.18	0.38	--	1.15	155.37	188.30	83.14	--	426.82	0.95	251.60
MSH	0.52	0.18	0.49	--	1.20	139.86	181.56	105.16	--	426.58	0.98	290.49
MSH	0.47	0.18	0.55	--	1.19	127.03	179.52	117.71	--	424.27	0.98	307.54
MSH	0.58	0.12	0.49	--	1.20	164.47	133.19	110.86	--	408.52	0.99	278.36
MSH	0.52	0.12	0.55	--	1.19	151.44	131.55	124.14	--	407.13	1.00	295.41
MSH	0.47	0.12	0.60	--	1.19	137.79	129.95	137.63	--	405.37	1.00	312.46
MSH	0.41	0.12	0.55	--	1.08	129.70	135.42	132.87	--	397.99	1.00	285.82
MHC	0.12	--	0.22	0.56	0.89	87.03	--	90.28	89.11	266.43	1.00	316.77
MHC	0.06	--	0.11	0.22	0.39	60.42	--	61.16	61.81	183.40	1.00	136.40

5.5 Discussion

5.5.1 Competitive traits of cover crop species

Sorghum sudangrass dominated the other species in mixtures in terms of biomass production. Similar asymmetric competition by sorghum sudangrass was seen in the model validation experiment (Bybee-Finley et al. 2016). As conditions were generally not nutrient-limited, especially not N-limited, or water scarce, competition was most likely driven by light availability.

Taller-statured species were better able to capture light, sometimes instigating other species, like pearl millet, to grow larger than they would have in monoculture or when paired with smaller-statured species. Terao et al. (1997) described how the spreading growth habit of cowpea allowed for more light capture, particularly red:far red light, when being shaded by a more competitive plant. Cowpea leaves were generally larger but fewer in number than the sunn hemp leaves that grew from a main stem that was often taller than the cowpea, allowing it to capture more light. The heavier, rockier soil conditions likely limited the overall growth of cowpea and the rate of fertilizer likely had a negative impact on the relative competitive ability of the tap-rooted legumes (Gregory and Reddy 1982, Sheahan 2012).

The ability to better capture additional resources can be proxied using the crop growth rate. In the validation experiment, grasses had faster growth rates than either legume, and sunn hemp had faster growth rates than cowpea in both monocultures and mixtures (Bybee-Finley et al. 2016). In addition to the faster growth rate, sorghum sudangrass has known allelopathic properties which suppress the growth of other species. Living root hairs continually excrete sorgoleone into the rhizosphere, although it has been shown to decrease as the plant matures (Weston and Czarnota

2008, Weston et al. 2013). Larger plant size and faster growth rate, in addition to allelopathic traits likely gave the sorghum sudangrass a competitive advantage compared to the other four species.

The theoretical maximum weights (1/ $b_{1,0}$) can be used to discern a species potential in a mixture but should be considered with seeding rates and competition coefficients. For example, cowpea had a large theoretical maximum, but this did not result in high biomass because of the low seeding density and high degrees of intra- and interspecific competition. Pearl millet and sunn hemp both had greater theoretical weights when planted in bicultures with sorghum sudangrass than they did in monocultures, showing how interspecific competition can instigate growth of the less competitive species. Pearl millet and sunn hemp had similar or lower intraspecific competition than sorghum sudangrass in bicultures yet increasing the seeding rate of sorghum sudangrass led to greater increases in biomass because of the larger size of sorghum sudangrass. Despite sunn hemp being a theoretically smaller plant when planted with pearl millet, increasing the seeding rate of sunn hemp led to a greater increase of biomass than increasing the seeding rate of pearl millet as pearl millet faced greater intraspecific competition than sunn hemp.

Generally, biomass in this experiment was similar to previous experiments in upstate New York (Brainard et al. 2011, Bybee-Finley et al. 2016), but greater biomass production was seen in warmer locations and when species were planted at higher seeding rates (Creamer and Baldwin 2000, Balkcom and Reeves 2005, Schomberg et al. 2007, Finney et al. 2009, Blanco-Canqui et al. 2011, 2012). Differences in biomass production and competitive dynamics in mixtures are affected by the genetics of the species, environment, and management interactions (G ×E×M). Growing conditions likely affected the competitive traits of the four species. For example, a warmer, low-N environment with sandier soil would likely be a more favorable environment for legumes than the conditions found in this experiment (Louarn et al. 2020). Multi-environment agronomic experiments like those undertaken by Mirsky et al (2017) that examined hairy vetch planting dates and seeding rates along the east coast and Schomberg (2007) that examined planting and harvest dates of sunn hemp in the southeastern United States would be necessary to understand how environmental conditions and management decisions are related to competition. Future work should explore competition in cover crop mixtures across varying environments to assess the robustness of competition coefficients

5.5.2 Complementarity

We did not find support for our first hypothesis that functionally diverse bicultures would produce greater biomass and have a higher NDI than functionally similar bicultures. The driving mechanism of complementarity in annual crop mixtures is thought to be resource-partitioning and is derived from the species traits that enable them to access resources in some unique way (Brooker et al. 2015, Bybee-Finley and Ryan 2018). Resource-partitioning is attributed to the functional diversity of species fitting into particular niches (Finney and Kaye, 2017). However, we were unable to relate functional type of the species to competition, although our experiment tested a limited range of functional types. Perhaps because cover crop species have been selected for characteristics that have made them desirable for crop production, and mixtures have a shared, single season of growth, species are likely accessing available resources in a fairly similar manner. The traits driving light competition (e.g. light interception) may be more important to determine complementarity in annual mixtures in temperate agricultural fields with adequate rainfall and fertility. Future work could explore the physiological mechanisms of competition in crop mixtures, such as experiments could measure light competition using crop growth rates, heights, or leaf area index (LAI), and root traits using rooting depth and root length density.

More biomass was produced in mixtures where species faced lower interspecific competition than intraspecific competition. The biculture treatments with the greatest NDI values all contained pearl millet, suggesting that pearl millet is an ideal species to mix with the other species that were studied. Possible reasons for this include: a) a smaller stature than sorghum sudangrass that reduced the amount of light competition for the other species in the biculture, b) a faster crop growth rate (Bybee-Finley et al. 2016) that allowed it to keep pace with sorghum sudangrass, c) its fibrous root system, and d) its plasticity in shoot and root development. Gregory and Reddy (1982) described pearl millet's root growth pattern as multi-axial with axes that grew at varying angles from the plant allowing for a considerable degree of mixing root systems when intercropped. Roots of pearl millet have also been shown to have the ability to grow to various lengths depending on growing conditions and intercropped species (Gregory 1986, Kizito et al. 2006). Although it had a relatively higher sowing density compared to other species, density appeared to be less of a factor for biomass production for pearl millet, perhaps because of its quick ability to adapt to growing conditions by vigorous tillering (Azam-Ali et al. 1984). Barot et al. (2017) in a review of ecological mechanisms for crop mixtures suggests that plasticity in below- and above-ground growth preempts greater resource capture. Further research is needed to verify the physiological characteristics that resulted in the complementary nature of pearl millet.

5.5.3 Predictive ability of competitive traits for higher order mixture

I found support for our second hypothesis that one can apply the competition coefficients estimated in the bicultures to accurately predict the biomass of three- and four-species polycultures. This finding means that experiments about cover crop mixtures would only need to examine combinations of two species at various rates to understand outcomes for mixtures containing three or four species. Using Eq. 5 parameterized from our restricted response surfaces with bicultures, we were able to estimate seeding rates for species grown in polycultures that produced high biomass distributed evenly across species at low costs.

It is unclear whether this framework, particularly Eq. 5, would be as accurate in higher diversity mixtures. While I was able to show that Eq. 5 worked well with predicting biomass from four-species polycultures across a range of environments, it is likely that higher diversity mixtures would necessitate replication of the response surface to ensure the accuracy of the competition coefficients. Competition coefficients could be made more robust if developed under different growing conditions. By understanding how key aspects of a G ×E×M gradient (e.g. a soil type or a latitude) interact with the model, the amount of deductive research required to design cover crop mixtures for various conditions could be further reduced.

The framework is premised on functional diversity (i.e., delivery of ecosystem services by species with different functions) and not response diversity (i.e., reducing the risk of losing ecosystem services by having varied responses to growing conditions) (Elmqvist et al. 2003). Because the framework measures the responses of the species, these two categories of diversity are inseparable. Yet, practitioners are often motivated to plant multiple species in precaution to unknown conditions. This framework does not consider the potential benefits that functional redundancy provides (Leslie and McCabe 2013). Additional research should examine multiple levels of redundancy within functional groups to improve understanding of the effects of response diversity.

5.5.4 Designing mixtures for multifunctionality

Previous work has suggested that to reduce such asymmetric competition in cover crop mixtures, the seeding rates of highly competitive species should be reduced and the seeding rates of less competitive species should remain near their monoculture rates (White et al. 2015). However, our framework is the first to describe this process based on empirical models. The MSH polycultures had the greatest multifunctionality based on our criteria. In the validation experiment, the MSH polyculture was also the most even treatment at 45 DAP. It also maintained or increased evenness by 90 DAP, suggesting that more symmetric competition earlier in the growing season results in more evenness later (Bybee-Finley et al. 2016).

The total proportion of the seeding rates for the MSH polycultures with evenness > 0.8 was more than 100%, indicating that in order to achieve multiple objectives seeding rates greater than replacement rates may be necessary. Although the higher seeding rates identified on the Pareto front are partially an artifact of the upper bound set on the optimization data frame to be within our experimental densities and the asymptotic property of Eq. 5 (i.e., an increasing density will continue to produce an increasing amount of biomass). The seeding densities used for the bicultures were mostly lower than the recommended monoculture seeding rates (cumulative proportions ≤ 1) and we assumed that the yield-density relationship remained asymptotic. To determine the density at which the yield-density relationship plateaus, seeding rates in experimental treatments would need to increase well beyond the recommended monoculture seeding rates (Li and Hara 1999, Kikuzawa 1999).

5.6 Conclusion

Cover crops are the main crop diversification practice supported by agriculture policies in the United States because their implementation requires minimal changes to current cropping systems as compared to other diversification practices, such as expanded crop rotations. Yet, adoption of cover crops remains limited, due in part to high seed costs (Wayman et al. 2017, Bergtold et al. 2019). The goal of cover crop mixtures is often to deliver multiple ecosystem services beyond what can be provided by single species (Isbell et al. 2011). These additional ecosystem services consequently provide stability and resilience to the agro-ecosystem (Loreau and de Mazancourt 2013). As seeding rates are an integral factor for biomass production and competition, precisely constructed cover crop mixtures can enhance the delivered ecosystem services in a cost-effective manner. Our framework describes the process of determining the seeding rates of species to achieve greater multifunctionality in the agro-ecosystem. Decision-making tools, like cover crop calculators[1], could integrate this framework into their design and provide practitioners with an improved ability to use cover crops to provide multiple ecosystem benefits and achieve more sustainable cropping systems.

[1] SmartMix Calculator: https://smartmix.greencoverseed.com; NRCS Cover Crop Seed Rate Calculator With Implementation Requirements for NY found on the Electronic Field Guide https://efotg.sc.egov.usda.gov/#/details and then populate query as follows: State:NY; Keyword Search: calculator; Subject Search: Conservation Practices.

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EPILOGUE

In this dissertation, I explored how understanding the farm as a social-ecological system could advance the adoption of crop diversification practices to enhance the resilience of a farm in the face of extreme weather events. I understand my role as an agroecologist to advance the science of crop diversification that would reduce the barriers and motivate adoption of such practices. I conclude there are two key problem points. The first, the positivist and reductionist approaches dominant in agronomic science are prohibitive to studying diversity because they draw conclusions from simplified systems. Studying diversity will require opening up agronomy to new epistemic (knowledge-making) traditions. Second, while agronomic sciences can show the benefits of crop diversification through controlled experiments, this is not enough to drive adoption. Adoption is a complex sociological process shaped by multiple institutional forces including regulations, practices, technologies, and norms.

In Chapter 1, I mapped a farm as a social-ecological system.

I outlined how an industrialized farm can be conceptualized as a social-ecological system. This comprehensive framing allows us to understand the push and pull of regulations, practices, technologies, actors, and their norms that perpetuate agricultural production practices. I propose that the relative advantage, compatibility, trialability, observability, and complexity characteristics for diffusion of innovations serve as feedback mechanisms of the complex system. Top-down, societal structures privilege annual, monoculture production and reduce the ability of the farmer to adaptively manage their land. Bottom-up, the agro-ecosystems of farms reinforce the social-ecological system as it currently exists. However, they could be managed to better absorb or adapt to extreme weather events using crop diversification which results in increased field- and farm-level variability. Such an idea invites new configurations of larger social and institutional structures in the social-ecological system that could enhance resilience of the farm by prioritizing greater adoption of crop diversification practices.

In Chapter 2, I conducted a well-structured qualitative study of farm-level decision making.

Using 25 structured interviews with conventional and organic dairy farmers in western NY, I constructed simple social-ecological networks of information sources and crop diversification practices by either farm type. To understand the strategy of crop diversification to enhance the resilience of a farm in the face of extreme weather events, it is necessary to make sense of the interrelatedness of the socio-technical configuration and the adoption of specific practices. I found that conventional farmers turned to more formal information sources and had a greater percentage of land in annual production. This higher amount of land in annuals meant that such farmers were more likely to perform annual crop diversification practices, like cover cropping. Conventional farmers driven by a highly competitive environment had little ability to adapt and more often synthesized information from external specialists who shared a simple goal: increased production. In contrast, organic farmers were more likely to draw information from community (informal) members and had more crop production in perennials, including pasture. Organic farms were smaller in size, adopted more ecological forms of weed control, gave animals more agency, and had greater crop complexity (thus variability) of the land, but lower milk production. They synthesized information from the land more directly and considered crop and animal production together. Lower engagement of organic farmers with formal information sources (e.g. Land Grants) is likely due to the lack of these institutional actors engaging with organic (ecology-based) production practices, not simply a desire of organic farmers to have local, place-based knowledge. It is telling that New York State has the largest number of organic dairies in the nation, but the land grant university, does not offer courses on organic dairy herd management.

Institutionalized motivation for high rates of production are a major headwind for expanding adoption of crop diversification, and resilience using this strategy. I hope to delve into such trade-offs as I continue to explore the farmer interviews. The interview instrument was constructed with a holistic approach in mind that would allow me to integrate more characteristics about the farm, such as soil types or labor to management ratio to further develop the social-ecological system with greater depth.

