PERENNIAL AGRICULTURE: AGROMONY AND ENVIRONMENT IN LONG-LIVED FOOD SYSTEMS

by

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Abstract

Perennial agricultural systems are fundamentally characterized by their longevity, as they consist chiefly of long-lived woody plants with permanent root and shoot systems that can be managed for continuous ground cover. This is known to promote a host of ecosystem services, and indeed agricultural landscapes that include perennials have been shown to support wildlife, enhance pest regulation, sequester carbon, limit erosion and water pollution, and promote pollination. Yet, the agroforestry and agroecology literatures that characterize environmental benefits of perennials (which mostly involve non-food producing trees and grasslands, especially in temperate climates) are largely separate from agronomic literature about the management and yields of perennial crops themselves. Thus little is known about how tree crops actually support a range of ecosystem services and other benefits.

This thesis takes a multi-disciplinary approach to study agronomic, nutritional, environmental, and social dimensions of perennial crops for human food. It first characterizes the distribution and yields of perennial staple crops worldwide, finding that perennial crops, many of which are not yet heavily commodified, can provide staple nutrition at yields comparable to those of annual staples while supplying more varied nutrition than common annual staples. Second, it surveys food production and environmental outcomes on fourteen perennial polyculture farms in the US Midwest, finding that these farms enhance biodiversity and several other ecosystem services, although these new plantings produce less food than neighboring annual cropland. Third, it explores the practices, livelihoods, and values of perennial farmers, finding that they implement

sophisticated adaptive management and derive satisfaction from fulfilling largely relational values alongside livelihood needs.

Perennial agriculture thus offers the potential to produce significant amounts of nutritionally important food in multifunctional landscapes. If managed in diversified systems, perennials can enhance multiple ecosystem services compared to simplified perennial management and annual cropland. More widespread transition to perennials in existing agricultural land should be informed by the specific ecological opportunities offered by perennial plants (including continuous groundcover), and by the knowledges and values of producers, to realize the potential of these systems for achieving sustainable food security.

Lay Summary

The accelerating climate and ecological crisis facing the world makes the challenge of feeding people while reducing humanity's impacts on the planet and regenerating its damaged life support systems an urgent one. Perennial agriculture, where long-lived plants (that are often woody trees and bushes) produce food year after year, can mitigate many of the problems with annual agriculture. But, the advantages and challenges of transitioning land to perennial agriculture depend on many factors, including how much food and nutrition perennial crops produce, what type of landscape they replace, how many environmental benefits they generate, how they are managed, and how easy and cost-effective it is for farmers to change their practices and livelihoods. This thesis explores these contexts for transitioning to perennial crops through global data assembly and original data collection in the US Midwest. The multifunctional environmental and agronomic benefits of perennial crops justify including them as part of the pathway towards sustainable food security.

Preface

This thesis is my original work. I identified the research problems, obtained research funding, designed the research program, gathered and analyzed the data (with some assistance, as specified below), and wrote the chapters. My advisory committee (Drs. Kai Chan, Sean Smukler, Kristin Mercer, and Navin Ramankutty) provided valuable feedback on my research design, initial results, and draft chapters. Chapters 2 through 4 were written as stand-alone pieces for publication in peer-reviewed journals. This has led to some overlap in the introductory content of the chapters. As the final publications will be co-authored, terms like “we” instead of “I” are used to reflect co-authorship for those chapters. The nature of my contribution and those of all co-authors to each chapter is explained below:

Chapter 2 is a verbatim manuscript of an article that is soon to be submitted. I am the lead author and wrote the first draft of the paper. I developed the project idea and core arguments in collaboration with the second author, Eric Toensmeier, with the support of Dr. Navin Ramakutty. A research assistant, Santiago Tomassi was employed to review literature which formed the main data for the paper. Drs. Navin Ramankutty, Sean Smukler and I worked together to refine the analysis. Dr. Kai Chan contributed to reviewing the manuscript and incorporating relevant literature.

Chapter 3 is based on my own empirical fieldwork. I oversaw all aspects of the study from design to final analysis, and am the lead author on the resulting manuscript, which is a version of the chapter herein. I developed the project idea and research methods; collected the data in the field with the Noah Sullivan and Harold Eyster; carried out the data analysis; and led the writing. Drs. Sean Smukler and Matthew Mitchell contributed to developing the fieldwork protocol. Keefe Keely contributed to finding fieldwork sites. Dr. Adrian Verster contributed to the genetic data analysis. Harold Eyster contributed to the biodiversity analysis. Aldona Czajewska carried out the counting and identification of arthropods. Drs. Matthew Mitchell, Kai Chan, and Sean Smukler, as well as my other committee members contributed to structuring the article. All the co-authors contributed to the interpretation of study results and provided feedback on multiple article drafts.

Chapter 4 is also based on my empirical fieldwork. I led the writing the interview protocol, conducted the interviews, coded the interviews, and led the writing of the manuscript. Dr. Mollie Chapman, Dr. Kai Chan, Adrian Semmelink, and Dr. Leila Harris contributed to formulating the interview protocol (the latter two played an advisory role and are not co-authors on the paper). Keefe Keeley contributed to finding interview subjects. Drs. Mollie Chapman, Keefe Keeley and Kai Chan contributed to situating the work in relevant literatures, crafting the argument, and provided feedback on the manuscript. This work was approved by the UBC Human Research Ethics Board, certificate H17-03248-A002.

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List of Abbreviations

CAP	Common Agricultural Policy
CRP	Conservation Reserves Program
DSF	Diversified Food Systems
EQUIP	Environmental Quality Incentives Program
ES	Ecosystem Services
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
NRCS	Natural Resources Conservation Service
UN	United Nations
USDA	United States Department of Agriculture

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I would like to thank the IRES community, which has been a welcoming and wonderful environment to have as a home base. I would like to thank the members of the CHANS lab and IRES, many of whom became colleagues and friends: Mollie Chapman, Sarah Klain, Poushali Maji, Verena Seufert, Alejandra Echeverri, John Driscoll, Matthew Mitchell, Adrian Semmelink, Dana James, Susanna Klassen, Sara Nawaz, Jeff Scott, and Ed Gregr.

Outside of IRES, I am grateful to have connected with many colleagues that have supported and shaped my work from its nascent stages, including Dr. Juli Carillo, Dr. Dolph Schluter, Eric Toensmeier, and Dr. Rafter Sass Ferguson. A key collaboration in this thesis was with Keefe Keeley and the wonderful people of the Savannah Institute, who connected me with the community of perennial farmers in the Midwest that much of my work was based on. I am very grateful to be connected to such a dynamic group of people who share my exact brand of botanical enthusiasm. I am indebted to the thirteen farm families who welcomed me onto their properties and into their homes – though unnamed in this thesis, I appreciate and think about every one of you.

I gratefully acknowledge the funding from NSERC that supported me for four years, and the Ekhaga Foundation grant which funded this work in its entirety. Original research is expensive, especially when it involves so many methods, time in the field, and extensive literature review. The financial support to carry out work on this scale was an immense privilege that I'm very grateful for. I would like to thank Gillian Harris and Linda Stewart for supporting me in the new experiences of administering a grant, hiring people, making large purchases, and fulfilling the financial and practical requirements of project management. I would like to thank my three research assistants, Noah Sullivan, Aldona Czajewska, and Santiago Tomassi. You carried out the exacting and unglamorous but crucial work of data collection stoically, precisely, and sometimes even heroically (Noah!).

I would like to thank my parents, Syd Kreitzman and Rahel Halabé, my brother Daniel Kreitzman, and my fiancé Aaron Dewitt. My privileges of freedom to explore and learn for so many years are the product of your hard work, love and steadfast support. Finally, I would like to gratefully acknowledge that my doctoral work took place on the unceded and ancestral land of the Musqueam people who have nurtured and protected it as a place of learning for thousands of years. hay čxʷ q̓ə.

מוקדש לאיל לוי

שתמיד יהיה לנו עם מי לדבר על עצים. ושנזכור לשיר כמו בצמרות הנקטרינה

Chapter 1: Introduction

1.1 Perennial agriculture in the global food system

The accelerating ecological decline and global warming that humans are inflicting on planet Earth bring about existential dilemmas for humanity: how can we envision a livable future for both our own species and non-human life? At the foundation of this dilemma (which reaches through the deep layers of human psychology to the largest international political structures) is an imperative: we must be able to feed ourselves. The paradox of this imperative is that the capacity to grow abundant food like never before is now threatening our own food security and safety in the long term. The domination of the Earth's surface by crop and pasture lands, which cover 50% of Earth's habitable land (i.e. not including glaciers, sand dunes, exposed rock etc; FAO 2020), are key drivers of ecological impacts that are exceeding multiple planetary boundaries including atmospheric temperature, global freshwater use, biogeochemical flows of nitrogen and phosphorus, land system change, chemical pollution, and biodiversity loss (IPBES 2019; Purvis et al. 2019; Campbell et al. 2017). In addition, much of the world's biodiversity depends on, and is threatened by, agricultural lands, and the expansion and management of these lands is driving the steep decline in wildlife abundance as well as the mass extinction the planet is currently experiencing.

Agricultural lands not only produce food, but they are also both producers and users of ecosystem services needed for their ongoing productivity, including climate regulation, air quality regulation, pollination, soil fertility, water quality and flow regulation, mediation of infectious diseases, and pest regulation (Zhang et al. 2007, Foley et al. 2005; Robertson &

Swinton, 2005). Since the “Green Revolution” of the post-war years, the ecosystem services that agriculture relied upon have been increasingly and readily substituted by chemical and fossil fuel energy inputs, thus reducing the dependence of agricultural production on intact ecological functions (Brauman et al. 2019). The resulting trend in management, towards system simplification and the use of chemical inputs, puts modern agriculture on a collision course with sustainability. The incompatibility of modern industrial agriculture with planetary boundaries stems from both the production of inputs needed to do agriculture this way (fertilizer, fuel, pesticides, herbicides), and from impacts of their actual application on the land (non-point source pollution, methane, CO_2, and nitrous oxide emissions, habitat destruction, degradation of soil) (Balvanera et al. 2019; Campbell et al. 2017).

The growth of the human population, projected to reach 10 billion by 2100, and changing diets towards more meat consumption are driving increased demand for food production (Godfray et al. 2010). Despite the undeniable pressure of this demand on land and resources, increasingly, there is a recognition that feeding everyone on the planet currently (or even 10 billion people) is as much an issue of equity and access as it is a technical problem: studies show that enough food is being produced today to feed the human population even while waste is taken into account (Ritchie et al. 2020), but hundreds of millions of people still remain food insecure, and that number is rising (FAO 2019). Thus, the reasons and solutions for food insecurity must be found in large part outside of the technical realm, a fact acknowledged by the United Nations in their recent report that cited war and economic downturns alongside global warming as interlinked drivers for rising food insecurity (FAO 2019), and by IPBES in Chapter 5 of the recent Global Assessment, which synthesized cross-cutting non-technical solutions for a sustainable future

(Chan et al. 2019). Solutions aimed at balancing agricultural production with the sustainable supply of ecosystems services and preservation of biodiversity vary, but they all involve major adjustments to both agricultural production and the social dimensions that dictate consumption patterns and policies (Foley et al. 2011, Campbell et al. 2017; Gerten et al. 2020; Ehrlich and Harte 2015; Robertson and Swinton, 2005; Chan et al. 2019). These solutions include interventions on the production side (closing yield gaps, decreasing fertilization in some areas while increasing it in others, changing irrigation patterns) and on the consumption and policy side (changing diets back to being more plant-based, reducing wasted food, and even curbing population growth). Many of these authors state the necessity for large-scale multilateral interventions to change production and actively manage demand for food. Yet as these scholars are largely natural scientists, their large-scale solutions are not necessarily grounded in coherent politics.

Another set of solutions emerge not from global syntheses or modeling efforts, but rather from more locally scaled ecological and social studies of agrarian systems. These solutions (which include agroecology, diversified farming systems, and food sovereignty) are generally sceptical of the productivist premise of "feeding the world" through optimization of production and trade, and instead centre on diversification of farming practices and the rights/empowerment of local people to control their own food system (Altieri and Toledo 2011; Clapp 2016; Wittman 2011; Kremen et al. 2012). Many of these solutions also take account of social and political relations of food system ownership and control alongside their ecological and agronomic dimensions.

Scaling up perennial agriculture to replace annual agriculture is one potential solution that has been little examined at either global or regional scales. Perennial plants are often an implicit or explicit part of agroecological or diversified farming practices, yet they are seldom centred in discussions of sustainable food systems (but see exceptions below). Perennial plants live for more than one year, and can be herbaceous or woody, and take different growth forms: herbs, shrubs, vines, or trees. Perennial crops are grown for animal fodder, raw materials, and food. Like annual crops, perennial crops can be grown in many different ways along the spectrum of management from extractivist industrial agriculture (e.g. almond monoculture, forest conversion for palm oil production), to diversified, traditional, or otherwise environmentally friendly systems (e.g. tropical homegardens, alley cropping, diversified orchards). The fundamental physiognomy and lifespans of perennials gives them multifunctional potential in a number of ways (discussed further in section 1.4 below). Because perennials live for many years, develop deep root systems, are often tall, and accumulate biomass, they embody an accumulation of stored energy in the system and can be managed to form stable associations with other components of the agro-ecosystem over the long term.

Perennialization of annual cereals is an area of research that has received some scientific attention recently, with the aim of breeding new crops that replace the annual staples that dominate the planet (Glover et al. 2010; Crews et al. 2018). But the much larger group of perennial crops (mostly woody) that already produce staple foods around the world have not received similar research attention (Toensmeier 2016). Many of these perennial crops are relatively unimproved and have variable genetic resources that promise rapid improvement through breeding (Mehlenbacher 2003). Moreover, research into relevant technology, commercialization pathways, and policies that would encourage investment and good management of these crops is lacking compared to the vast subsidies and extension resources poured into conventional annual crops.

Tree crops are not completely neglected; on the contrary, there is a large literature devoted to orcharding and agronomy of individual woody perennial species. However, this agronomic literature, found in agricultural journals and technical grey literature for growers, is not well integrated with the much more visible academic and policy oriented literature about agricultural sustainability, agroforestry, and agroecology. Agroforestry, or the integration of woody perennials into agricultural landscapes, is a natural umbrella for the interdisciplinary study of tree crops (and their integration with other non-woody perennials and livestock). Interestingly, the five agroforestry practices as defined by the United States Department of Agriculture (USDA; riparian buffers, forest farming, alley cropping, shelterbelts, and silvopasture) do not include growing tree crops in and of themselves. Indeed, prominent reviews of agroforestry practices in the temperate North do not include studies about tree crops (Torralba et al 2016). In the tropics, the situation is somewhat different due to the prevalence of perennial crops both as cash-crop commodities and in diversified homegarden subsistence spaces; both of these are discussed under the agroforestry umbrella (De Beenhouwer et al. 2013; Scales and Marsden 2008). But even these well studied practices do not comfortably fit into the five USDA categories listed above, since they are chiefly neither augmented natural forests as in the case of forest farming nor linearly designed interplantings as in the case of alley cropping. Other authors have more recently proposed including tree crops into the definition of agroforestry (van Noordwijk et al. 2016), and the European Union recognizes “multifunctional tree crops” under its definition of agroforestry, but the artificial separation of tree crops from agroforestry literature is currently the norm. This may be in part because of a lack of synthetic information about the diversity of management practices and ecological functions present within tree-crop-primary systems.

Evidently, no one set of terms is perfect for all things: attempts to create new terminology to distinguish diverse perennial systems from typical "orchard-style" tree crops such as multifunctional woody polycultures (MWPs; Lovell et al. 2018) may not be inclusive of perennials that are tree-like, but not woody, like giant herbaceous monocots (banana and enset) or of non-woody perennial components like herbaceous vegetation. The term "perennial polycultures" on the other hand, which is what I largely use in chapters 3 and 4, can be vague and has also been applied to entirely herbaceous perennial fodder crops (i.e. hay, pasture, or even non-harvested prairie strips; Weißhuhn et al. 2017; Crews et al. 2018). Perhaps the umbrella term agroforestry could be expanded and applied to tree-crop centred systems where the perennial itself is the crop rather than just an edge or linear element within an annual based system, with additional terms or descriptions applied as needed. In this thesis, I will chiefly use the terms "perennial staple crops" or "tree crops" in chapter 2 to denote perennial crops grown for human food under any type of management (from monoculture to polyculture); "perennial staple crops" refers to herbaceous or woody perennial crops that produce staple nutrition (i.e. large amounts of proteins fats and carbohydrates), and "tree crops" refers to food-producing perennials crops (but not restricted to staples) that are woody or are not woody, but have a tall tree-like growth form. In chapters 3 and 4, I chiefly use the term "woody perennial polyculture" to refer to fields that include multiple woody and herbaceous perennials, to distinguish these from hay fields, some of which could be considered herbaceous perennial polycultures.