In Chapter 3, I reviewed the scientific landscape of intercropping.
I detailed the benefits, mechanisms, common practices and research designs of mixed intercropping in industrialized agricultural systems. I also described barriers to intercropping research such as the confounding effects of the replacement seeding rates in experiment designs and the difficulties with synthesizing findings across

experiments. I highlighted response surface designs for the former and proposed a set of data standards to work toward overcoming the latter. Unlike some other plant sciences whose scope can be successfully reduced, agronomy is situational; generalizable research outcomes from controlled experiments in particular field sites are not always helpful for decision-making on a particular farm and context. Research outcomes are even more dependent on context when crop diversity is the research topic. New ways to synthesize information, and to identify and describe patterns can help advance a cohesive knowledge base.

This chapter has been published open access. To date, the article has been cited ~ 50 times by scientists, many of whom belong to non-western academic institutions, performing intercropping experiments across a range of applications. To transform increasingly industrialized agro-ecosystems, agronomic science will need to be more contextualized and accessible. One idea, journals could require an indexable geo-reference for field site-based experiments. This would help both with contextualization of results and synthesis across environmental and temporal gradients.

In Chapter 4, I quantified four diversification strategies in three crops.
I report findings from a multi-year, multi-site experiment designed to understand the ways that different levels of diversification effect crop production, weed suppression, forage quality, soils, seed costs, and yield stability. The purpose of the experiment was to understand how the deployment of diversity would enhance the resilience of dairy farms in the face of extreme weather events. In it, interspecific diversity

(different species) led to increased yields and yield stability. In the perennials, temporal diversification across the growing season was seen in interspecific mixtures. This finding, apparently the first in scientific publications, highlights the tremendous lag of agroecological science to the practices performed by farmers. In my farmer interviews, several farmers detailed this phenomenon explicitly. As such, it seems it would be impactful for institutions to engage with alternative means of substantiation beyond scientific research when advancing resilience through crop diversification.

To understand the roles of intra- and interspecific diversity in a pragmatic matter, the diversity treatments were based on my experiences of common practices by dairy farmers in the region. I used replacement seeding rates to keep methods consistent across crops, but this was problematic. Legume seeding rates should be kept near monoculture rates to reduce competition from grasses; the methodology led to poor establishment in the winter annual crop. The diversity treatments also used different numbers of grasses and legumes, and the 'head' species was not in the same family across crops. Both led to some difficulties quantifying the role of different plant families in diversification strategies. Additionally, some species were observationally indistinguishable, leading to difficulties at reporting results at the species level. Assigning all the crops to have a 'head' species in the same functional group or using more easily distinguishable species, would be an approach targeted more to scientific discovery of crop diversity but would come at a loss of practical understanding of diversification strategies with species that are typical for farmers in the region.

Even if all above issues were adequately addressed, experiments that compare degrees of richness run the risk of expressed diversity treatments not representing the intended diversity treatments. To some extent this is inevitable for all experiments, however the lack of assuredness likely dissuades some agronomists from engaging with crop diversification as a research area. Balancing practical research questions and fitting within the boundaries of deductive logic and traditional experiment designs makes constructing crop diversity experiments difficult.

For greater advancement of the discipline, I am drawn to Ostrom's aphorism that if it is true in practice, it is true in theory. I think it would be worthwhile to engage more deeply with normative approaches and retroductive logic when initially exploring questions of diversity. The qualitative work could then inform more quantitative approaches. That is, study tacit knowledge of diversification practices and then endeavor to codify it through 'science'. For example, a researcher could first identify a farmer with a high degree of success intercropping and work backward to understand their methods and how they select species and their seeding rates. Afterwards, the researcher could design experiments to advance understanding of the practice. A strategy like this would allow for agroecological science to at least keep pace with agroecological practices.

In Chapter 5, I developed a process to reduce barriers of adoption for annual intercropping.

As I saw in Chapter 4, mixtures using replacement seeding rates often have asymmetric competition in which some species dominate. For farmers planting cover crop mixtures this means they are likely spending money without seeing the benefits. To reduce barriers to adoption of cover crop mixtures, the cost: benefits ratio of crop mixtures needs to improve. I created a method to construct crop mixtures based on leveraging seeding rates to reduce crop competition so that species are present with similar relative abundance.

By applying a yield-density model to a series of response surface designs, I was able to quantify the competitive relationships of each species. This addresses the point raised in Chapter 3 about findings of intercropping experiments being confounded by the experiment design. I also was able to show that these competitive relationships could be used to predict biomass of higher order mixtures, i.e. results from relatively simple biculture series can be generative and supplant three- and four-species mixture series. This reduces some barriers around research design complexity mentioned in Chapters 3 and 4 (i.e., can do simpler experiments and derive results for more complex mixtures). I hope this finding can be used to expand our working knowledge of competitive traits of species.

The predictive model provides precise seeding rate recommendations to reduce crop competition and enhance multifunctionality of cover crop mixtures using high species evenness and biomass production as proxies. As it stands, the optimization is more precise than many current farm capabilities and could be adjusted to better fit farm equipment and capacities of the farmer. Moreover, the heuristics that can be derived from optimal mixtures (e.g. ensure the rate of species A is greater than the rate of species B) can be used to inform farmers.

The model I developed could be integrated into crop mixture decision-making tools for farmers or agronomists who are constructing cover crop mixtures. To date, only heuristics based on expertise (not quantifiable data) have been used for cover crop 'calculators'. As of now, not enough competitive relationships of crops have been quantified to do this. For greater impact, the decision-making tools should be free, easy to access, and outreach efforts should be made available to farms most likely to use cover crop mixtures. I venture that a song about competitive traits and seeding rates of cover crop mixtures could help in the meantime to prompt consideration of the ecological dynamics amongst species.

I see incredible value in improving methods for constructing mixtures, and advancing practices premised on improving ecological processes of agroecosystems. For example, the predictive model could be paired with a plant trait database to design mixtures more precisely based on assembling desired plant traits (**G**×**G**×E×M). If response surface designs were applied across environmental gradients, we could quantify environmental factors (e.g., soil type, temperature, precipitation) on competition (G×G×**E**×M) using such yield-density models. If response surface designs were applied across managerial gradients, we could quantify managerial factors (e.g. fertilizer rates, tillage practices) on competition (G×G×E×**M**) using yield-density models. All this to say, the pace and quality of diversification research, and hence diversification practices, could greatly improve with minimal efforts of using response surface designs and attention given to synthesize findings.

Conclusion

As someone who has worked on advancing crop diversification science for the past eight years and larger questions of food and development for the years before that, I feel it is my duty to share some final thoughts about the findings of this dissertation. I have written at great length about crop diversification as a strategy for resilience of farms in the face of extreme weather and great progress has been made in terms of framing resilience for industrialized agroecosystems to build on existing diffusion literature, understanding of how evidence of resilience at the field-level is assembled, and establishing generative research methods to advance the research and practices of diversification. Each component addresses some shortcoming of efforts for greater crop diversification and hopefully eases the barriers for more transformative actions within the socio-technical configuration. The enormity of transforming our industrialized agrifood system means grappling with topics of colonialism, exploitation, and rural-urban divides.

Yet, my work here is ascetic to justice. It presents ideas without regard to power, historical legacies, or why some might be more enabled to access or implement such ideas. The research questions themselves are about how to change the ways of farming with little regard to who is or is not farming in these industrialized systems. In order to advance more multi-functional agroecosystems, agronomy must be understood not only with an ecological lens, the farmer must be included as well.

Appendix A

Description of information sources

Agronomic service providers scout fields for pests and disease, recommend seed varieties, crop rotations, and nutrient recommendations. Increasingly agronomists take/process/interpret remote-sensing measurements like satellite imagery or drone footage to substantiate their recommendations. Agronomists are not usually independent agents but belong to a consulting group that serves the area with an agronomist providing support for multiple farmers. This provides an agronomist a unique ability to observe practices occurring on other farms. As some farmers are more boundary-pushing, agronomists can see the experimentation on these farms and then advance or raise concerns of such practices on other farms. In Western NY many farmers used an agronomic service provider called ‘Western New York Crop Management Association’.

Nutritionists provide insight on seed varieties and forage quality~yield trade-off although their recommendations for harvest dates/stages are often tempered by weather conditions and time management of multiple farm operation. Nutritionists assess quality of stored feed throughout the year. If a farmer has multiple sources of stored feed (i.e. multiple faces of bunker silos), nutritionists will determine the ratios of the sources to deliver optimal quality to the cow and what if any additional supplements might be necessary. For this reason, only larger operations that have multiple sources and supplemental feed would work with a nutritionist regularly. Some farmers meet concurrently with the agronomist and the nutritionist.

Employees on the farm can provide insight from their own experiences, especially if they had their own farm or grew up on a farm. They are embedded in the farm and can function as a sounding board for new ideas and can consider different aspects than the farmer. This is useful for thinking through a problem and potential solutions. Employees may provide expert knowledge, but they also serve to legitimize a solution (Borgatti and Cross 2003). If an operation is large enough and does not have adequate family help, farms hire workers for full or part-time help. Some farms are large enough to have a designated role for a crop manager who thinks specifically about crop production. In multi-generational farms where dairy farming is part of the identity of the family, it is common for one sibling to be the dairy manager or herd master and the other to work on the crops. The crop manager would then have the most knowledge on land management practices. Many large farms hire Hispanic employees, but I did not see any cases where these employees were in managerial positions or operating field equipment. I only witnessed them moving cows and operating the milk parlor.

Veterinarians care for the health of the cow by treating injuries (e.g. hoof issues), infections (e.g. mastitis), and pregnancies. Veterinarians can recommend changes in cows' diets to alleviate health concerns or improve milk production, but this aspect was not mentioned during the interviews. Milk cooperatives are most concerned about the food safety of milk. Many milk contracts can only be completed if somatic cell counts are below threshold levels. Milk cooperatives often provide awards for high milk quality or consistently meeting safety standards which farmers often display. Only the small, grassfed milk cooperative was described as providing agronomic services.

Financial consultants provide advice on financial structuring of the farm to increase profit margins. Financial consultants that specialize in dairy operations can provide recommendations on farm-level quotas or production caps set by milk buyers or the capture of some price premium through improved milk components, government support available, etc. Banks offer access to financial capital often in the form of a loan that would allow the farmer to more effectively capture economies of scale. This can be seen in the trend of consolidation in the dairy industry and the declining number of medium-sized dairy farms (MacDonald et al. n.d., Guptill 2009). Because crop diversification practices are not well-known as other promoted practices, a loan application for such practices is less likely to be well-received compared to a practice with greater recognition (e.g., no-till).

Interview instrument

For convenience, questions contained in the dissertation chapter have been highlighted.

Interview Guide for a New York Dairy Farmer

1. How many years have you been farming? _____ (years)
2. How many milking cows do you have? _____ (#)
3. How much milk are you making? _____per cow/day
4. Do you raise your own calves and heifers? Y/N
5. Are you certified organic? Y/N
    a. *Tell me about that.*
    b. *What motivated you?*
    c. *How long have you been organic?*
6. Do you produce a value-added product? Y/N
    a. If yes, what is it? ______________
7. Where do you sell your milk? ________(name)
    a. Do they offer any agronomic services/advice? Y/N
    b. If yes, have you ever used it? Y/N
    c. Have they ever asked you to change your management practices? Y/N
    d. If yes, what did they ask you to do? *(e.g., Chobani and GM crops)* ______________
8. Do you have access to capital for the day to day operations on your farm? Y/N
9. Do you have access to capital you need for projects you would like to accomplish? Y/N
10. Are you supported by an off-farm income?

No	Yes, someone in **my family**	Yes, **me**	Yes, **both** me and my family

11. How do you typically spend your time?

Mostly laboring	More laboring than managing	Laboring and managing evenly	More managing than laboring	Mostly managing

*Laboring = driving tractors, fixing equipment, handling cows

12. How has your operation changed over the past 5 years? ______________
    a. *Have you built any new barns?*
    b. *Have you changed the way you're milking?*
    c. *Have you changed any of your cropping practices?*

13. Who do you confer with to make decisions on the farm?

14. Who are some people (~5) you would turn to **for advice** when considering a change in cropping system/land management practices?
    SNA RESPONSE SHEET—one per person:
    1. How do you know this person?
    2. occupation:
    3. gender:
    4. age:
    5. How much do you trust this person?
    6. How often do you talk to this person?
    7. Did they grow up on a farm?
    8. If you said, farmer:
        a. How far away is their farm? _______(distance)
        b. What is their farm size? _______(acres)
        c. What is their herd size? _______(# milking cows)
        d. How long have they been farming? _______(years)
        e. What land management practices do they do *(Choose from list)*

15. Which of these people you named know each other?
    Generate matrix: have them put checks for anyone who they think knows each other. Have an 'I don't know" category.

Generate network matrix by filling out names of people on the 1st column and row.

Put an "X" if the people know each other. Put an "?" if you are unsure.

Names on 1st row & column							

16. On your farm, what is your soil like?
    a. *How is your soil quality?*
       ____
    b. Generally, what is your soil organic matter content (%)?
       _____(%)
    c. Has it changed since you've been farming? If so, how?
       ____

17. How much have you heard or read about these different practices? More positive/negative? **GO TO RESPONSE SHEET MATRIX**.

	How much have you heard or read about this practice?						Have you heard or read more positive or negative things		
	A great deal				Nothing		Positive	Neutral	Negative
Pasture	5	4	3	2	1		☐	☐	☐
Perennial crops	5	4	3	2	1		☐	☐	☐
Double-cropping	5	4	3	2	1		☐	☐	☐
Cover crops	5	4	3	2	1		☐	☐	☐
Intercropping annuals	5	4	3	2	1		☐	☐	☐
Intercropping perennials	5	4	3	2	1		☐	☐	☐
Grass waterways	5	4	3	2	1		☐	☐	☐
Prairie strips	5	4	3	2	1		☐	☐	☐
Reducing tillage	5	4	3	2	1		☐	☐	☐
Tile drainage	5	4	3	2	1		☐	☐	☐
Irrigation	5	4	3	2	1		☐	☐	☐
Crop insurance	5	4	3	2	1		☐	☐	☐

18. How many acres do you farm?
    _____ (acres)
19. Do you own all of it? Y/N
    a. If no, how many acres do you generally rent?
       _____ (acres)

20. What is your typical crop rotation like?
    ____
    a. *What crops do you grow?*
    b. *What is the sequence? (e.g. after 3 years of alfalfa, how many years do you grow corn)*
    c. *How many years is the rotation?*
    d. *Why? What's the reasoning behind this rotation?*
    e. *Would you ever want to try do something else?*
    f. *What's holding you up/are barriers?*
    g. *Do you treat your rented acres similarly to the ones you own?*

h. *What about your nearby acres v the ones further out?*

21. About how many acres do you have in **pasture**? _______
22. When did you start?
    ____(years)
23. If no, have you ever tried?
24. If answered none, are you thinking about adopting? Y/N
25. Why? What are your motivations and barriers for this practice?

26. About how many acres do you have in **perennial row crops**? _______
27. When did you start?
    ____(years)
28. If no, have you ever tried?
29. If answered none, are you thinking about adopting **perennial crops**? Y/N
30. What are your motivations and barriers for this practice?

31. How many of these acres of **perennial row crops are intercropped** (e.g. grass-legume mixtures)_______
32. When did you start?
    ____(years)
33. If no, have you ever tried?
34. If answered none, are you thinking about adopting? Y/N
35. Why? What are your motivations and barriers for this practice?

36. About how many acres do you **double crop**? _______
37. When did you start?
    ____(years)
38. If no, have you ever tried?
39. If answered none, are you thinking about adopting? Y/N
40. Why? What are your motivations and barriers for this practice?

41. About how many acres do you **cover crop**? _______
42. When did you start?
    ____(years)
43. If no, have you ever tried?
44. If answered none, are you thinking about adopting **cover crops**? Y/N
45. What are your motivations and barriers for this practice?

46. How many of these acres of **annual crops are intercropped** (e.g. grass-legume mixtures)_______
47. If no, have you ever tried?
48. When did you start?
    ____(years)
49. If answered none, are you thinking about adopting? Y/N
50. Why? What are your motivations and barriers for this practice?

51. On your fields that need it (*e.g., gullies-forming*), how many of them have **swales or grass waterways**?

None, and I've never tried	I tried, but stopped	Little	Around half	Most

52. When did you start?

____(years)

53. If answered none, are you thinking about adopting? Y/N

54. To what extent do you have **prairie strips or insectaries** on the land you farm?

None, and I've never tried	I tried, but stopped	Little	Around half	Most

55. When did you start?

____(years)

56. If answered none, are you thinking about adopting? Y/N

57. To what extent do you **reduce tillage** on the land you farm?

None, and I've never tried	I tried, but stopped	Little	Around half	Most

58. Have you reduced the frequency, the intensity, or both?
59. When did you start?

____(years)

60. If answered none, are you thinking about adopting? Y/N

61. On the fields that need it, how much of them have **tile drainage**?

None, and I've never had any	I had it but don't maintain it	Little	Around half	Most

62. When did you start?

____(years)

63. If answered none, are you thinking about adopting? Y/N

64. Do you have access to water for irrigation? Y / N
65. On your fields that need it, how much of them have access to **irrigation**?

None, and they've never had any	They used to but don't anymore	Little	Around half	Most

66. When did you start?

____(years)

67. If answered none, are you thinking about adopting? Y/N

68. How many of your fields have **crop insurance**?

None, and I've never had any	I bought some once, but don't anymore	Little	Around half	Most

69. When did you start?

____(years)

70. If answered none, are you thinking about adopting? Y/N

71. What are your feed rations and/or grazing rotations for milking cows?
72. On average, how much feed do you import? Sell off-farm?
73. *How do you store your feed?*
74. Since you've been farming, have your yields increased, decreased, or stayed the same?
    a. *What do you attribute this to?*
    b. *Have they changed in the past 5 years?*

75. Have you missed planting dates due to inclement weather?

    ____
    a. *What happened as a result?*
    b. *Were you able to plant a short-season variety or a different crop?*

76. In the past 5 years, have you had significant yield loss on your fields?

    ____
    a. *About how many?*
    b. *What happened?*
    c. *Have you had any extreme weather events (e.g., drought, wet spring)?*

    d. *Have you ever gotten disaster payments?*
    e. *Have you gotten any other benefits? (E.g. tax breaks)*
    f. *How have you recovered from them?*

77. Do you think your farm is resilient?
    a. In what way do you think you can cope with change?
    b. To extreme weather?

78. Do you have access to the equipment you need for your practices? Y/N
    a. If no, what equipment would you like to have?

    ____
    b. What custom operations do you employ?
    c. What custom operations do you provide?

Who or where do you go **for information** when considering a change to a land management practice?

GO TO RESPONSE SHEET

CHECK ALL THAT APPLY

1	__Family	10	__Input sales representative: of
2	__Friend	11	what_____________
3	__Neighbor	12	__Milk co-op
4	__Church group	13	__Milk processor
5	__Grazing group	14	__Bank, loan officer
6	__Agronomist/CCA	15	__Cooperative extension
7	__Nutritionist	16	__4H, FFA
8	__Veterinarian	17	__Cornell University
9	__Feed co-op	18	__Soil and water conservation district

19 __Natural resources conservation service
20 __Other (*specify)*:___________

How much do you trust the information of each source with **regard to land management practices**?

GO TO RESPONSE SHEET

(Check a box for each prompt)

	Strongly distrust	Slightly distrust	Neutral	Trust	Strongly trust
Cornell University	☐	☐	☐	☐	☐
Cooperative extension	☐	☐	☐	☐	☐
Veterinarian	☐	☐	☐	☐	☐
Family	☐	☐	☐	☐	☐
Friend	☐	☐	☐	☐	☐
Agronomist/CCA	☐	☐	☐	☐	☐
Nutritionist	☐	☐	☐	☐	☐
Neighbor	☐	☐	☐	☐	☐
Bank/loan officer	☐	☐	☐	☐	☐
Natural Resource Conservation Service	☐	☐	☐	☐	☐
Soil and Water Conservation District	☐	☐	☐	☐	☐
Milk processor	☐	☐	☐	☐	☐
Milk co-op	☐	☐	☐	☐	☐
Input sales representative	☐	☐	☐	☐	☐
Feed co-op	☐	☐	☐	☐	☐
4H, FFA	☐	☐	☐	☐	☐
Church group	☐	☐	☐	☐	☐
Grazing group	☐	☐	☐	☐	☐
Other (*specify*):_______________	☐	☐	☐	☐	☐

79. Which **organizations** are you involved with where you discuss your land management practices?
GO TO RESPONSE SHEET
(Check a box for each prompt)

	Not familiar, Not a member	**Familiar, Not a member**	**Familiar, Non-active Member**	**Familiar, Active Member**
Feed co-op	☐	☐	☐	☐
Church group	☐	☐	☐	☐
4H, FFA	☐	☐	☐	☐
Soil and water conservation district	☐	☐	☐	☐
Milk co-op	☐	☐	☐	☐
Milk processor	☐	☐	☐	☐
Grazing group	☐	☐	☐	☐
Dairy Farmers Association	☐	☐	☐	☐
National Farmers Organization	☐	☐	☐	☐
Farm Bureau	☐	☐	☐	☐
Northeast Dairy Producers Association (NEDPA)	☐	☐	☐	☐
Northeast Organic Farmers Association of New York (NOFA-NY)	☐	☐	☐	☐
NY Certified Organic Association (NYCO)	☐	☐	☐	☐
Northeast Organic Dairy Producers Association (NODPA)	☐	☐	☐	☐
Other:_______________	☐	☐	☐	☐

80. Which **meetings or events** do you attend where you discuss your land management practices?
GO TO RESPONSE SHEET
(Check a box for each prompt)

	Never attended	**Attended once, but no longer attend**	**Attend events, rarely**	**Attend some events**	**Attend most events**
Cooperative extension conferences/meetings	☐	☐	☐	☐	☐
Meetings or Symposia at Cornell	☐	☐	☐	☐	☐
Empire Farm Days	☐	☐	☐	☐	☐
Trade show (not Empire Farm Days)	☐	☐	☐	☐	☐
Grazing group meetings	☐	☐	☐	☐	☐
Milk co-op meetings	☐	☐	☐	☐	☐
Milk processor meetings	☐	☐	☐	☐	☐
Conservation meetings (*e.g., SWCD or Trout Unlimited)* Which ones: _______________	☐	☐	☐	☐	☐
Farmland protection/Agricultural enhancement meetings	☐	☐	☐	☐	☐
Northeast Dairy Producers Association (NEDPA) meetings	☐	☐	☐	☐	☐
Northeast Organic Farmers Association of New York (NOFA-NY) events	☐	☐	☐	☐	☐
New York Certified Organic Association (NYCO) Meetings	☐	☐	☐	☐	☐
Northeast Organic Dairy Producers Association (NODPA) Field Days	☐	☐	☐	☐	☐
Other: ______________ (specify)	☐	☐	☐	☐	☐

81. Where have you heard or read about crop diversification practices like complex crop rotations, double-cropping, intercropping, or have grass waterways or prairie strips?
GO TO RESPONSE SHEET

(Check a box for each prompt)

	Nothing 1	2	3	4	A great deal 5
Agriculture websites	☐	☐	☐	☐	☐
Government websites	☐	☐	☐	☐	☐
Listservs (like Odairy)	☐	☐	☐	☐	☐
Cooperative extension mailings	☐	☐	☐	☐	☐
Technical fact sheets	☐	☐	☐	☐	☐
Where do you get these from? ____________________					
Handouts from milk co-ops	☐	☐	☐	☐	☐
Handouts from milk processors	☐	☐	☐	☐	☐
Handouts from conservation groups	☐	☐	☐	☐	☐
Dairy magazines (more focused on animal nutrition)	☐	☐	☐	☐	☐
Field crop magazines (more focused on agronomy)	☐	☐	☐	☐	☐
Webinars	☐	☐	☐	☐	☐
Radio	☐	☐	☐	☐	☐
Podcasts	☐	☐	☐	☐	☐
Other: ____________________	☐	☐	☐	☐	☐

82. How often do you access these resources?
GO TO RESPONSE SHEET

(Check a box for each prompt)

	Never	Less than monthly	Monthly	Weekly	Daily
Agriculture websites	☐	☐	☐	☐	☐
Government websites	☐	☐	☐	☐	☐
Listservs (like Odairy)	☐	☐	☐	☐	☐
Cooperative extension mailings	☐	☐	☐	☐	☐
Technical fact sheets	☐	☐	☐	☐	☐
Handouts from milk co-ops	☐	☐	☐	☐	☐
Handouts from milk processors	☐	☐	☐	☐	☐
Handouts from conservation groups	☐	☐	☐	☐	☐
Dairy magazines (more focused on animal nutrition)	☐	☐	☐	☐	☐
Field crop magazines (more focused on agronomy)	☐	☐	☐	☐	☐
Webinars	☐	☐	☐	☐	☐
Radio	☐	☐	☐	☐	☐
Podcasts	☐	☐	☐	☐	☐
Other: ________________	☐	☐	☐	☐	☐

83. What best describes your level of education?
GO TO RESPONSE SHEET

- ☐ Less than a high school diploma
- ☐ High school degree or equivalent (e.g. GED)
- ☐ Some college, no degree
- ☐ Associate degree (e.g. AA, AS)
- ☐ Bachelor's degree (e.g. BA, BS)
- ☐ Master's degree (e.g. MA, MS, MEd)
- ☐ Professional degree (e.g. MD, DDS, DVM)
- ☐ Doctorate (e.g. PhD, EdD)

84. What best describes your income level in the past 12 months before taxes?
GO TO RESPONSE SHEET

- ☐ Less than $25,000.
- ☐ $25,000 to $34,999.
- ☐ $35,000 to $49,999.
- ☐ $50,000 to $74,999.
- ☐ $75,000 to $99,999.
- ☐ $100,000 to $149,999.
- ☐ $150,000 to $199,999.
- ☐ $200,000 or more.

85. What is the future of your farm in ten years?
86. Follow-up on any questions that seem relevant resilience-enhancing land management practices.

A.3. Trust to information sources used

Table A. 1. Average trust and standard deviation of information sources farmers that engaged with when seeking to change to a land management practice by farm type.

Category	Position	Conventional		Organic	
		Mean	(sd)	Mean	(sd)
Growing Feed	Agronomist	4.89	(0.33)	4.17	(0.75)
	Grazing group	--	--	4.25	(0.71)
	Nutritionist	4.45	(0.93)	4.50	(0.55)
Community	Church	3.00	NA	4.00	(0.82)
	Family	4.50	(0.55)	4.40	(0.52)
	Friend	4.00	(0.89)	4.00	(0.53)
	Neighbor	3.63	(0.52)	4.00	(0.63)
Cow Care	Milk cooperative	--	--	3.33	(0.58)
	Veterinarian	3.80	(0.84)	4.50	(0.58)
Land Grant	Cornell	4.22	(0.67)	3.80	(1.10)
	Extension	4.14	(0.69)	4.00	NA
Finance	Bank	3.67	(0.82)	4.50	(0.71)
	NRCS	4.43	(0.79)	4.00	(1.41)
	SWCD	4.43	(0.79)	4.50	(1.00)
Input	Input salespeople	3.50	(0.55)	3.00	NA

A.4. Advice sources and relationship characteristics of farmers

Table A. 2. Advice counts by position for each farm type. Average trust and frequency of interaction and their standard deviation is also reported.