The capacity of perennial crops to maintain a certain level of productivity while also delivering protective functions on soil and biodiversity (discussed in detail in section 1.4 below) gives them, like other types of agroforestry and diversified farming systems, a potentially transformative role in working landscapes. The establishment of year-round vegetative groundcover is generally considered the solution for restoring soils and other ecosystem services in agroecosystems degraded from annual agriculture (Schulte et al. 2006). Soil and habitat restoration through revegetation often goes hand in hand with taking land out of production entirely (e.g., USDA's Conservation Reserve Program), and is often applied only after severe degradation has already occurred. However, removing land from cultivation in the absence of conditions that allow for revegetation can exacerbate the loss of soil and attendant functions rather than arrest it, for example if abandonment leads to overgrazing or deterioration of water-retention infrastructure like terraces (Arnaez et al. 2010; Harden 1996). Thus, it is the revegetation of degraded land, not its removal from production, that is the key to restoration. The transformative potential of tree crop systems to protect soil depends chiefly on practices that *complement* the structure and longevity of the dominant trees, including the use of multi-strata vegetation, year-round vegetative groundcover, animal integration, and other practices that foster functionally diverse agroecosystems (van Noordwijk et al. 2016; Jose 2009; Schulte et al. 2006). Like other agroforestry practices, the transformative potential of perennial food crops lies in transcending the duality between annual cropping and removing land from production to include a larger range of viable options for the use of farmland (Schulte et al. 2006). Unlike other agroforestry practices, transitions to perennial agriculture with food-producing crops have the added value of providing direct nutrition to people, thereby enacting the solution of chiefly feeding people rather than resource-intensive domestic animals (Foley et al. 2011; Cassidy et al. 2013), and also of creating rich and delicious cultural landscapes that are full of delight.

In summary, the further integration of agronomic literature about tree crops that are grown for human food together with science-policy oriented sustainability scholarship is the academic space that this thesis aspires to advance. This nexus of research lays a better foundation for the necessary next steps in advancing the science-based development and adoption of perennial crops, and the transformative potential therein.

1.2 Research objectives on two scales

This thesis addresses the role that perennial crops play in the food system today, and the role that they might play in the future. Specific research questions for each chapter are laid out below (see the chapter overview section). More generally, this thesis includes studies on two scales that each have different objectives.

At the global scale, I seek to synthesize data about perennial staple crops to facilitate their consideration in food security and sustainability scholarship and policy. The objective was first, to establish perennial staple crops as a group, including both familiar and largely unfamiliar perennial crops; and second, to assemble yield, geographic distribution, nutrition, and carbon sequestration data these crops in the global context of comparable species in annual agriculture. The analysis of global production totals and comparisons of yield on the basis of nutritional category rather than immediate geographic context allows for a larger scale understanding of the agronomic potential of many perennial crops that are poorly studied in the research community and not well supported by development and agricultural policy.

At a regional scale, I focused on one region of interest in temperate North America where a unique type of management of perennial crops has been adopted by a small but growing number of farms. The objective of the two studies carried out at this scale was to elucidate the ecological functions and social contexts of perennial polycultures in place. Perennial polyculture of multiple food-producing perennial species in the same space was the management type that I was interested in because it is situated on the more diverse and complexity-rich side of the perennial management spectrum. Examples of these diverse systems in temperate climates are scarce. By studying the ecological and social dynamics of recent land transitions situated in a specific place, I was able to interrogate tradeoffs and realities that are not discernable from a global synthesis, including ones that arise from social and economic resources and constraints.

Together, the objectives on these two scales aim to highlight the global potential of a little-studied class of perennial crops, and provide an in-depth and interdisciplinary analysis of a perennial transition where it is taking place.

1.3 Historical context of permanent agricultures

Throughout history, perennials have been an important part of agricultural landscapes around the world, often signaling the transition from nomadic lifestyles to long-term settlement (Smith 2010). In the Mediterranean basin, olive, date, carob, and chestnut endure as important crops from before recorded history (Zohary et al. 2012; Zohary 2002). The acorn, now seldom eaten, was the carbohydrate base of numerous human societies, called “balanocultures” (Bainbridge 1985). Other perennial staples have been more persistent: the “Castagnetu,” or domestic/wild chestnut forest, still constitutes the basis of agrarian life in inland Corsica (Michon 2011). Olives still dominate parts of the Mediterranean landscape and form the basis of cultural identity in several regions (Fleskens et al. 2009). In the tropics, many species of palms used for their starchy trunks, and sugary or oily fruit, are staple foods and have been for millennia (Toensmeier 2016). The walnut and pistachio forests of Kyrgyzstan have an anthropogenic origin one to two thousand years ago, and remain an important source of resources and livelihoods today (Beer et al. 2008). In North and South America, flour made from mesquite pods was a staple for many Indigenous cultures (Felker 2005). The range of ancient and Indigenous agroforestry practices is broad, from using fire to encourage desirable wild fruit and mast trees (Abrams and Nowacki 2008), to domestication and intensive cultivation of plantations and gardens (for example in Amazonia, Miller and Nair 2006). Despite their persistence in some regions, colonization and the adoption of cereal-based annual agriculture in more parts of the world has generally spelled the decline of ancient perennial crop-based societies (Smith 2010).

The 1929 book “Tree Crops, a Permanent Agriculture” by J Russell Smith was inspired by several of these worldwide cultures that based themselves on perennial crops. The book is a foundational document in perennial agricultural science, as it collates yield, geographic, and sociological information about perennial crops that Smith wanted to develop in the United States. Smith, like his contemporary Aldo Leopold, was motivated by experiencing the catastrophic soil erosion on the American plains during the 1920s and 1930s (“the dust bowl”). Like Leopold, he was concerned with the devastating effects of growing annual grains on hillsides, which results in soil erosion from which recovery is slow to impossible. Leopold bought an abandoned farm in Wisconsin that had been ravaged by erosion and brought it back to life by planting thousands of pines and other forest trees, a process he documented in his famous book, “A Sand County Almanac” (Leopold 1949). Smith, in contrast, directed his energy to food-growing trees. He documented tree agriculture systems from around the world, titling his chapters after the core foods to which he analogized his tree crops, for example: “A Corn Tree -- The Chestnut”, “A Meat-and-Butter Tree for Man -- The Persian Walnut”. While Smith was interested in food for humans, he also emphasized growing tree products as fodder for animals, recognizing the vast amount of annual agriculture that is intended for fodder. Smith ends his book by calling for a research program to bring about the full potential of tree crops through ambitious breeding and the establishment of “institutes for mountain agriculture”. It is perhaps an indictment of progress on this front that his research program is still very much pertinent: many of the food and fodder trees Smith discusses are not yet optimized for mass production nor are they particularly important components of western food systems. For example, the task of developing a low-tannin acorn has been known and talked about for decades but the substantial breeding work necessary has yet to be carried out.

In the decades after Smith’s book was published in 1929, agriculture became increasingly large, industrial, and chemically intensive, with accompanying yield gains (Ray et al. 2012). Until the oil crisis of the 1970s, mainstream society celebrated the wonders of technological advancement and automation in agriculture and mostly ignored conservation concerns. When the permaculture movement took root in Australia in the 1970s, Smith’s book was an important text, and in fact, the first permaculture book by Mollison and Holmgren in 1978 was largely a reiteration of it.