Category	Position	Counts		Trust				Frequency			
		Organic	Conventional	Organic		Conventional		Organic		Conventional	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD
Growing Feed	Agronomist	2	9	5.00	0.00	4.78	0.44	2.50	0.71	4.11	0.33
	Employee	3	4	5.00	0.00	4.25	0.50	4.33	0.58	5.00	0.00
	Nutritionist	1	5	4.67	0.58	4.80	0.45	3.67	NA	3.60	0.55
Community	Family	13	4	4.85	0.38	5.00	0.00	2.92	0.90	4.25	0.50
	Friend	16	11	4.56	0.51	4.91	0.30	2.27	0.88	3.00	1.26
	Neighbor	5	6	4.20	0.84	4.80	0.45	3.00	1.00	3.40	0.55
Cow Care	Milk cooperative	1	0	5.00	NA			4.00	NA		
	Veterinarian	3	5	4.67	0.58	4.40	0.89			2.80	1.10
Land Grant	4H/FFA	1	0	5.00	NA			3.00	NA		
	Extension	1	0			5.00	NA			2.00	NA
	Professor	1	3	4.00	NA	5.00	0.00	1.00	NA	2.33	1.15
Financial	Bank	1	0	5.00	NA			3.00	NA		
	Farm Services Agency	0	1			5.00	NA			3.00	NA
	SWCD	0	1			5.00	NA			2.00	NA
Input	Input	7	3	4.57	0.53	5.00	0.00	3.57	1.27	2.67	0.58
Big Data	Benchmark group	0	1			5.00	NA			2.00	NA
	Data scientist	0	1			5.00	NA			4.00	NA
	IT representative	0	1			5.00	NA			3.00	NA

Appendix B

B.1 Cultivar descriptions and seeding rates

Table B. 1. Cultivar names, population by weight, and costs by each diversity treatment per crop. Cultivars in bold denote the ‘head’ cultivar whose population density was matched by the other cultivars of that species.

Crop	Diversity	Species	Cultivar	Seeds per kg^{-1}	Seeding rate kg ha^{-1}	Seed cost \$ kg^{-1}	Seed cost \$ ha^{-1}
Winter annuals	Low	Triticale	Trical 815	27082	237.4	1.06	251.18
	Conspecific	Triticale	**Trical 815**	27082	59.3	1.06	62.79
		Triticale	Fridge	29721	54.1	0.97	52.33
		Triticale	NE426GT	28920	49.7	0.99	49.32
		Triticale	Hy octane	22681	70.9	0.60	42.64
	Heterospecific	Triticale	Trical 815	27082	59.3	1.06	62.79
		Winter Pea	Austrian	9762	49.4	1.41	69.77
		Cereal Rye	Wheeler	30400	63.0	0.90	56.99
		Red Clover	Mammoth	360778	4.2	5.69	23.99
	High	Triticale	**Trical 815**	27082	14.8	1.06	15.70
		Triticale	Fridge	29721	13.5	0.97	13.08
		Triticale	NE426GT	28920	12.4	0.99	12.33
		Triticale	Hy octane	22681	17.7	0.60	10.66
		Cereal Rye	**Wheeler**	30400	15.8	0.90	14.25
		Cereal Rye	Spooner	39599	12.9	0.68	8.82
		Cereal Rye	Aroostook	41520	10.3	1.04	10.63
		Cereal Rye	Guardian	30199	14.9	0.62	9.26

		Winter Pea	**Austrian**	9762	12.4	1.41	17.44
		Winter Pea	Frostmaster	6841	17.6	2.29	40.45
		Winter Pea	Whistler	5401	21.8	1.98	43.30
		Winter Pea	Windham	7802	14.6	1.87	27.38
		Red Clover	**Mammoth**	360778	1.1	5.69	6.00
		Red Clover	Starfire	507668	0.8	8.55	7.01
		Red Clover	Duration	433747	0.9	6.72	6.09
		Red Clover	Freedom	299708	1.3	11.24	14.43
Summer annuals	Low	Sudangrass	Hayking	68537	59.3	4.14	245.94
	Conspecific	Sudangrass	**Hayking**	68537	14.8	4.14	61.49
		Sudangrass	Piper	94887	10.7	2.38	25.51
		Sudangrass	SSG886	57415	17.7	3.53	62.47
		Sudangrass	Promax	72373	14.0	4.63	65.04
	Heterospecific	Sudangrass	Hayking	68537	14.8	4.14	61.49
		Pearl millet	Wonderleaf	154566	10.5	2.56	26.87
		Sorghum sudangrass	Greengrazer	45682	16.5	0.88	14.54
		Ryegrass	Enhancer	331633	7.8	4.01	31.23
	High	Sudangrass	**Hayking**	68537	3.7	4.14	15.37
		Sudangrass	Piper	94887	2.7	2.38	6.38
		Sudangrass	SSG886	57415	4.4	3.53	15.62
		Sudangrass	Promax	72373	3.5	4.63	16.26
		Pearl millet	**Wonderleaf**	154566	2.6	2.56	6.72
		Pearl millet	FSG315	143501	2.7	3.17	8.45
		Pearl millet	Exceed	123823	3.3	2.95	9.69
		Pearl millet	Tifleaf3	137769	2.8	2.42	6.73

		Sorghum sudangrass	**Greengrazer**	45682	3.9	0.88	3.47
		Sorghum sudangrass	400 x 38	38325	4.9	4.76	23.39
		Sorghum sudangrass	AS6401	37190	5.1	2.60	13.17
		Sorghum sudangrass	Sweet 6	34487	5.5	3.00	16.37
		Ryegrass	**Enhancer**	331633	1.9	4.01	7.81
		Ryegrass	Tetraprime	292263	2.3	2.51	5.88
		Ryegrass	Marshall	444051	1.5	1.54	2.24
		Ryegrass	Kodiak	281548	2.3	1.81	4.14
Perennials	Low	Alfalfa	Viking370HD	279191	24.6	12.79	314.99
	Conspecific	Alfalfa	**Viking370HD**	279191	6.2	12.79	78.75
		Alfalfa	FSG 420 LH	536002	3.2	9.26	30.03
		Alfalfa	KF Secure BR	280664	6.2	9.13	56.54
		Alfalfa	Roadrunner	451214	3.9	11.02	42.47
	Heterospecific	Alfalfa	Viking370HD	279191	6.2	12.79	78.75
		Orchardgrass	Extend	827268	7.5	8.38	62.60
		Timothy	Climax	2278947	4.3	6.39	27.70
		White Clover	Alice	796562	1.2	9.79	11.43
	High	Alfalfa	**Viking370HD**	279191	1.5	12.79	19.69
		Alfalfa	FSG 420 LH	536002	0.8	9.26	7.51
		Alfalfa	KF Secure BR	280664	1.5	9.13	14.13
		Alfalfa	Roadrunner	451214	1.0	11.02	10.62
		Orchardgrass	**Extend**	827268	1.9	8.38	15.65
		Orchardgrass	Benchmark Plus	852372	1.6	7.05	11.29
		Orchardgrass	Niva	1052633	1.2	10.23	12.52
		Orchardgrass	Intensiv	1026907	1.3	10.23	13.58

Timothy	**Climax**	2278947	1.1	6.39	6.93
Timothy	Summit	2000002	1.3	4.81	6.39
Timothy	Glacier	2312677	1.2	4.63	5.64
Timothy	Promesse	2447384	1.1	0.44	0.48
White Clover	**Alice**	796562	0.3	9.79	2.86
White Clover	Liflex	867304	0.3	14.64	4.05
White Clover	Ladino	1045808	0.4	8.82	3.14
White Clover	Kopu II	1319646	0.2	13.56	2.55

B.2 Management table NY

Table B. 2. Field operations performed for the experiment in NY.

System	Crop	Year	Month	Day	Operation (planting, tilling, fertilizing, harvesting)	Equipment	Details (planting, tillage = depth (cm); fertilizer = type and amount (kg ha-1))
Double-cropped	Winter annuals	2016	Aug	18	Fertilizer	Liquid dairy manure spreader	65, 478 L ha-1 liquid dairy manure
	Winter annuals	2016	Aug	18	Tillage	Kvernland Moldboard Plow	20 cm depth
	Winter annuals	2016	Sept	9	Planting	John Deere no-till drill	1.27 cm depth
	Winter annuals	2017	May	16	Harvest	RCI forage chopper	10-13 cm height
	Winter annuals	2017	May	TBD	Mowed	John Deere flail chopper	10-13 cm height
	Winter annuals	2017	June	15	Fertilizer	Willmar spinner spreader	1793 kg ha-1 of poultry manure (5-4-3)
	Winter annuals	2017	June	15	Tillage	Sunflower chisel plow; Unverferth rolling harrow	18-23 cm
	Summer annuals	2017	June	18	Planting	John Deere no-till drill	2.54 cm depth
	Summer annuals	2017	Aug	9	Harvest	RCI forage chopper	10-13 cm height
	Summer annuals	2017	Aug	12	Mowed	John Deere flail chopper	10-13 cm height

Summer annuals	2017	Sept	19	Fertilizer	Willmar spinner spreader	2242 kg ha-1 of poultry manure (5-4-3)
Summer annuals	2017	Sept	19	Tillage	Sunflower chisel plow; Unverferth rolling harrow	18-23 cm depth
Winter annuals	2017	Sept	20	Planting	John Deere no-till drill	1.27 cm depth
Winter annuals	2018	May	22	Harvest	RCI forage chopper	10-13 cm height
Winter annuals	2018	May	24	Mowed	John Deere flail chopper	10-13 cm height
Winter annuals	2018	May	25	Tillage	Sunflower chisel plow; Unverferth rolling harrow	18-23 cm
Winter annuals	2018	May	25	Fertilizer	Gandy drop spreader	897 of (5-4-3) and 841 kg ha-1 of (8-2-2) poultry manure
Summer annuals	2018	May	26	Planting	John Deere no-till drill	5 cm depth
Summer annuals	2018	July	13	Harvest	RCI forage chopper	10-13 cm height
Summer annuals	2018	July	13	Mowed	John Deere flail chopper	10-13 cm height
Summer annuals	2018	July	16	Fertilizer	Gandy drop spreader	897 of (5-4-3) and 841 kg ha-1 of (8-2-2) poultry manure
Summer annuals	2018	Aug	21	Harvest	RCI forage chopper	10-13 cm height
Summer annuals	2018	Aug	22	Mowed	John Deere flail chopper	10-13 cm height
Summer annuals	2018	Sept	5	Fertilizer	Gandy drop spreader	2242 kg ha-1 of poultry manure (5-4-3)

	Summer annuals	2018	Sept	5	Tillage	Sunflower chisel plow; Unverferth rolling harrow	18-23 cm depth
	Winter annuals	2018	Sept	6	Planting	John Deere no-till drill	1.27 cm depth
	Winter annuals	2019	May	24	Harvest	RCI forage chopper	
Perennials	Perennials	2016	Aug	18	Fertilizer	Liquid dairy manure spreader	65, 478 L ha-1 liquid dairy manure
	Perennials	2016	Aug	18	Tillage	Kvernland Moldboard Plow	20 cm depth
	Perennials	2016	Aug	20	Planting	John Deere no-till drill	
	Perennials	2017	May	4	Planting	Broadcast with a spinner spreader	all treatments were replantedin their original rates
	Perennials	2017	June	8	Harvest	RCI forage chopper	10-13 cm height
	Perennials	2017	June	10	Mowed	John Deere flail chopper	10-13 cm height
	Perennials	2017	July	28	Fertilizer	Willmar spinner spreader	336 kg ha-1 of potassium sulfate (0-0-51) and 897 kg ha-1 poultry manure (5-4-3)
	Perennials	2017	July	29	Harvest	RCI forage chopper	10-13 cm height
	Perennials	2018	May	23	Mowed	John Deere flail chopper	10-13 cm height
	Perennials	2018	May	24	Harvest	RCI forage chopper	10-13 cm height
	Perennials	2018	June	2	Mowed	John Deere flail chopper	10-13 cm height
	Perennials	2018	July	3	Fertilizer	Gandy drop spreader	57 kg ha-1 of potassium sulfate (0-0-51) and 374 kg ha-1 of poultry manure (5-4-3)
	Perennials	2018	July	3	Harvest	RCI forage chopper	10-13 cm height
	Perennials	2018	July	3	Mowed	John Deere flail chopper	10-13 cm height

	Perennials	2018	Aug	9	Fertilizer	Gandy drop spreader	57 kg ha-1 of potassium sulfate (0-0-51) and 374 kg ha-1 of poultry manure (5-4-3)
	Perennials	2018	Aug	13	Harvest	RCI forage chopper	10-13 cm height
	Perennials	2018	Aug	13	Mowed	John Deere flail chopper	10-13 cm height
	Perennials	2018	Oct	10	Fertilizer	Gandy drop spreader	57 kg ha-1 of potassium sulfate (0-0-51) and 374 kg ha-1 of poultry manure (5-4-3)
	Perennials	2018	Oct	3	Harvest	RCI forage chopper	10-13 cm height
	Perennials	2019	Oct	3	Mowed	John Deere flail chopper	10-13 cm height
	Perennials	2019	May	23	Harvest	RCI forage chopper	10-13 cm height

B.3. Management table NH

Table B. 3. Field operations performed for the field experiment in NH.

System	Crop	Year	Month	Day	Operation (planting, tilling, fertilizing, harvesting)	Equipment	Details (planting, tillage = depth (cm); fertilizer = type and amount (kg ha-1))
Double-cropping	Winter annuals	2016	Aug	early	Fertilizer	Manure Spreader: Gehl, MS325	186 m2 ha-1 of UNH compost
	Winter annuals	2016	Sept	8	Planting	Krauss 5200 NT Drill	Depth was set to the highest setting to accommodate tilled soil. Rolling ahead of planting helped firm seedbed. Furrow was aproximately 1/2" deep. After planting rolled in with Brillion.
	Winter annuals	2017	May	24	Harvest	RCI 36A harvester	10 cm depth
	Winter annuals	2017	May	24	Mowed	RCI 36A harvester	10 cm depth
	Summer annuals	2017	June	20	Fertilizer	Push spreader	1400 kg ha-1 of poultry manure (8-2-2) and 244 kg ha-1 of sul-po-mag (0-0-22)
	Summer annuals	2017	June	20	Lime	Kverneland PS403 Spreader	2.3 Mg ha^{-1}
	Summer annuals	2017	June	21	Tillage	Taylor Way chisel plow	41 cm depth
	Summer annuals	2017	June	26	Prep		If harrowing was sufficient, we would then roll;If necessary or possible, we

							would use a perfecta, then roll and reflag. This was only possible if there was enough time for roots to break down.
	Summer annuals	2017	June	28	Planting	Krauss 5200 NT Drill	
	Summer annuals	2017	Aug	17	Harvest	RCI 36A harvester	10 cm depth
	Summer annuals	2017	Aug	17	Mowed	RCI 36A harvester	10 cm depth
	Winter annuals	2017	Aug	22	Fertilizer	Push spreader	1400 kg ha-1 of poultry manure (8-2-2) and 244 kg ha-1of sul-po-mag (0-0-22)
	Winter annuals	2017	Aug	23	Tillage	Taylor Way Chisel plow	41 cm depth
	Winter annuals	2017	Aug	29	Prep		
	Winter annuals	2017	Sept	22	Planting	Krauss 5200 NT Drill	
	Winter annuals	2018	May	22	Harvest	RCI 36A harvester	10 cm depth
	Winter annuals	2018	May	22	Mowed	RCI 36A harvester	10 cm depth
	Summer annuals	2018	May	25	Fertilizer	Walk-behind spreader	1400 kg ha-1of poultry manure (8-2-2) and 48 kg ha-1 of sul-po-mag (0-0-22)
	Summer annuals	2018	June	1	Tillage	Taylor Way Chisel	41 cm depth
	Summer annuals	2018	June	6	Prep		
	Summer annuals	2018	June	7	Planting	Krauss 5200 NT Drill	
	Summer annuals	2018	July	16	Harvest	RCI 36A harvester	10 cm depth
	Summer annuals	2018	July	16	Mowed	RCI 36A harvester	10 cm depth
	Summer annuals	2018	July	19	Fertilizer	Walk-behind spreader	1400 kg ha-1 of poultry manure (8-2-2)
	Summer annuals	2018	Aug	23	Harvest	RCI 36A harvester	10 cm depth
	Summer annuals	2018	Aug	24	Mowed	RCI 36A harvester	10 cm depth

	Winter annuals	2018	Aug	30	Tillage	Taylor Way Chisel plow	41 cm depth
	Winter annuals	2018	Sept	19	Fertilizer	Walk-behind spreader	1400 kg ha-1 of poultry manure (8-2-2) and 483 kg ha-1 of sul-po-mag (0-0-22)
	Winter annuals	2018	Sept	19	Prep		
	Winter annuals	2018	Sept	21	Planting	Krauss 5200 NT Drill	pass with Brillion
	Winter annuals	2019	June	25	Harvest	RCI 36A harvester	10 cm depth
Perennials	Perennials	2016	Aug	early	Fertilizer	Manure Spreader: Gehl, MS325	186 m2 ha-1 of UNH compost
	Perennials	2016	Aug	31	Planting	Krauss 5200 NT Drill	Rolled with 10-ft Brillion after planting
	Perennials	2017	May	13	Harvest	RCI 36A harvester	10 cm depth
	Perennials	2017	May	13	Mowed	RCI 36A harvester	10 cm depth
	Perennials	2017	June	20	Fertilizer	Push spreader	342 kg ha-1 of poultry manure (8-2-2) and 380 kg ha-1 of sul-po-mag (0-0-22)
	Perennials	2017	June	20	Lime	Kverneland PS403 Spreader	2.3 Mg ha^{-1}
	Perennials	2017	July	26	Harvest	RCI 36A harvester	10 cm depth
	Perennials	2017	July	26	Mowed	RCI 36A harvester	10 cm depth
	Perennials	2017	Aug	1	Fertilizer	Push spreader	342 kg ha-1 of poultry manure (8-2-2) and 380 kg ha-1 of sul-po-mag (0-0-22)
	Perennials	2018	May	31	Harvest	RCI 36A harvester	10 cm depth
	Perennials	2018	May	31	Mowed	RCI 36A harvester	10 cm depth
	Perennials	2018	June	8	Fertilizer	Hand applied	467 kg ha-1 of sul-po-mag (0-0-22)

Perennials	2018	July	10	Harvest	RCI 36A harvester	10 cm depth
Perennials	2018	July	10	Mowed	RCI 36A harvester	10 cm depth
Perennials	2018	July	13	Fertilizer	Hand applied	467 kg ha-1 of sul-po-mag (0-0-22)
Perennials	2018	Aug	9	Harvest	RCI 36A harvester	10 cm depth
Perennials	2018	Aug	9	Mowed	RCI 36A harvester	10 cm depth
Perennials	2018	Aug	16	Fertilizer	Hand applied	467 kg ha-1 of sul-po-mag (0-0-22)
Perennials	2018	Oct	11	Harvest	RCI 36A harvester	10 cm depth
Perennials	2019	June	27	Harvest	RCI 36A harvester	10 cm depth
Perennials	2019	June	27	Mowed	RCI 36A harvester	10 cm depth

B.4. Management table VT

Table B. 4. Field operations performed for the field experiment in VT.

System	Crop	Year	Month	Day	Operation (planting, tilling, fertilizing, harvesting)	Equipment	Details (planting, tillage = depth (cm); fertilizer = type and amount (kg ha-1))
Double-cropped	Winter annuals	2016	Aug	1	Tillage	Moldboard plow	
	Winter annuals	2016	Aug	18	Fertilizer	Tebbes MS140 Box Spreader	6725 kg ha-1 poultry manure (8-2-2)
	Winter annuals	2016	Sept	12	Planting	Sunflower 9412 grain drill	cultipacked after planting
	Winter annuals	2017	May	27	Harvest	Carter harvester	10-13 cm height
	Winter annuals	2017	May	27	Mowed	New Holland 415 discbine	10-13 cm height
	Winter annuals	2017	June	7	Fertilizer	Tebbes MS140 Box Spreader, K by hand	1121 kg ha-1 poultry manure (8-2-2) and 29 kg ha-1 potassium sulfate (0-0-51-18)
	Winter annuals	2017	June	7	Tillage	Aerway™	15.2 cm depth
	Summer annuals	2017	June	8	Planting	Sunflower 9412 grain drill	3.8 cm depth
	Summer annuals	2017	Aug	3	Harvest	Carter harvester	10-13 cm height
	Summer annuals	2017	Aug	4	Mowed	New Holland 415 discbine	10-13 cm height

	Summer annuals	2017	Aug	7	Fertilizer	Tebbes MS140 Box Spreader	1121 kg ha-1 poultry manure (8-2-2) and 29 kg ha-1 potassium sulfate (0-0-51-18)
	Summer annuals	2017	Sept	6	Harvest	Carter harvester	10-13 cm height
	Summer annuals	2017	Sept	8	Fertilizer	Tebbes MS140 Box Spreader, K by hand	1121 kg ha-1 poultry manure (8-2-2) and 56 kg ha-1 potassium sulfate (0-0-51-18)
	Summer annuals	2017	Sept	8	Tillage	Aerway™	15.2 cm depth
	Winter annuals	2017	Sept	11	Planting	Sunflower 9412 grain drill	3.8 cm depth
	Winter annuals	2018	May	25	Harvest	Carter harvester	10-13 cm height
	Winter annuals	2018	May	25	Mowed	New Holland 415 discbine	10-13 cm height
	Winter annuals	2018	May	31	Fertilizer	Tebbes MS140 Box Spreader	1401 kg ha-1 poultry manure (8-2-2) and 84.06 kg ha-1 potassium sulfate (0-0-51-18)
	Winter annuals	2018	May	31	Tillage	Aerway™, disked	15.2 cm depth
	Summer annuals	2018	May	31	Planting	Sunflower 9412 grain drill	3.8 cm depth
	Summer annuals	2018	July	16	Harvest	Carter harvester	10-13 cm height
	Summer annuals	2018	July	16	Mowed	New Holland 415 discbine	10-13 cm height
	Summer annuals	2018	July	16	Fertilizer	Tebbes MS140 Box Spreader, K by hand	1401 kg ha-1 poultry manure (8-2-2)

	Summer annuals	2018	Aug	20	Harvest	Carter harvester	10-13 cm height
	Summer annuals	2018	Aug	20	Mowed	New Holland 415 discbine	10-13 cm height
	Summer annuals	2018	Aug	31	Tillage	Disc TBD; Aerway™	15.2 cm depth
	Summer annuals	2018	Aug	31	Fertilizer	Tebbes MS140 Box Spreader, K by hand	1401 kg ha-1 poultry manure (8-2-2) and 165 kg ha-1 potassium sulfate (0-0-51-18)
	Winter annuals	2018	Aug	31	Planting	Sunflower 9412 grain drill	3.8 cm depth
	Winter annuals	2019	May	28	Harvest	Carter harvester	10-13 cm height
Perennials	Perennials	2016	Aug	18	Fertilizer	Tebbes MS140 Box Spreader	6725 kg ha-1 poultry manure
	Perennials	2016	Aug	24	Tillage	Moldboard plow	
	Perennials	2016	Aug	24	Planting	Sunflower 9412 grain drill	
	Perennials	2017	May	31	Harvest	Carter harvester	10-13 cm height
	Perennials	2017	June	TBD	Mowed	New Holland 415 discbine	10-13 cm height
	Perennials	2017	June	8	Fertilizer	Gandy spreader	263 kg ha-1 potassium sulfate (0-0-51-18)
	Perennials	2017	July	21	Harvest	Carter harvester	10-13 cm height
	Perennials	2017	July	21	Mowed	New Holland 415 discbine	10-13 cm height
	Perennials	2017	Aug	3	Fertilizer	Gandy spreader	263 kg ha-1 potassium sulfate (0-0-51-18)

	Perennials	2017	Sept	1	Reseed	Sunflower 9412 grain drill	alfalfa and clover seeded at 11.2 kg ha-1
	Perennials	2018	May	30	Harvest	Carter harvester	10-13 cm height
	Perennials	2018	May	31	Mowed	New Holland 415 discbine	10-13 cm height
	Perennials	2018	June	6	Fertilizer	Gandy drop spreader	106 kg ha-1 K with potassium sulfate (0-0-51-18)
	Perennials	2018	July	3	Harvest	Carter harvester	10-13 cm height
	Perennials	2018	July	3	Mowed	New Holland 415 discbine	10-13 cm height
	Perennials	2018	July	7	Fertilizer	Gandy drop spreader	140 kg ha-1 K with potassium sulfate (0-0-51-18)
	Perennials	2018	Aug	13	Harvest	Carter harvester	
	Perennials	2018	Aug	13	Mowed	New Holland 415 discbine	10-13 cm height
	Perennials	2019	June	6	Harvest	Carter harvester	10-13 cm height

B.5. Seed costs

Table B. 5. Seed costs of the crop diversity treatments.

Crop	Diversity	$ kg^{-1}	$ ha^{-1}
Winter annuals	Low	1.06	251.18
	Conspecific	0.89	207.09
	Heterospecific	1.21	213.55
	High	1.40	256.83
Summer annuals	Low	4.14	245.94
	Conspecific	3.74	214.50
	Heterospecific	2.70	134.13
	High	3.05	161.68
Perennials	Low	12.79	314.99
	Conspecific	10.68	207.79
	Heterospecific	9.43	180.48
	High	8.20	137.01

B.6. Soils

Table B. 6. Differences of soil characteristics between the annual and perennial cropping systems by site. Untransformed or back-transformed means from the models are reported. Absence of letters indicate no significant pairwise differences at P < 0.05 within an effect term. *SOM was affected by a diversity*system interaction

Soil characteristics	NY			NH			VT		
	P	Annual	Perennial	P	Annual	Perennial	P	Annual	Perennial
pH	**<0.01**	7.92 a	7.83 b	**<0.01**	6.34 a	6.21 b	0.31	6.67	6.97
Aggregate stability (%)	0.78	20.83	21.47	0.97	53.24	53.18	**<0.01**	37.92 a	45.91 b
Bulk density (g cm^{-3})	**<0.01**	1.29 a	1.32 b	0.21	0.33	0.28	0.11	1.45	1.43
Gravimetric moisture (%)	**0.01**	0.17 a	0.16 b	0.18	0.21	0.21	**0.04**	0.16 a	0.13 b
Reactive carbon (mgC kg^{-1})	**0.01**	549.75 a	517.16 b	0.89	560.53	558.10	0.07	657.51	596.67
Soil organic matter (%)	0.97	3.81	3.80	**0.05**	3.54	3.97	**<0.01***	4.74 a	4.22 b
Soil respiration (mgC g^{-1})	0.34	0.75	0.73	0.48	0.45	0.46	0.79	0.74	0.74
Al (ppm)	0.94	5.05	5.03	**<0.01**	61.04 a	74.52 b	0.73	14.77	14.84
Ca (ppm)	0.07	3037.66	2721.41	**<0.01**	600.30 a	521.18 b	0.50	3303.40	3883.75
K (ppm)	**<0.01**	43.06 a	66.78 b	**0.02**	105.73 a	128.00 b	0.49	47.11	48.57
Mg (ppm)	0.25	322.00	308.91	0.10	148.28	160.82	0.92	84.33	95.66
P (ppm)	**<0.01**	14.44 a	3.50 b	**0.01**	6.25 a	5.54 b	**<0.01**	5.76 a	4.33 b
Zn (ppm)	**0.03**	0.58 a	0.47 b	0.79	0.97	0.98	**0.05**	0.54 a	0.44 b
β-1,4-Glucosidase (nmol h^{-1} g^{-1})	0.94	86.37	86.86	**<0.01**	91.44 a	123.72 b	0.48	131.46	126.42

β-1,4-N-Acetyl-glucosaminidase (nmol h^{-1} g^{-1})	0.60	17.35	17.82	**0.02**	40.09	a	51.56	b	0.59	33.37	27.43
L-leucine aminopeptidase (nmol h^{-1} g^{-1})	0.84	102.93	109.24	**0.02**	32.23	a	41.61	b	0.65	99.23	79.60

B.7. Supplememt for winter annuals

Table B. 7. Results from the ANOVA of the winter annuals testing the main effects of diversity treatment, site, year, and their interactions on yield, yield per cost, weed biomass, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Within each site-year, a comparison of treatments with the presence or absence of intra- and interspecific diversity is also presented. Intra – absence consists of the Low and Heterospecific treatments, Intra – presence consists of the Conspecific and High treatments, Inter – absence consists of the Low and Conspecific treatments, and Inter – presence consists of the Heterospecific and High treatments. Untransformed or back-transformed means from the model are reported. The same letters within an effect term indicates no significant pairwise differences at $P < 0.05$. Letter absence indicates no significant differences across all pairwise comparisons of the effect term.