Unlike Smith, who was interested in large scale soil conservation and production of food and fodder on commercial scales, the early permaculturists were focused on small scale home or village gardens with a strong focus on self-sufficiency (Mollison & Slay 1995). Another contrast is that while Smith was an economic botanist attempting to speak to the mainstream of American agriculture through growers' associations and extension offices, the permaculturists were (at times emphatically) non-scientific, and positioned their movement in opposition to the mainstream (Feguson and Lovell 2013). More importantly however, they collected, adapted, and developed a set of design principles based on mimicking natural communities for the purpose of food production, with a strong emphasis on perennial plants that once established, would continue to produce for decades or centuries.

It is important to note that the concept of permaculture cannot be seen as original. Smith, as well as Mollison and Holmgren derived many of their combinations of plants, cultivation practices, layout design, and water-engineering earthwork practices (terracing, dams, swales) from traditional agricultural practices from European, Asian and American agricultural societies. For example, multistrata "food forests" are modelled after the ubiquitous homegardens of the tropics (Fernandes and Nair 1986). Sophisticated earthworks and gravity-based irrigation technologies were developed by many ancient civilizations including the Inca and Maya (Mays and Gorokhovich 2010). These concepts were somewhat integrated and repackaged for western audiences, in Smith's case, with the goal of soil conservation, and in Mollison and Holmgren's case, in the pursuit of a holistic, small-scale, self-sufficient model for a sustainable life. As permaculture principles are derivative of traditional knowledge from around the world, the permaculture movement has been criticised for appropriating knowledge and divorcing practices from their origin and cultural context (Morel et al. 2019). Undoubtedly though, the movement has also been a popular means through which knowledge about the role of perenniality and long-term planning in agriculture has disseminated in the wider public, more so than academic fields such as agroecology or agroforestry (Ferguson and Lovell 2013).

In the last decade or so, a newer generation of tree crop enthusiasts have emerged that hold more Smithian attitudes: they regard permanent agricultures as ways to provide large amounts of food, sequester carbon, and re-envision agricultural landscape on a large scale through agricultural and industrial transitions as opposed to just maintaining a self-sufficient garden or village (Shepard 2013; Toensmeier 2016). These efforts are becoming increasingly integrated with science (Jacke & Toensmeier 2005; Ferguson & Lovell 2013; Wolz et al. 2017).

1.4 Ecological basis for perennial agriculture

Much of the justification for advancing the study of perennial agriculture in this thesis is grounded in ecology. Here, I review this basis through the lens of fundamental ecology, ecosystem services, and complex adaptive systems. Many of the studies about the ecological basis for perennial agriculture come from landscape ecology and perennial grassland systems rather than actual tree crops. Some come from agroforestry systems, and some come from actual food-producing tree crop systems. Below, I cite studies from all of these categories to establish the ecological basis for perennial land transition.

1.4.1 Perennials for biodiversity in the agricultural matrix

Landscape ecology has increasingly moved beyond the classical neutral theories of island biogeography that emphasized the size of habitat patches and the distance between them (Hubbell 1997) to arrive at a recognition that the quality of the matrix mosaic between habitat patches (including the different types of edges within the mosaic) is as or more important than the patches themselves (Ricketts 2001; Ries et al. 2004). This understanding is reflected in conservation scholarship that calls for the enhancement of the quality of working landscapes for wildlife alongside the stronger protection of intact habitat (Kremen 2015; Kremen and Merenlender 2018). The matrix and edge environments formed by perennial systems fundamentally differ from annual systems, affecting how wild species can occupy, move through, and even evolve within them. For example, perennials may reduce the contrast between primary habitat and matrix thus promoting mobility of organisms: high contrast between native habitat and matrix habitat, which is characteristic of uniform annual croplands, is associated with lower permeability for migration in landscape studies (Biswas & Wagner 2012; Eycott et al. 2012).

Perennial food systems like fragmented traditional orchards have been studied by landscape ecologists both as habitat islands and as components of surrounding landscape (Bailey et al. 2010; Horak et al. 2013). Species richness across most taxa in orchard fragments correlated with the proportion of surrounding orchards in the landscape, indicating their importance both as primary and surrounding habitat (Horak et al. 2013). For some species, perennials are not providing primary habitat, but rather connectivity: in their study of mammal dispersal in an Australian agricultural landscape, Brady et al. (2011) found that the presence of trees in the matrix (“landscape complexity” in the model) was the parameter that most positively correlated with mammal species richness. Likewise, a modeling study of a carabid beetle highlighted the importance of perennial growth forms like agroforestry dykes and hedgerows on the movement and recruitment of beetles (Benjamin et al. 2008). Studies in the tropics have found that non-forest perennial vegetation like arboreal agricultural habitats and live fences are important to sustaining a wide variety of bird species (Estrada et al. 1997; Hughes et al. 2002). Drawing from this literature, a meta-analysis of landscape studies found that matrix habitats that were more similar to organisms’ native habitat were more permeable to their movement (Eycott et al. 2012). This evidence suggests that perennial vegetation, including perennial food systems, can effectively change the isolation of organisms living in nearby natural habitat.

Studies and meta-analyses of actual perennial agricultural landscapes (i.e. agroforestry systems) have found that they harbour more biodiversity in both temperate (Torralba et al. 2016) and tropical climates (De Beenhouwer et al. 2013) than more simplified agricultural landcovers. In the tropics, the most diverse agroforestry systems can support communities that are as species-rich, abundant and diverse as forests, though these have different composition and include non-forest species, and diversity declines with the simplification of the agroforestry system (Bhagwat et al. 2008; Harvey and González Villalobos 2007; Philpott et al. 2008). Agroforestry systems do not necessarily lead to species declines and homogenization: in one study, mixed agroforestry systems had equal beta-diversity of birds compared to forest (Karp et al. 2012). Despite these advantages, mixed agroforestry in the tropics does not harbour as many evolutionarily unique species (i.e. those with few phylogenetic relatives and long branch lengths) compared to forests (Frishkoff et al. 2014). Thus, while agroforestry systems and perennial cropland may not constitute adequate habitat for forest specialist species, they can support biodiversity that more homogeneous cropland cannot, as well as provide connectivity and secondary habitat between higher quality habitat patches.

1.4.2 Perenniality and ecosystem services

In addition to constituting habitat for wild organisms, there is evidence that perennial agriculture can balance productive and protective functions by supplying many agricultural ecosystem services (Zhang et al. 2007; Jose 2009). The main categories of these services and the ways in which perennial agriculture grown under different conditions might supply them are reviewed below.

1.4.2.1 Carbon storage

Carbon sequestered in agricultural systems is stored in several pools: above-ground biomass, below-ground biomass, dead biomass, and soil organic carbon (SOC). Some of this carbon is more stable and remains sequestered for longer, while other pools are subject to metabolic breakdown and re-release into the atmosphere. The relationship of perennial agriculture with carbon sequestration is both through biomass accumulation in wood, and through SOC.

The accumulation of biomass over time in both root and shoot vegetative structures is well documented for forests, timber plantations, and grasslands (IPCC 2019). The same is not true for many species of agricultural trees, only a handful of which are documented in the IPCC's most recent carbon modeling guidelines (a tally which I improve on in chapter 2). Several important differences exist between tree crops and forests: first, tree crops are typically pruned to remain a certain size, thus changing the rate of biomass accumulation and reducing it over their lifetime; second, the fate of biomass at the end of the growing cycle varies from burning, to slower decomposition, to stable persistence in the form of wood products. Despite these sources of uncertainty, the accumulation of biomass in woody crops does take place, and regardless of its eventual fate, represents a more stable carbon pool than the biomass from annual crops which are entirely consumed or decomposed every year.

The contribution of perennials to soil SOC is twofold. First, perennial crops can generally be grown without tillage (i.e. the turning of soil), which leads to increased microbially-mediated oxidation of organic matter, releasing carbon into the atmosphere (Brady & Weil 1986a). Indeed, conversion of forest or other permanent vegetative cover to tilled agriculture is one of the most carbon-emissions intensive processes in the world (Ramankutty & Foley 1999). Second, dead biomass and root exudates from perennial plants directly add carbon from the living biomass pool to the soil organic carbon pool. Leaves and pruned branches are deposited on the soil. The labile portion of this organic matter is easily digested by microorganisms, remineralized, and released back into the soil, where its mineral components can be absorbed by plant roots, or oxidized and re-released into the atmosphere (Brady & Weil 1986b). Complex organic molecules with high lignin content are not readily digested, and become the slow fraction of the soil organic matter which remains in the soil as stored carbon, slowly releasing organic nutrients and humic acids (Brady & Weil 1986b). Eventually, some organic compounds cannot be further broken down, and they become part of the passive organic matter pool in the soil (Brady & Weil 1986b). Woody plants in particular have a higher proportion of lignin-rich organic compounds which contribute to the slow organic matter fraction that resists remineralization for longer. As residues are continuously added to the soil, the steady accumulation of both active and passive organic matter is expected (Brady & Weil 1986b).

Empirically, perennial agriculture could cause increases or decreases in stored carbon in soils, depending if it is established on formerly annual cropland, grasslands, or forest; a recent meta-analysis shows that SOC generally increases after conversion from annual cropland to perennials but decreases after conversion from natural grassland and forest (Ledo et al. 2020).

1.4.2.2 Soil organic matter and fertility

Though there is much debate about the stability and reliability of soil SOC for carbon sequestration, there is strong consensus in soil science about its role in soil structure and fertility (Bradford et al. 2019). If perennial agriculture is adopted on annual croplands, or on other soils where fertility has degraded, subsequent increase in SOC would be accompanied by a suite of soil ecosystem services, including soil aggregation, water infiltration and holding capacity, cation exchange capacity, breakdown of mineral nutrients, and pH buffering (Dominati et al. 2010; Brady & Weil 1986b). There is robust evidence that perennial grassland/pasture systems have higher phosphorus, more biological activity, better water retention properties, and higher soil organic carbon levels compared to annual systems (Conant et al. 2001; Potthoff et al. 2005; Crews & Brookes 2014). While the extrapolation to woody perennial systems shouldn’t be taken for granted, untilled orchards with perennial ground cover likely share many of these characteristics.

One caveat for increases in SOC from perennial systems is that decomposing woody plant residue has a higher C:N ratio and potentially competes with growing plants for available nitrogen (Brady & Weil 1986b). Ensuring an adequate nitrogen supply in soils so that organic matter decomposition and nitrogen supply to living plants can take place is an important aspect of balancing soil in an agroecosystem with plentiful organic residues from woody plants.

Empirical evidence on soil fertility in tree crop systems that use permanent ground cover is promising, though it has not yet been synthesized formally. In a comparison of soil properties between tilled and untilled olives, Gómez et al. (1999) found that soil organic matter was significantly higher in the no till treatment. Soil compaction was also higher in the no till treatment, negatively affecting water infiltration, but this difference was restricted to alleys between trees where traffic occurs, (not under the canopy), and disappeared eight weeks after tillage. The no till treatment had equal yield overall and a higher yield in one year that the site experienced drought. This indicates that while plowing can increase water infiltration in rows between trees, this benefit can be short lived, and is outweighed by other properties of the no till treatment in water restricted conditions.

Other studies looking at orchards managed with clean tillage or herbicide management (i.e. no vegetation under trees, either due to turning the soil—tillage—or chemical treatment) compared to sod cultures (permanent ground cover under trees) have found increased root infiltration of beneficial mycorrhizal fungi in both chestnuts (Ishii et al. 2008) and Japanese apricots (Cruz & Ishii 2012). A comparison between permanent ground cover and clean tillage in apples found increased soil carbon but decreased K and P in the sod culture, indicating that trees and understory species can compete for nutrients (Xi-rong 2005). A similar study in citrus found that most soil nutrients decreased in sod culture in the first two years, but increased thereafter compared to clean tillage management, while water retention was consistently better in sod culture (Huai & Lin 2005). In a study of newly planted apple orchards under different ground covers, water retention and soil organic matter were higher in various combinations of vegetative ground cover compared to tillage and herbicide treatments (Merwin et al. 1994). These examples show that important soil physical properties tied to fertility can be pro-actively managed using permanent ground cover in perennial agriculture, though the consistency and generality of these findings remains unknown in the absence of a meta-analysis.

1.4.2.3 Soil retention/erosion and nutrient pollution

Since orchards can be (and often are) grown on hilly landscapes, water can be a powerful erosive force leading to sheet erosion, gullies, and rapid loss of topsoil (Smith 1929; Brady & Weil 1986c). Indeed, soils under the plow erode at rates 1-2 orders of magnitude greater than erosion rates from geologic forces or erosion under native vegetation or no-till practices (Montgomery 2007). At such rates, hillslopes (which naturally have narrower soil profiles than valleys) can erode through in similar periods of time to the longevity of civilizations, arguably exacerbating or causing their demise as productivity from hill agriculture plummets (Montgomery 2012). In addition, nutrient pollution from farmland is one of the most dramatic impacts of agriculture, leading to algal blooms and eutrophication of vast freshwater and marine habitats (Howarth et al. 2002). This results from two drivers: excessive nutrient additions, and hydrology that leads to runoff (Howarth et al. 2002).

The ability to grow tree crops together with permanent vegetative ground cover creates a double advantage in the face of erosive water that drives both soil loss and nutrient pollution: both canopy cover and vegetative groundcover (if present) under trees reduces water runoff by absorbing the energy of raindrops before they hit the soil (Brady & Weil 1986c). Additional practices like terracing, strategically placed rainwater trenches (swales), and shallow ditches placed along the contours of a hillside (keylining) can be used to reduce water runoff, instead soaking water into the ground and spreading it out from valleys to ridges and (Mollison & Slay 1995). These practices, while not restricted to perennial plantings, are fundamental to many ancient perennial agricultural systems and have been developed in detail by permaculture practitioners.

Despite these apparent advantages, standard management for many perennial crops like almonds and grape vines in arid environments is clean tillage or herbicide use that leaves the soil bare in order to reduce nutrient and water competition (Zuazo & Pleguezuelo 2008) and allow for mechanization. However, vegetative strips of grains and herbs between rows did protect almond orchards from erosion in one example (table II in Zuazo & Pleguezuelo 2008). Likewise, cover crops were significantly the most beneficial management practice in preventing erosion for a model of management in olives (Gómez et al. 2003). This result was confirmed in a field study by the same authors which found that cover cropping beneath the olive trees significantly reduced both nutrient runoff, and sediment loss, but that correct management of cover crops was needed to reduce water competition with the trees (Gómez et al. 2009).

A study of nitrogen runoff and soil erosion over different agricultural crops in eastern China found that much higher sediment loss, nitrogen loss, and water runoff came from vegetables and upland cropping than from chestnut orchards and bamboo forests (Gao et al. 2004). A study in the US Midwest found that small grains grown with rotations of perennial legumes and rotationally-grazed perennial pastures had approximately balanced N budgets compared to the large N surpluses generated by corn and soybean fields. Another study in China of citrus orchards under different mulching treatments showed that straw mulching reduced nitrogen, phosphorus, and sediment loss compared to a no mulch control (Liu et al. 2012). Taken together, these studies show that sediment loss and nutrient runoff in perennial plantations can compare favorably to annuals in the same region, and can be managed for additional benefits through the use of ground cover (either mulch or cover crops).

1.4.2.4 Pollination and pest control

Pollination and biological pest control are two of the best-characterized ecosystem services. The most common way of studying these services is through the lens of proximity of crops to forest fragments or edge habitats (eg. Kremen et al. 2004; Karp 2018). The extent to which perennial crops can themselves function as source habitat for wild pollinators will depend on the forage and undisturbed nesting sites available to them (Landis et al. 2000). The USDA and various state authorities have published pamphlets outlining agroforestry practices to encourage native pollinators; these mostly relate to non-food agroforestry in hedges, windbreaks, buffers, and forest patches (USDA 2006). These practical guides could also be relevant to improving pollinator habitat within fields of food-growing trees, and even more beneficial if the trees themselves are insect pollinated, an investment in a potentially self-sustaining ecosystem service.

For pest control, recent meta-analysis shows that nearby non-crop habitat does not consistently increase pest-control services to crops (Karp et al. 2018). Studies conducted within the bounds of the crops are promising however. For example, balanced pest-predator food webs, and increased presence and evenness of pest predators have been demonstrated on organic farms (Macfadyen et al. 2009; Crowder et al. 2010; Vandermeer et al. 2010). The higher food web complexity involving pest species, and the greater presence of pest predators in organic agriculture suggests that self-regulating interactions can establish in agricultural settings where the key driver of insect populations are not insecticides.