	Yield	Yield per cost	Weed biomass	CP	NDF	ADF
	-------------------------------*P*-------------------------------					
Diversity	**<0.01**	**<0.01**	0.85	0.1	**<0.01**	**<0.01**
Site	0.12	0.13	**<0.01**	**<0.01**	**<0.01**	**<0.01**
Year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**
Diversity × site	0.63	0.71	0.29	**<0.01**	**<0.01**	**<0.01**
Diversity × year	0.49	0.09	0.05	**<0.01**	**<0.01**	**<0.01**
Site × year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**0.0**
Diversity × site × year	0.71	0.49	**<0.01**	0.6	**0.0**	**<0.01**
	(kg ha^{-1})	(kg ha^{-1} \$$^{-1}$)	(kg ha^{-1})		(% of DM)	
Diversity						
Low	4318 b	17.19 c	30	12.4	59.1 bc	35.0 b
Conspecific	4311 b	20.82 ab	24	12.3	59.0 c	35.0 b
Heterospecific	4883 a	22.87 a	28	12.4	60.4 ab	35.9 ab
High	4768 ab	18.57 bc	25	12.0	61.6 a	36.9 a
Site						
NY	4207	18.33	57 a	11.1 b	61.0 b	36.1 b

NH	5227		22.68		4	b	9.8	c	66.8	a	40.3	a
VT	4276		18.57		42	a	15.8	a	52.2	c	30.7	c
Year												
2017	5868	a	25.53	a	8	c	12.8	b	60.1	ab	36.8	a
2018	2938	c	12.72	c	26	b	10.8	c	59.2	b	34.7	c
2019	4904	b	21.33	b	67	a	13.3	a	60.8	a	35.7	b
Diversity × site												
NY												
Low	3729		14.85		41		11.0		60.2	ab	35.3	bc
Conspecific	4209		20.33		47		11.1		59.1	b	34.3	c
Heterospecific	4491		21.03		86		11.6		62.2	a	37.6	a
High	4397		17.12		63		10.9		62.5	a	37.1	ab
NH												
Low	5158		20.54		9		9.7		68.0		41.0	a
Conspecific	4695		22.67		3		10.0		67.2		41.3	a
Heterospecific	5638		26.4		3		9.6		65.9		39.3	b
High	5418		21.1		2		10.0		66.2		39.7	ab
VT												
Low	4068		16.19		55		16.7	a	49.1	c	28.7	c
Conspecific	4028		19.45		43		15.7	ab	50.7	c	29.3	bc
Heterospecific	4520		21.17		33		15.8	ab	53.2	b	30.9	b
High	4489		17.48		39		14.9	b	56.0	a	33.8	a
Diversity × year												
2017												
Low	5423		21.59		10		13.3	a	57.0	b	34.6	b
Conspecific	5606		27.07		1		13.3	a	57.6	b	34.6	b
Heterospecific	6333		29.66		12		12.5	ab	61.8	a	38.2	a
High	6111		23.79		11		12.0	b	63.9	a	39.9	a
2018												
Low	3071		12.23		23		10.3		59.1		34.3	
Conspecific	2607		12.59		28		10.6		58.7		34.6	
Heterospecific	3082		14.43		29		11.2		59.2		35.0	

	High	2992		11.65		25		10.9		59.6		34.7	
2019													
	Low	4462		17.76		84		13.7		61.3		36.2	
	Conspecific	4720		22.79		85		12.9		60.6		35.8	
	Heterospecific	5234		24.51		54		13.4		60.2		34.6	
	High	5202		20.25		51		13.0		61.2		36.0	
Site × year													
NY													
	2017	4943	a	21.61	a	6	c	11.2		61.8		36.8	a
	2018	2884	b	12.42	b	59	b	11.1		60.0		34.8	b
	2019	4793	a	20.96	a	260	a	11.2		61.2		36.7	a
NH													
	2017	5450	a	23.61	a	0	b	10.8	a	69.5	a	42.0	a
	2018	4375	b	18.99	b	1	b	7.6	b	65.1	b	39.7	b
	2019	5856	a	25.43	a	15	a	11.1	a	65.9	b	39.4	b
VT													
	2017	7211	a	31.36	a	25	b	16.3	b	48.9	c	31.7	a
	2018	1554	c	6.76	c	50	ab	13.6	c	52.5	b	29.4	b
	2019	4063	b	17.6	b	56	a	17.5	a	55.4	a	30.9	a
Diversity × site × year													
NY 2017													
	Low	4205		16.74		9		11.4		59.6	b	35.0	bc
	Conspecific	5321		25.69		3		11.6		59.5	b	34.7	c
	Heterospecific	5226		24.47		10		11.0		62.8	ab	38.0	ab
	High	5021		19.55		3		10.7		65.3	a	39.5	a
	Intra – absence	4716		20.605		10		11.2		61.2		36.5	
	Intra – presence	5171		22.62		3		11.2		62.4		37.1	
	Inter – absence	4763		21.215		6		11.5		59.6	b	34.9	b
	Inter – presence	5124		22.01		7		10.9		64.1	a	38.8	a

	2018										
	Low	2989	11.9	24	b	10.4	59.4		34.0		
	Conspecific	2429	11.73	38	ab	10.7	58.2		33.3		
	Heterospecific	2831	13.25	164	a	12.2	60.6		36.1		
	High	3288	12.8	70	ab	11.0	61.7		35.9		
	Intra – absence	2910	12.575	94		11.3	60.0		35.1		
	Intra – presence	2859	12.265	54		10.9	60.0		34.6		
	Inter – absence	2709	11.815	31	b	10.6	58.8		33.7	b	
	Inter – presence	3060	13.025	117	a	11.6	61.2		36.0	a	
	2019										
	Low	3995	15.9	192		11.1	61.7		37.0	ab	
	Conspecific	4878	23.56	275		11.0	59.6		35.0	b	
	Heterospecific	5416	25.36	237		11.6	63.1		38.8	a	
	High	4883	19.01	361		11.0	60.5		36.1	ab	
	Intra – absence	4706	20.63	215		11.4	62.4	a	37.9	a	
	Intra – presence	4881	21.285	318		11.0	60.1	b	35.6	b	
	Inter – absence	4437	19.73	234		11.1	60.7		36.0		
	Inter – presence	5150	22.185	299		11.3	61.8		37.5		
NH	2017										
	Low	5471	21.78	0		10.9	67.6	b	40.2	b	
	Conspecific	4646	22.44	0		11.3	66.7	b	39.7	b	
	Heterospecific	5973	27.97	0		10.5	71.6	a	43.9	a	
	High	5710	22.23	0		10.6	72.0	a	44.0	a	
	Intra – absence	5722	24.875	0		10.7	69.6		42.1		
	Intra – presence	5178	22.335	0		11.0	69.4		41.9		

Inter – absence	5059	b	22.11		0		11.1		67.2	b	40.0	b
Inter – presence	5842	a	25.1		0		10.6		71.8	a	44.0	a
2018												
Low	4536		18.06		3		6.8		67.2	a	41.4	a
Conspecific	4114		19.86		1		7.5		67.8	a	42.9	a
Heterospecific	4536		21.24		0		7.8		63.3	b	38.1	b
High	4316		16.8		1		8.4		61.9	b	36.4	b
Intra – absence	4536		19.65		2		7.3		65.3		39.8	
Intra – presence	4215		18.33		1		8.0		64.9		39.7	
Inter – absence	4325		18.96		2		7.2	b	67.5	a	42.2	a
Inter – presence	4426		19.02		1		8.1	a	62.6	b	37.3	b
2019												
Low	5469		21.77		39		11.3		69.3	a	41.5	a
Conspecific	5325		25.71		12		11.2		67.0	ab	41.5	a
Heterospecific	6403		29.99		14		10.5		62.7	c	35.8	b
High	6228		24.25		6		11.2		64.7	bc	38.8	a
Intra – absence	5936		25.88		27		10.9		66.0		38.7	
Intra – presence	5777		24.98		9		11.2		65.9		40.2	
Inter – absence	5397	b	23.74	b	26		11.3		68.2	a	41.5	a
Inter – presence	6316	a	27.12	a	10		10.9		63.7	b	37.3	b
VT 2017												
Low	6592		26.25		32	a	17.5		43.6	b	28.5	c
Conspecific	6852		33.09		0	b	17.0		46.7	b	29.5	c
Heterospecific	7801		36.53		43	a	15.9		51.0	a	32.7	b
High	7601		29.59		57	a	14.7		54.3	a	36.1	a
Intra – absence	7197		31.39		38		16.7	a	47.3	b	30.6	b

Intra – presence	7227		31.34	29		15.9	b	50.5	a	32.8	a
Inter – absence	6722	b	29.67	16	b	17.3	a	45.2	b	29.0	b
Inter – presence	7701	a	33.06	50	a	15.3	b	52.7	a	34.4	a
2018											
Low	1689		6.72	69		13.8		50.8	b	27.5	b
Conspecific	1278		6.17	97		13.7		50.2	b	27.6	b
Heterospecific	1878		8.79	23		13.5		53.6	ab	30.7	a
High	1373		5.35	37		13.4		55.3	a	31.9	a
Intra – absence	1784		7.755	46		13.7		52.2		29.1	
Intra – presence	1326		5.76	67		13.6		52.8		29.8	
Inter – absence	1484		6.445	83	a	13.8		50.5	b	27.6	b
Inter – presence	1626		7.07	30	b	13.5		54.5	a	31.3	a
2019											
Low	3922		15.61	73	ab	18.8		52.9	b	30.2	b
Conspecific	3956		19.1	130	a	16.6		55.1	ab	30.9	ab
Heterospecific	3882		18.18	35	ab	18.1		54.9	ab	29.2	b
High	4494		17.5	27	b	16.8		58.5	a	33.3	a
Intra – absence	3902		16.895	54		18.5	a	53.9	b	29.7	b
Intra – presence	4225		18.3	79		16.7	b	56.8	a	32.1	a
Inter – absence	3939		17.355	102	a	17.7		54.0	b	30.6	
Inter – presence	4188		17.84	31	b	17.5		56.7	a	31.3	

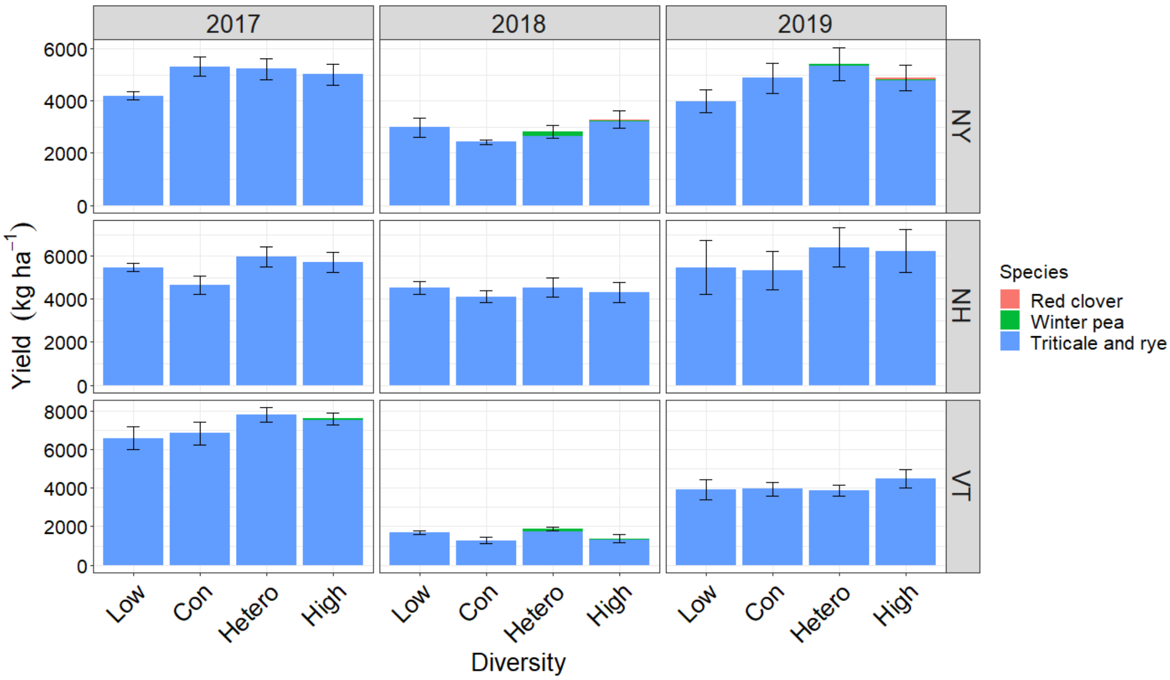

Figure B. 1. Stacked bar charts of yield by species for each harvest of the winter annuals. Standard error bars reflect the variability of total yield in each diversity level. Low and Conspecific treatments contained only triticale. Triticale, cereal rye, winter pea, and red clover were planted in the Heterospecific and High treatments. Triticale and rye were not separated due to difficulty visually differentiating species.

B.8. Common weeds by biomass

Table B. 8. Top five weeds contributing the most biomass to each crop in each site.

Crop	NY	NH	VT
Winter annuals			
	Stellaria media (L.) Vill.	*Veronica peregrina* L.	*Silene latifolia* Poir.
	Elymus repens (L.) Gould	*Vicia* spp.	*Taraxacum officinale* F. H. Wigg.
	Lamium purpureum L.	*Capsella bursa-pastoris* (L.) Medik.	*Capsella bursa-pastoris* (L.) Medik.
	Lolium multiflorum Lam.	*Chenopodium album* L.	*Noccaea perfoliata* (L.) Al-Shehbaz
	Rumex crispus L.	*Lamium amplexicaule* L.	*Festuca* spp.
Summer annuals			
	Ambrosia artemisiifolia L.	*Chenopodium album* L.	*Galinsoga quadriradiata* Cav.
	Persicaria maculosa Gray	*Amaranthus* spp.	*Amaranthus* spp.
	Setaria viridis (L.) P. Beauv.	*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.	*Setaria viridis* (L.) P. Beauv.
	Setaria pumila (Poir.) Roem. & Schult.	*Digitaria sanguinalis* (L.) Scop.	*Elymus repens* (L.) Gould
	Bromus tectorum L.	*Portulaca oleracea* L.	*Chenopodium album* L.
Perennials			
	Taraxacum officinale F. H. Wigg.	*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.	*Silene latifolia* Poir.
	Poa trivialis L.	*Sinapis arvensis* L.	*Capsella bursa-pastoris* (L.) Medik.
	Ambrosia artemisiifolia L.	*Digitaria sanguinalis* (L.) Scop.	*Festuca* spp.
	Plantago major L.	*Elymus repens* (L.) Gould	*Taraxacum officinale* F. H. Wigg.
	Poa annua L.	*Silene latifolia* Poir.	*Elymus repens* (L.) Gould

B.9. Supplement for summer annuals

Table B.9. Results from the ANOVA of the summer annuals testing the main effects of diversity treatment, site, year, cut, and their specified interactions on yield, yield per cost, weed biomass, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Within each site-year, a comparison of treatments with the presence or absence of intra- and interspecific diversity is also presented. Intra – absence consists of the Low and Heterospecific treatments, Intra – presence consists of the Conspecific and High treatments, Inter – absence consists of the Low and Conspecific treatments, and Inter – presence consists of the Heterospecific and High treatments. Untransformed or back-transformed means from the model are reported. The same letters within an effect term indicates no significant pairwise differences at P < 0.05. Letter absence indicates no significant differences between all pairwise comparison within an effect term.