For example, the work of Vandermeer et al. (2010) in a complex organic coffee system in Southern Mexico is particularly interesting as a case study of a perennial system. Using both modeling and 10 years of field observations on 13 fungal and insect components, they concluded that the complex ecological network of many insect and fungal species resulted in the ecosystem service of buffering the entire system against extreme outbreaks of pests and disease. Vandermeer et al. (2010) do not dismiss the idea that serious pest outbreaks sometimes require industrial solutions, but they report on a perennial system where the pests, pathogens and predators are never eliminated, but keep each other in an acceptable balance over the 10 year study time. A more controlled study involving temperate orchards in West Virginia compared an apple monoculture under standard insecticide management with a polyculture orchard containing four different fruit species under lower insecticide management; each was further divided based on presence or absence of herbaceous companion plants (Brown 2012). Over the three years of data collection, no major difference in fruit yield or quality was observed between the four treatments, indicating the viability of diversified orchards. Greater presence of both predatory insects and pest insects were found in two biodiverse tree treatments.

This complexity of these cases is mirrored in a systematic review of 30 studies concerning the effect of companion understory biodiversity in orchards on pest control from insects (Simon et al. 2010). The authors find that the effect of plant management for higher diversity were mostly positive (16 cases) or null (9), but sometimes negative (5); moreover they report that the underlying mechanisms of the pest control ecosystem service are seldom demonstrated, whether they involve a complex assemblage or only a few pests (Simon et al. 2010). Taken together, these findings demonstrate that diversified perennial agriculture (whether the diversity comes from the woody perennials themselves of herbaceous companion plants) provide spatially complex environments that can foster the establishment of multi-level trophic interactions between pests and pest regulators.

1.4.3 Perennial agriculture as a complex adaptive system

Agricultural systems, like natural ones, can be understood as ecological communities of interacting species. In agriculture, the species composition, disturbance regime, and abiotic conditions are maintained artificially far from a steady state in order to optimize production of usually one specific crop. In contrast, natural communities persist and renew themselves without any inputs or management, through the interactions of the organisms with each other and with the abiotic environment (which also includes disturbance and succession, but over typically longer timescales than in agriculture).

A thought experiment is helpful here: a farmer dies suddenly, leaving a corn field, an apple orchard, a perennial polyculture, and a patch of mature forest. Before her relatives can decide what to do with the farm, it sits abandoned for several years. How much would each area change in the absence of the farmer's active management? Almost certainly the corn field, which would likely go from a corn monoculture, to a field with a variety of second generation corn plants with inferior phenotypes, weeds and native plants that would eventually undergo succession to a community with little or no corn. This reveals that annual cropping systems are perpetually maintained by deliberate disturbance to be in a controlled early-successional stage (Swift et al. 2004). The farmer's mature forest on the other hand persists with no management. The farmer's two perennial systems, depending on their management, are somewhere in between, maintaining some degree of their intended function for years and decades after initial establishment.

Tilman et al.'s (1997) classic experimentation with perennial forage grasses showed that ecosystem functions like primary production were most dependent on the presence of functional groups of perennial forage rather than particular composition of forage species. This experiment is an elegant demonstration of the idea that functional groups (in this case legumes, C3 grasses, C4 grasses, woody plants, and forbs) can be occupied by several redundant species and result in similar ecosystem function. Perennial-based systems are suitable for creating multifunctional polycultures such as the one in Tilman et al.'s experiment. Because of their variable heights and shade tolerances, woody perennials can grow together with each other and with herbaceous plants that occupy different functional groups. Deep roots of trees and perennial grasses can both access nutrients and water from deeper layers, and at the same time extend the horizon of soil formation by enacting weathering on deeper layers of mineral soils and emitting root exudates. Above ground, trees extend photosynthetic surfaces upward and create variability in the spatial topography of the plant community. Spatial and temporal heterogeneity, redundancy, and functional diversity are three of the criteria outlined by Cabell & Oelofse (2012) as features of a resilient agroecosystem.

In addition to the potential for functional diversity, the succession undergone in perennial systems is notable. Fundamentally, perennial systems are longer lived and have longer disturbance cycles than annual systems, providing opportunities for long-term (and repeating) ecological interactions that change over time as plants mature, creating new conditions in which biotic and abiotic interactions take place. A succession takes place within a perennial agricultural system, over the span of just a few years (perennial pigeon pea, vining beans, bananas) to thousands of years (olive trees, brazil nuts). This succession prolongs adaptive cycles and selects for different phenotypes on many scales, from the microbiological to the human. This "slowness" in agricultural cycles poses challenges but also lends advantages. In a perennial system with intact functional relationships, the recycling of nutrients from canopy to soil, the permanent ground cover, the long-term associations of roots and fungi, the role of forage animals as fertilizers, and countless other biotic interactions create a system that would qualify as a complex adaptive system (Walker et al. 2004; Levin 2005).

What exactly qualifies as a complex adaptive system in agriculture, and what constitutes resilience, is debatable. Whether a system is complex and adaptive or managed depends largely on how it is bound, i.e. whether people's interactions with the space are included as components in the system or considered as separate (Chapman et al. 2017). Whether a system is considered resilient depends on the thresholds of disturbance it experiences and its adaptability in the face of these disturbances, which allow it to retain its essential function, structure, identity, and feedbacks (Walker et al. 2004). According to some authors, the concept of resilience also encodes a subjective and political normativity about what essential structure, function and identity are, and whether disturbance events or continuation of the status quo are considered desirable and by whom (Cretney 2014). Despite these conceptual grey areas, perennial systems seem more disposed than annual systems to regulate themselves while largely maintaining their basic function and structure. This might not be the case under all disturbance regimes or with all management conditions, because though perennials may be more robust in the face of disturbance if they grow in generally favorable conditions, they also take a longer time to recover if the disturbance is fatal to the dominant plants. Generally though, the redundancy, heterogeneity and functional diversity that manifest in diversified perennial systems mimic the self-perpetuation and successional dynamics of stable natural ecosystems.

1.4.4 Summary

Diminishing the use of environmentally costly external inputs requires that they be replaced with functioning ecological relationships and resulting ecosystem services that can provide resources and regulate processes needed for agricultural production (Kremen and Merenlender 2018). Moreover, the enhancement of agricultural matrix for wildlife habitat is an important component of conservation, alongside the protection of intact nature (Kremen and Merenlender 2018). A more thorough literature review and meta-analysis is necessary to provide an unbiased assessment of several ecosystem services in perennial agriculture under various management practices. However, fundamentals of ecology and studies from perennial grasslands, agroforestry, and tree crop systems together suggest a robust ecological basis for a more widespread transition to tree crops grown in conjunction with continuous ground cover. The ecosystem services associated with woody perennial polycultures (i.e. multiple woody crops combined with permanent pasture and even animals) are more difficult to summarize due to the lack of scientific evidence in the temperate North. But concepts from ecology and resilience theory together with evidence from the tropics suggest that such farms could constitute nature-mimicking systems that self-regulate to a greater extent than annual croplands, potentially improving habitat, reducing the need for inputs, and mitigating offsite impacts.

1.5 Transitions to perennial food systems

As agroforestry has gained scientific and policy traction ever since the term was coined in the 1970s, transitions to food systems that incorporate perennials (though not necessarily as the main food-producing components of the system) have received considerable attention. A variety of theories of human action and technology adoption from a range of academic fields have been employed in studies of agroforestry adoption, including diffusion of innovation and the theory of planned behavior (reviewed in Meijer et al. 2015); agricultural innovation systems (AIS; Borremans et al. 2018), universal theory of acceptance and use of technology (UTAUT; Trozzo et al. 2015); and expected utility theory (EUT; Borges et al. 2015). These theories have been deployed in various combinations to account for the sociological, psychological, and economic dynamics involved in these transitions. As many authors point out, the adoption of perennial agriculture (if it involves diversity) is not a single agricultural innovation or technology, but rather a suite of practices and cognitive resources involving multiple inputs, outputs, species, and techniques (Mercer 2004; Meijer et al 2015). The lack of a standardized “package” for adoption of these practices means that farmer knowledge, learning and experimentation is especially important, in contrast to green revolution technologies that are sold in defined units with specific application instructions (Mercer 2004; Barret 2002).