	Yield	Yield per cost		Weed biomass		CP	NDF		ADF
		--------------------------------*P*--------------------------------							
Diversity	0.45	**<0.01**		**0.01**		0.50	**<0.01**		0.06
Site	**<0.01**	**<0.01**		**<0.01**		**<0.01**	**<0.01**		**<0.01**
Year	**<0.01**	**<0.01**		**<0.01**		**<0.01**	0.06		**<0.01**
Diversity × site	**<0.01**	**<0.01**		0.06		0.10	**<0.01**		0.14
Diversity × year	**0.04**	**<0.01**		0.08		**<0.01**	0.64		0.23
Site × year	**<0.01**	**<0.01**		**<0.01**		**<0.01**	**<0.01**		**<0.01**
Diversity × site × year	**<0.01**	**<0.01**		**<0.01**		**<0.01**	**<0.01**		**<0.01**
	(kg ha^{-1})	(kg ha^{-1} $\$^{-1}$)		(kg ha^{-1})			(% of DM)		
Diversity									
Low	5295	21.53	c	921	a	14.0	58.9	ab	35.9
Conspecific	5792	27.00	c	660	ab	13.8	59.4	a	35.7
Heterospecific	5792	43.18	a	662	ab	14.2	57.4	c	34.6
High	5838	36.11	b	587	b	14.0	57.9	bc	35.2
Site									

NY	6492	a	35.84	a	560	b	11.9	c	63.0	a	39.3	a
NH	4573	b	25.54	b	1573	a	14.4	b	57.3	b	35.5	b
VT	5974	a	34.49	a	382	b	15.7	a	54.8	c	31.3	c
Year												
2017	3293	b	18.80	b	889	a	12.6	b	58.7		36.9	a
2018	8066	a	45.11	a	546	b	15.4	a	58.1		33.8	b
Diversity × site												
NY												
Low	6650		27.04	b	720		12.1		62.8	ab	39.6	
Conspecific	7200		33.56	b	466		12.0		63.5	ab	39.1	
Heterospecific	6154		45.88	a	716		12.0		61.5	b	38.3	
High	5964		36.89	ab	409		11.3		64.3	a	40.0	
NH												
Low	4453		18.10	b	1801		14.0		59.1	a	37.0	a
Conspecific	4943		23.04	b	1398		14.3		59.1	a	36.0	ab
Heterospecific	4716		35.16	a	1451		14.8		56.2	b	34.5	b
High	4180		25.86	b	1675		14.5		54.7	b	34.4	b
VT												
Low	4784	b	19.45	b	600	a	15.9		54.7		31.2	
Conspecific	5235	b	24.40	b	438	ab	15.2		55.5		31.8	
Heterospecific	6507	ab	48.51	a	276	b	15.7		54.5		31.0	
High	7370	a	45.58	a	292	b	16.0		54.6		31.2	
Diversity × year												
2017												
Low	2780		11.31	b	1216	a	12.5		58.9	ab	37.1	
Conspecific	3134		14.61	b	850	ab	12.7		60.0	a	37.3	
Heterospecific	3470		25.87	a	744	b	12.6		57.6	b	36.3	
High	3787		23.42	a	810	ab	12.5		58.2	ab	36.8	

2018													
Low	7810		31.76	d	697	a	15.5	ab	58.8	a	34.8	a
Conspecific	8451		39.40	c	512	ab	15.0	b	58.8	a	34.0	ab
Heterospecific	8114		60.50	a	588	ab	15.7	a	57.1	b	32.9	b
High	7889		48.79	b	425	b	15.4	ab	57.5	ab	33.6	ab
Site × year												
NY												
2017	1622	b	8.76	b	657	a	9.6	b	61.6	b	40.7	a
2018	11362	a	62.93	a	478	b	14.1	a	64.4	a	37.9	b
NH												
2017	2868	b	15.76	b	2305	a	12.1	b	60.7	a	39.9	a
2018	6278	a	35.32	a	1072	b	16.7	a	53.8	b	31.1	b
VT												
2017	5388	b	31.89	b	460	a	16.0	a	53.7	b	30.1	b
2018	6559	a	37.09	a	317	b	15.4	b	55.9	a	32.5	a
Diversity × site × year												
NY 2017												
Low	1713		6.97		747		9.6		61.2	ab	40.8	
Conspecific	1987		9.26		587		9.7		63.5	a	41.2	
Heterospecific	1228		9.15		682		10.1		58.7	b	38.9	
High	1559		9.64		623		9.0		63.1	a	41.9	
Intra – absence	1470		8.06		714		9.8		60.0	b	39.8	b
Intra – presence	1773		9.45		605		9.4		63.3	a	41.6	a
Inter – absence	1850		8.12		667		9.7		62.3		41.0	
Inter – presence	1393		9.40		652		9.5		60.9		40.4	

	2018												
	Low	11586	ab	47.11	c	694	ab	14.5		64.4		38.5	
	Conspecific	12412	a	57.86	b	370	bc	14.3		63.6		37.0	
	Heterospecific	11080	ab	82.61	a	752	a	13.9		64.3		37.8	
	High	10368	b	64.13	b	267	c	13.7		65.5		38.2	
	Intra – absence	11333		64.86		723	a	14.2		64.3		38.1	
	Intra – presence	11390		61.00		319	b	14.0		64.5		37.6	
	Inter – absence	11999	a	52.49	b	532		14.4	a	64.0		37.8	
	Inter – presence	10724	b	73.37	a	510		13.8	b	64.9		38.0	
NH	2017												
	Low	3093		12.58		2503		11.7		61.7	a	40.6	
	Conspecific	3271		15.25		1957		12.2		63.0	a	40.7	
	Heterospecific	2850		21.25		2303		11.8		60.5	ab	39.9	
	High	2258		13.97		2501		12.6		57.7	b	38.3	
	Intra – absence	2972		16.91		2403		11.8	b	61.1		40.3	
	Intra – presence	2765		14.61		2229		12.4	a	60.3		39.5	
	Inter – absence	3182		13.91		2230		12.0		62.3	a	40.7	a
	Inter – presence	2554		17.61		2402		12.2		59.1	b	39.1	b
	2018												
	Low	5812		23.63	c	1295		16.3	b	56.5	a	33.4	a
	Conspecific	6615		30.84	bc	998		16.4	b	55.2	a	31.4	ab
	Heterospecific	6581		49.07	a	913		17.8	a	51.8	b	29.0	c
	High	6103		37.75	b	1121		16.5	b	51.8	b	30.4	bc

		Intra – absence	6197		36.35		1104		17.0	a	54.2		31.2	
		Intra – presence	6359		34.29		1059		16.4	b	53.5		30.9	
		Inter – absence	6213		27.23	b	1146		16.3	b	55.8	a	32.4	a
		Inter – presence	6342		43.41	a	1017		17.1	a	51.8	b	29.7	b
VT	2017													
		Low	3535	b	14.37	b	958	a	16.1		53.8		29.9	
		Conspecific	4143	b	19.31	b	532	ab	16.1		53.5		29.9	
		Heterospecific	6332	a	47.21	a	258	c	16.0		53.7		30.2	
		High	7544	a	46.66	a	337	bc	16.0		53.8		30.3	
		Intra – absence	4933		30.79		608		16.0		53.7		30.0	
		Intra – presence	5843		32.99		434		16.1		53.6		30.1	
		Inter – absence	3839	b	16.84	b	745	a	16.1		53.6		29.9	
		Inter – presence	6938	a	46.93	a	298	b	16.0		53.7		30.2	
	2018													
		Low	6033		24.53	b	375		15.7	a	55.7		32.5	
		Conspecific	6326		29.49	b	360		14.4	b	57.5		33.7	
		Heterospecific	6682		49.82	a	294		15.5	ab	55.2		31.9	
		High	7196		44.51	a	252		15.9	a	55.4		32.2	
		Intra – absence	6326		29.49		360		14.4		57.5		33.7	
		Intra – presence	6357		37.17		334		15.6		55.4		32.2	
		Inter – absence	6033		24.53	b	375		15.7	a	55.7		32.5	
		Inter – presence	6504		39.66	a	327		14.9	b	56.4		32.8	

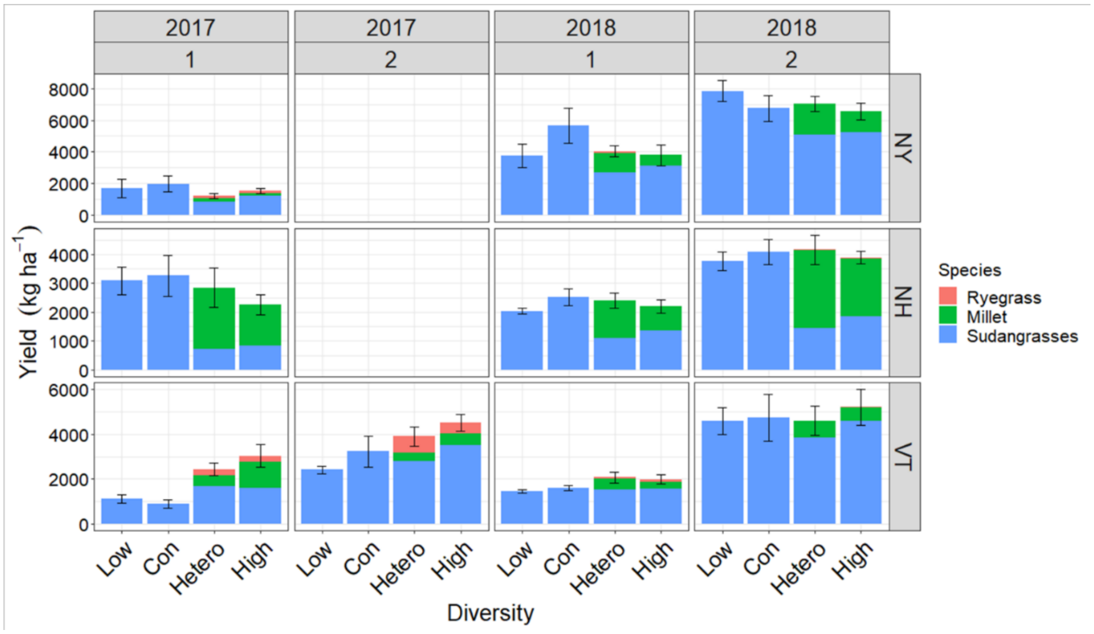

Figure B2. Stacked bar charts of yield by species for each harvest of the perennials. Numbers in the panel beneath the year refer to the number of cuts taken. Standard error bars reflect the variability of total yield in each diversity level. Con and Hetero in the x-axis refer to Conspecific and Heterospecific diversity treatments.

B.10. Supplement for perennials

Table B. 9. Site, year, and diversity treatment interaction results from the ANOVA of the summer annuals on yield, yield per cost, weed biomass, crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Within each site-year, a comparison of treatments with the presence or absence of intra- and interspecific diversity is also presented. Intra – absence consists of the Low and Heterospecific treatments, Intra – presence consists of the Conspecific and High treatments, Inter – absence consists of the Low and Conspecific treatments, and Inter – presence consists of the Heterospecific and High treatments. Untransformed or back-transformed means from the model are reported. The same letters within an effect term indicates no significant pairwise differences at P < 0.05. Letter absence indicates no significant differences between all pairwise comparison within an effect term.

	Yield	Yield per cost	Weed biomass	CP	NDF		ADF
		--------------------------------*P*--------------------------------					
Diversity	0.45	**<0.01**	**0.01**	0.50	**<0.01**		0.06
Site	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**		**<0.01**
Year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	0.06		**<0.01**
Diversity × site	**<0.01**	**<0.01**	0.06	0.10	**<0.01**		0.14
Diversity × year	**0.04**	**<0.01**	0.08	**<0.01**	0.64		0.23
Site × year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**		**<0.01**
Diversity × site × year	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**		**<0.01**
	($kg\ ha^{-1}$)	($kg\ ha^{-1}\ \$^{-1}$)	($kg\ ha^{-1}$)		(% of DM)		
Diversity × site × year							
NY 2017							
Low	1713	6.97	747	9.6	61.2	ab	40.8
Conspecific	1987	9.26	587	9.7	63.5	a	41.2
Heterospecific	1228	9.15	682	10.1	58.7	b	38.9
High	1559	9.64	623	9.0	63.1	a	41.9

	Intra – absence	1470		8.06		714		9.8		60.0	b	39.8	b
	Intra – presence	1773		9.45		605		9.4		63.3	a	41.6	a
	Inter – absence	1850		8.12		667		9.7		62.3		41.0	
	Inter – presence	1393		9.40		652		9.5		60.9		40.4	
	2018												
	Low	11586	ab	47.11	c	694	ab	14.5		64.4		38.5	
	Conspecific	12412	a	57.86	b	370	bc	14.3		63.6		37.0	
	Heterospecific	11080	ab	82.61	a	752	a	13.9		64.3		37.8	
	High	10368	b	64.13	b	267	c	13.7		65.5		38.2	
	Intra – absence	11333		64.86		723	a	14.2		64.3		38.1	
	Intra – presence	11390		61.00		319	b	14.0		64.5		37.6	
	Inter – absence	11999	a	52.49	b	532		14.4	a	64.0		37.8	
	Inter – presence	10724	b	73.37	a	510		13.8	b	64.9		38.0	
NH	2017												
	Low	3093		12.58		2503		11.7		61.7	a	40.6	
	Conspecific	3271		15.25		1957		12.2		63.0	a	40.7	
	Heterospecific	2850		21.25		2303		11.8		60.5	ab	39.9	
	High	2258		13.97		2501		12.6		57.7	b	38.3	
	Intra – absence	2972		16.91		2403		11.8	b	61.1		40.3	
	Intra – presence	2765		14.61		2229		12.4	a	60.3		39.5	
	Inter – absence	3182		13.91		2230		12.0		62.3	a	40.7	a
	Inter – presence	2554		17.61		2402		12.2		59.1	b	39.1	b