The accumulation of agroforestry-based initiatives in the tropics during the 1990s and early 2000s have provided data for syntheses of agroforestry adoption studies to be carried out in the form of both thorough reviews (Mercer 2004) and quantitative meta-analyses (Pattanayak et al. 2003; Meijer et al. 2015). Both Mercer (2004) and Pattanayak et al. (2003) use a chiefly instrumental framework of five major influencers on agroforestry adoption: household preferences, resource endowments, market incentives, biophysical factors, and risk and uncertainty. Mercer (2004) summarizes that agroforestry adoption generally follows the predictions of economics, in that farmers will invest in it when they expect the gains to be better than other uses of their land, labour and capital, and that adopters are usually better-off households who can afford to take more risks due to larger incomes or greater resource endowments (land, labour, capital, experience, education). The author also calls for the use of richer data rather than the use of proxies and general categories, and more research into critical processes such as the influence of social groups, adaptation, and adoption and learning over time. Meijer et al. (2015) put some of these suggestions into practice by creating a new framework that more explicitly incorporated non-economic (“intrinsic”) factors, which have been shown to be key to explaining participation in voluntary programs such as payments for ecosystem services (Rode et al. 2015). These involved how farmers viewed benefits and challenges, and how these perceptions and attitudes affected the uptake of agroforestry practices. While the separation of intrinsic and extrinsic factors and the approximate conflation of these categories with instrumental and non-instrumental logics can be challenged (Chan et al 2016), Meijer et al.'s work creates a more interdisciplinary framework for agroforestry adoption that operationalizes the push to improve on the chiefly economically-focused analyses of adoption in tropical countries.

The investigation of transitions to perennial agricultural systems in the temperate North are not as well synthesized or theorized based on empirical studies, though there are numerous good examples of regional case studies (Atwell et al. 2009; Borremans et al. 2016; Chapman et al. 2019; Blesh and Wolf 2014; Sereke et al. 2016; Trozzo et al. 2015; Mattia et al. 2018; Stanek et al. 2019). While some of these studies find that economic risk and knowledge barriers are most significant in the lack of adoption (Borremans et al. 2016; Trozzo et al. 2015; Mattia et al. 2018; Stanek et al. 2019) other studies of farmers within jurisdictions with existing payment for environmental service schemes found that monetary incentives alone cannot overcome reluctance arising from values and identities that have a perceived conflict with program rules or aims (Chapman et al. 2019; Sereke et al 2016; Atwell et al 2009).

In both the global North and South, many studies have focused on the barriers to adoption due to the fact that uptake of agroforestry has often lagged behind investment, leading to poor enrollment in funded programs (Pattanyak et al. 2003; Chapman et al. 2017; Atwell et al. 2009;

Sereke et al 2016). A much smaller number of studies have conducted in-depth analysis based on farmers who are adopters (Blesh and Wolf 2014). As discussed in Blesh and Wolf (2014) there is a need for studies that address *how* farmers transition successfully, to complement the studies that focus on *why* they do (or more often do not). The praxis of adopting and continuing with a tree crop/agroforestry enterprise over the long term is one that justifies attention alongside the cognitive and relational justifications for doing so. In their study of Iowa farmers' transition from conventional farming to small-grain production with perennial legume rotations and rotational grazing, Blesh and Wolf (2014) found that farmers overcame obstacles by cultivating ecological and enterprise diversity, by developing new management competencies, and by developing connections with knowledge organizations and government programs.

Similarly to these insights, a recent synthetic study combining theory, original data and literature review resulted in five pathways toward increased adoption in Flanders, Belgium, each relating to a cluster of structure, function, and transformation (Borremans et al 2018). These were: 1) investing in research on productivity and management to improve recommendations with respect to biophysical and labour constraints; 2) creating markets for agroecological products to stimulate entrepreneurial and private sector involvement; 3) establishing a stable legal landscape and attractive incentive program to improve on existing institutional resources; 4) establishing networks of researchers and farmers to promote learning and communication; and 5) increasing the dialogue between influential groups to increase the social acceptability of agroforestry. While I've simplified them substantially here, the pathways suggested in this study echo and elaborate on many of the themes elucidated in other in-depth interview-based studies on perennial adoption that attend to biophysical, cognitive, social, and structural dimensions of transition

(Atwell et al 2009; Blesh and Wolf 2014; Sereke et al 2016). To my knowledge, the Borremans et al. 2018 study is the most comprehensive and analytically robust synthesis of pathways to temperate agroforestry adoption and up-scaling, even though it was conducted with a focus on Flanders specifically. In contrast, more general reviews and opinion pieces on the subject of perennial or agroforestry adoption in the temperate North have been more introductory, chiefly advocating for their multifunctional benefit, rather than reviewing their actual prevalence and the specific challenges they pose (e.g. Jose et al. 2012; Smith et al. 2013). Perhaps the time is ripe for a new review on temperate perennial system adoption that thoroughly synthesizes the findings of recent empirical work. The integration of knowledge from practitioners of perennial agriculture and those who have not overcome barriers to initial adoption will be key to generating and enacting ambitious and realistic pathways for up-scaling of perennial crops.

1.6 Chapter Overview

1.6.1 Chapter 2: Perennial staple crops: yields, distribution, and nutrition in the global food system

Staple crops, which have large amounts of carbohydrates, proteins, and/or fats, provide the bulk of calories in people's diets. Perennial plants can produce staple foods and environmental benefits, but their agronomic and nutritional properties haven't been considered synthetically in comparison to annual staples. This chapter offers a framework to classify perennial staple crops according to their nutritional categories and cultivation status, and reviews yields, nutritional data, and carbon sequestration of these crops on a global scale. In it, I ask the questions: 1) What are the yield ranges of under-studied perennial staple crops? 2) What is the current extent and spatial distribution of perennial staple crop production? 3) What are the nutritional properties of perennial staple crops? 4) How much carbon are existing perennial staples holding in both biomass and soil?

The chapter defines and categorizes perennial staple crops, compares their yields to those of annual staple crops in nutritionally analogous groups, reports their total production, maps their geographical distribution, synthesizes nutritional information, and estimates their standing carbon stock. It also contains a simple projection for carbon sequestration from perennial staple crops in 2040. This baseline information on the yield potential, production, nutrition, and climate regulation of perennial staple crops is intended to enable future work that incorporates these important, but under-studied, foods into global and regional planning for land transitions, market interventions, and agricultural policy.

1.6.2 Chapter 3: Biodiversity and ecosystem services indicators of perennial polycultures in the US Midwest

This chapter, which takes place on the regional scale of the US Midwest, explores environmental and food production outcomes of a particular type of perennial management: perennial polyculture. Theoretical concepts from ecology and complex adaptive systems suggest that structural heterogeneity and functional diversity are key for supporting biodiversity, ecosystem services, and resilience, but these concepts have not been extensively applied in agriculture which is still dominated by annual monocropping systems. Perennial agriculture, and particularly woody perennial polycultures that combine a variety of long-lived woody perennial crops with continuous ground cover seem to embody these ecological concepts. However, our understanding of the benefits and trade-offs of these practices compared to conventional agriculture is limited, especially in the temperate North. The US Midwest is emerging as a hotbed of such systems in the temperate North in the form of farm-scale perennial polyculture enterprises, but they are currently only a tiny fraction of the landscape and regional agricultural production, which is dominated by highly industrialized agricultural systems.

In this study, I compare the environmental and agronomic outcomes of on-farm woody perennial polyculture agriculture with conventional annual crops and herbaceous perennial hay. Specifically, I ask two questions: 1) what are the effects of land transition to diversified perennial systems on a broad range of indicators relevant to biodiversity and ecosystem services? and 2) how do perennial systems vary as they mature? To this end, this chapter reports on a natural experiment (Diamond 1983) directly comparing a broad range of indicators relevant to biodiversity and multiple ecosystem services between perennial polyculture fields and adjacent conventional annual and hay fields. I hypothesize that woody perennial polyculture fields would support higher levels of biodiversity and ecosystem services than annual fields and that these differences would increase with the age of the woody perennial polyculture fields.