	2018													
		Low	5812		23.63	c	1295		16.3	b	56.5	a	33.4	a
		Conspecific	6615		30.84	bc	998		16.4	b	55.2	a	31.4	ab
		Heterospecific	6581		49.07	a	913		17.8	a	51.8	b	29.0	c
		High	6103		37.75	b	1121		16.5	b	51.8	b	30.4	bc
		Intra – absence	6197		36.35		1104		17.0	a	54.2		31.2	
		Intra – presence	6359		34.29		1059		16.4	b	53.5		30.9	
		Inter – absence	6213		27.23	b	1146		16.3	b	55.8	a	32.4	a
		Inter – presence	6342		43.41	a	1017		17.1	a	51.8	b	29.7	b
VT	2017													
		Low	3535	b	14.37	b	958	a	16.1		53.8		29.9	
		Conspecific	4143	b	19.31	b	532	ab	16.1		53.5		29.9	
		Heterospecific	6332	a	47.21	a	258	c	16.0		53.7		30.2	
		High	7544	a	46.66	a	337	bc	16.0		53.8		30.3	
		Intra – absence	4933		30.79		608		16.0		53.7		30.0	
		Intra – presence	5843		32.99		434		16.1		53.6		30.1	
		Inter – absence	3839	b	16.84	b	745	a	16.1		53.6		29.9	
		Inter – presence	6938	a	46.93	a	298	b	16.0		53.7		30.2	
	2018													
		Low	6033		24.53	b	375		15.7	a	55.7		32.5	
		Conspecific	6326		29.49	b	360		14.4	b	57.5		33.7	
		Heterospecific	6682		49.82	a	294		15.5	ab	55.2		31.9	
		High	7196		44.51	a	252		15.9	a	55.4		32.2	

Intra – absence	6326	29.49		360	14.4		57.5	33.7
Intra – presence	6357	37.17		334	15.6		55.4	32.2
Inter – absence	6033	24.53	b	375	15.7	a	55.7	32.5
Inter – presence	6504	39.66	a	327	14.9	b	56.4	32.8

Appendix C

C.1. Intended and actual seeding density

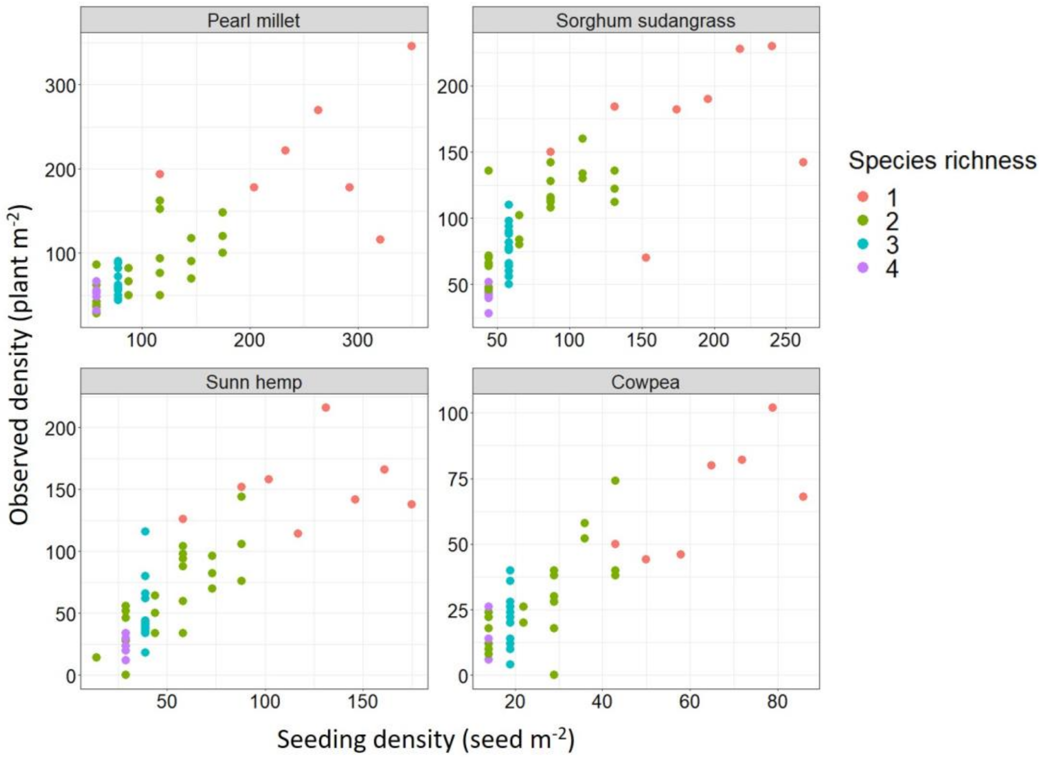

Figure C. 1. The intended seeding density of each species by the observed density. Monoculture seeding rates of a species were typically greater than those of mixtures. The density of cowpea and sunn hemp generally increased with higher seeding rates. However, the density of the two grasses, particularly pearl millet, responded with greater variability to increased seeding rates.

C.2. Linear yield-density model

$$\frac{1}{W_1} = \frac{N_1}{Y_{1,2}} = b_{1,0} + b_{1,1} * N_1 + b_{1,2} * N_2 \qquad \text{(Eq. C1)}$$

The linear relationship of the yield-density model of a two-species mixture (Eq 2), in which W_1 is the per plant weight of species *1* in a biculture of species *1* and *2*. N_1 and N_2 are the plant densities of each species and $Y_{1,2}$ is the biomass of species *1* in the biculture. The term $b_{1,0}$ is the intercept. The term $b_{1,1}$ ($m^2\ g^{-1}$) is a measure of intraspecific competition and describes how the per plant weight (W_1) decreases when additional plants of the same species are added. The term $b_{1,2}$ ($m^2\ g^{-1}$) is a measure of interspecific competition of species *2* on species *1* and describes how the per plant weight (W_1) decreases when plants of species *2* are added.

C.3 Graphical illustration of yield-density model in various scenarios

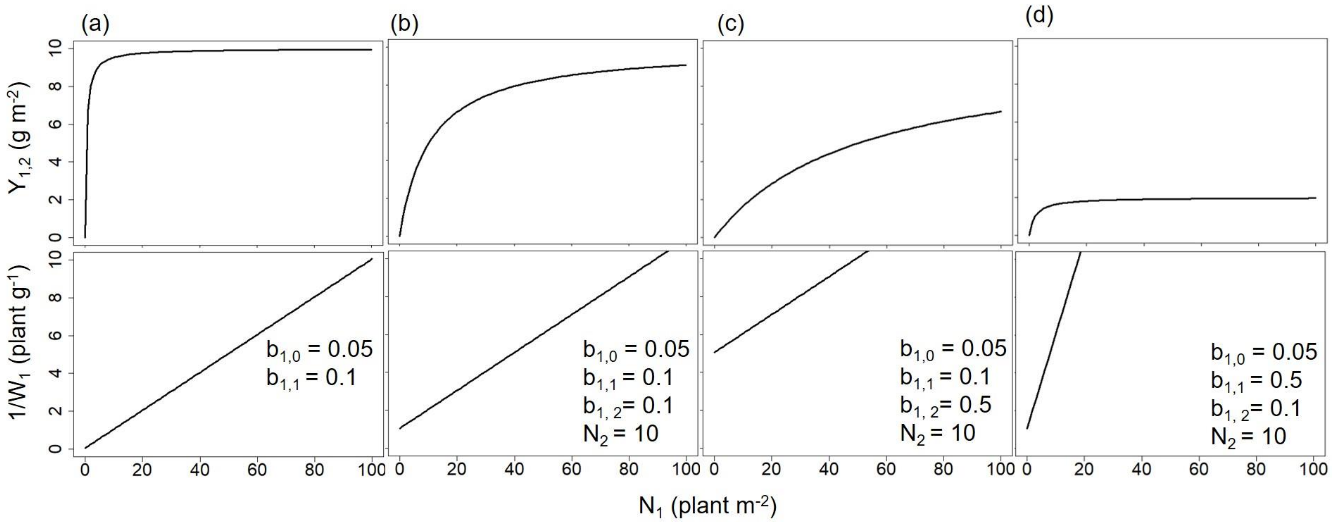

Figure C. 2. Different competition scenarios of the yield-density relationship between species, *1* and *2*, as described by Eq 2. The upper panels represent the hyperbolic relationship between biomass and density and the lower panels represent the linear reciprocal of the hyperbolic model. a) As species *2* is absent, only intraspecific competition is present. b) Intra- and interspecific competition are the same. c) Intraspecific competition remains the same as in (a) and (b), while interspecific competition has increased; as a result the slope of the line is the same as in (a) and (b), but the *y* intercept of the linear model has shifted upwards. d) Intraspecific competition has increased, while interspecific competition is the same as in (b); as a result, the slope of the linear model has increased, but the *y* intercept is the same as in (b). $Y_{1,2}$ is the biomass (g m^{-2}) of species *1* in a biculture with species *2*, N is the density (plant m^{-2}), $b_{1,0}$ is the intercept, $b_{1,1}$ represents intraspecific competition, $b_{1,2}$ represents the interspecific competition. To focus on the changes from competition, $b_{1,0}$ was kept constant in all scenarios, although this is unlikely to occur.

C.4. Raw competition coefficients

Table C. 1. Raw competition coefficients and their standard errors, as determined by Eq 1 and Eq 2.

Treatments	Species	b1,0 (plant g^{-1})	SE	b1,1 (m^2 g^{-1})	SE	b1,2 (m^2 g^{-1})	SE
M	M	0.1336	0.1290	0.0028	0.0006		
S	S	0.0491	0.0160	0.0019	0.0001		
H	H	0.1606	0.0728	0.0021	0.0005		
C	C	0.0930	0.0166	0.0033	0.0003		
MS	M	0.1319	0.0950	0.0028	0.0005	0.0082	0.0042
MS	S	0.0658	0.0241	0.0018	0.0002	0.0002	0.0002
MH	M	0.1646	0.0922	0.0027	0.0005	0.0029	0.0012
MH	H	0.2091	0.0577	0.0018	0.0004	0.0013	0.0004
MC	M	0.1920	0.0902	0.0026	0.0005	0.0008	0.0022
MC	C	0.0970	0.0145	0.0033	0.0004	0.0033	0.0004
SH	S	0.0839	0.0267	0.0017	0.0002	0.0007	0.0003
SH	H	0.1502	0.0548	0.0022	0.0004	0.0043	0.0007
SC	S	0.0644	0.0260	0.0018	0.0002	0.0015	0.0006
SC	C	0.1007	0.0218	0.0032	0.0004	0.0041	0.0007
HC	H	0.1548	0.0430	0.0022	0.0003	0.0017	0.0010
HC	C	0.0931	0.0128	0.0033	0.0002	0.0034	0.0004

The model for the bicultures generated intraspecific competition coefficients that were quite similar to the intraspecific coefficients generated by the monocultures. Thus the decrease of per plant weight from an additional plant of the same species in a biculture was similar to the rate in monoculture. In some instances, some of the ranges of intraspecific competition (coefficient +/- SE) of the bicultures did fall outside of the monoculture ranges (Appendix S1: Table S1). The pearl millet in the MC biculture had a lower competition coefficient than in monoculture, meaning an additional pearl millet plant in biculture did not cause as much of a decrease in per plant weight as an additional plant in monoculture. The same is true for sunn hemp in the MH biculture and cowpea in the SC biculture. Cowpea in the MC biculture had a greater range of intraspecific competition coefficients, signaling the potential for an increased or decreased rate in per plant weight with each additional plant as compared to cowpea in monoculture. Similarly, sorghum sudangrass had a greater range of intraspecific competition in the MS and SC bicultures than in monoculture but a reduced decrease in per plant weight in the SH biculture.

C.5. Model validation fits

Table C. 2. The metrics for assessing model fits for Figure 5 of each species in the nine site-years, which took place in three locations over two years, in which some sites had experiment replicates. M, pearl millet; S, sorghum sudangrass; C, cowpea; H, sunn hemp; RMSE, root mean square error; slope, the coefficient of correlation between observed and predicted; *P* value (slope ≠1) describes if the model predictions had bias; r^2, the coefficient of determination describes the strength of the correlation.

Site	Species	No. of observations	RMSE	Slope	*P* value (slope≠1)	r^2
AurL13	M	17	1.10	0.36	0.02	0.13
	S	18	1.56	-0.29	<0.001	0.08
	H	18	1.09	0.37	0.02	0.14
	C	17	1.41	-0.06	<0.001	0.003
AurE14	M	16	0.53	0.85	0.30	0.72
	S	16	0.76	0.69	0.13	0.48
	H	16	0.66	0.76	0.19	0.58
	C	16	0.50	0.87	0.34	0.76
AurL14	M	15	0.73	0.71	0.16	0.51
	S	15	0.95	0.52	0.06	0.27
	H	16	0.91	0.56	0.07	0.31
	C	15	0.76	0.69	0.15	0.48
BelE13	M	16	0.71	0.73	0.16	0.54
	S	16	0.66	0.77	0.20	0.59
	H	16	0.91	0.56	0.07	0.32
	C	16	0.69	0.75	0.18	0.56
BelL13	M	16	0.76	0.69	0.13	0.48
	S	16	0.77	0.68	0.13	0.47
	H	16	0.58	0.82	0.26	0.68
	C	16	0.48	0.88	0.36	0.77
BelL14	M	16	0.58	0.82	0.26	0.67
	S	16	0.98	0.49	0.05	0.24
	H	16	0.67	0.76	0.19	0.58
	C	16	1.15	0.30	0.02	0.09
WilL13	M	14	0.58	0.82	0.29	0.67
	S	14	0.63	0.79	0.26	0.62
	H	15	0.71	0.73	0.18	0.53
	C	15	1.04	0.42	0.04	0.17
WilE14	M	24	1.21	0.23	0.001	0.05

	S	24	1.06	0.42	0.01	0.17
	H	24	0.75	0.71	0.07	0.50
	C	24	0.75	0.71	0.07	0.50
WilL14	M	24	0.62	0.80	0.13	0.64
	S	24	0.70	0.74	0.08	0.55
	H	24	0.91	0.57	0.02	0.32
	C	24	0.97	0.51	0.01	0.26