1.6.3 Chapter 4: Local knowledge and relational values of Midwestern perennial polyculture farmers

This chapter, which explores the knowledge and perspectives of perennial polyculture farmers in the US Midwest, is the companion social science study to the biophysical work reported in

Chapter 3. Agricultural producers, academics, and policy makers are increasingly interested in multifunctional tree crop systems, but little is known about the farmers that have adopted these practices in the temperate North. Understanding how perennial polycultures might be scaled up thus requires learning from the farmers that are at the forefront of this land use transition to answer a range of questions: What unique management knowledge is being implemented by farmers to manage complexity on multiple scales? What key challenges have farmers faced? And what values and motivations underpin these fledgling efforts?

In this study, I report on findings from 13 interviews with 18 midwestern perennial polyculture farmers including a) the land uses of and livelihoods generated by perennial polyculture farms; b) the motivations of farmers currently operating perennial polyculture enterprises; c) their local expertise on unique aspects of managing perennial polyculture systems and how this relates to complex adaptive systems; d) the community relationships and knowledge networks they participate in; and, e) the challenges and barriers to thriving/expansion that they face and how these intersect with existing policies. I synthesize the themes that emerged from these topics using a relational values framing, and connect the findings to both mainstream agricultural science and permaculture. Finally, I set an agenda for policy and program development in the private, nonprofit, or government sectors that emerges from these holders of local knowledge.

1.6.4 Chapter 5: Conclusion

The conclusions chapter reviews key findings and contributions from the thesis, discusses its limitations and emerging research needs, and finally explores synthetic intersections of the results of the three data chapters with a view to the future.

Chapter 2: Perennial staple crops: yields, distribution, and nutrition in the global food system

2.1 Introduction

The challenge of growing and supplying food to a growing human population involves balancing the production of multiple outputs (food, fodder, raw materials, livelihoods) with multiple ecosystem services and impacts (climate regulation, soil conservation, wildlife habitat, energy use, pollution, etc; Robertson & Swinton, 2005; Foley et al. 2011; Campbell et al. 2017; IPBES 2019; Chan et al 2019). Recent literature has recognized that both protected areas *and* a favorable working landscape matrix are required for conservation of natural services and wildlife (Kremen 2015; IPBES 2019). The current agricultural system worldwide is dominated by annual monocrops that do not constitute such favorable matrix environments, namely wheat (Triticum spp.), maize (*Zea mays*), soybean (*Glycine max*) and rice (*Oryza sativa*), which cover over 1.29 billion hectares of land globally (FAO 2020). These systems, which experienced steep yield gains over the post-war decades in most of the world (Ray et al. 2012) are heavily reliant on external inputs of energy, fertilizers, and pesticides, leading to severe ecological consequences. These include 10-12% of greenhouse gas emissions leading to global warming (IPCC 2015), nutrient pollution leading to eutrophication in aquatic ecosystems (Withers et al. 2014), erosion of soils leading to loss of arable land and carbon cycle disruption (Lal 2003), and the pervasive decline of life on Earth due to landscape simplification that degrades habitat for wildlife (IPBES 2019; Diaz et al. 2019, Foley et al. 2005). Perennial-based agriculture, which can include both woody and herbaceous crops that are grown over multiple years without replanting, is a transformative alternative to the annual systems driving these impacts (Wolz et al. 2017), yet their contributions to the global food system are not well known. This chapter synthesizes data on a global scale to classify perennial crops that produce staple nutrition (here called “perennial staple crops”, and reviews their yields, nutrition, and carbon sequestration.

Perennials are a key component in the habitat quality of the agricultural landscape matrix, and are thus often accounted for in landscape ecology and landscape genetics studies, as they allow for better movement of organisms between habitat patches (Brady et al. 2011; Benjamin et al. 2008; Eycott et al. 2012) or serve as primary habitat patches themselves (Bailey et al. 2012; Horak et al. 2013). In addition to their benefits to wildlife habitat and biodiversity, ecological studies link perenniality in agricultural landscapes to additional ecosystem functions and services that directly or indirectly contribute to the wellbeing of people: soil carbon sequestration (Young et al. 2009; Cates et al. 2016), pollination (Morandin & Kremen 2013; Bennet & Isaacs 2014), pest regulation (Landis et al. 2000; Karp et al 2018), water quality (Gao et al. 2004; Blesh and Drinkwater 2013), and soil retention (Zuazu & Pleguezuelo 2008; Brady & Weil 1986). Meta-analyses of empirical findings from agroforestry systems (i.e., agricultural systems that have a woody perennial component) have confirmed their ability to enhance multiple ecosystem services, though the specific services they bolster are highly context dependent (Pumariño et al. 2015; Torralba et al. 2016).

Applied ecological literatures (agroecology and agroforestry) as well as the grassroots permaculture movement have long advocated for the integration of long-lived perennial species in diversified agricultural landscapes (Asbjornsen et al. 2014, Jose 2009; Mollison and Slay 1995; Ferguson and Lovell 2014). Agroforestry is defined as a system that produces crops and/or livestock products and includes woody plants. While most agroforestry practices involve integrating non-food producing perennials into the edges of annual agricultural landscapes (as buffers, hedges etc), in some cases, the woody plants are themselves the primary crop, and tree crops have recently been added to the definition of agroforestry by some authors (van Noordwijk et al. 2016). This integration is a welcome development, as it helps break down the somewhat artificial boundary that has separated agroforestry practices that are established and studied chiefly for ecosystem services (especially in the temperate North) and tree crop systems that are established and studied chiefly for food production (Lovell et al. 2017). Food production from perennial crops is an important and underappreciated dimension in the expanded definition of agroforestry that needs to be centred and understood alongside the environmental benefits of these multifunctional systems.

The potential of perennial systems has been reflected in recent, major UN and grey literature reports on climate change that list agroforestry and tree crops among the top solutions for both climate mitigation and food production (IPCC 2019a, Hawken 2019). However, as discussed, any potential environmental benefits of growing food perennially must be assessed in the context of the yield intensity and nutritional value (as well as the economics) of perennial crops compared to those of annual crops.

Efforts to this end are actively taking place through breeding projects to either perennialize herbaceous annual staple crops, or domesticate wild perennial grasses for food production (e.g Kernza, and domesticated version of a wild perennial wheatgrass; Glover et al. 2010). For these breeding projects, agronomic and environmental outcomes can be directly compared to the equivalent annual species. But scientific analyses on a global food system scale are lacking for already existing and nutritionally important perennial staple crops. This may be due to the higher complexity of comparing many dissimilar species, the perception that perennials are not an important part of diets, the relatively lower prevalence of perennial staples in the temperate North, and/or the long generation times needed for breeding these crops (Mehlenbacher 2003; Molnar et al., 2013).

Perennial staple crops have long been a part of people's diets. Most studies of perennials focus on economically, but not nutritionally important commodities in the tropics (coffee and cocoa), or on sugar and micronutrient-rich fruits in temperate regions (apples, pears, etc). However, diverse species of perennials also provide staple nutrition in the form of carbohydrates, fats, and proteins that, in some cases, compare favorably to the yields of annual staple crops. The contribution of perennial staple crops to food production at present, and their potential for growth in the future is not yet clear because the yields, distribution, and nutritional value of these crops have not been systematically categorized, synthesized, and compared to annual crops in the scientific literature.

In this paper, we address this gap and ask the questions: 1) What are the yield ranges of under-studied perennial staple crops? 2) What is the current extent and spatial distribution of perennial staple crop production? 3) What are the nutritional properties of perennial staple crops? 4) How much carbon are existing perennial staples holding in both biomass and soil? To this end, we define and categorize perennial staple crops, compare their yields to those of annual staple crops in nutritionally analogous groups, report their total production, map their geographical distribution, synthesize nutritional information, and estimate their standing carbon stock. We hope that this baseline information on the production, nutrition, and climate regulation of perennial staple crops will enable future work that incorporates these important, but under-studied, foods into global and regional planning for land transitions, market interventions, and agricultural policy that are required for achieving sustainable food-security.

2.2 Perennial staple crops

The term staple crop typically means a food that's eaten regularly and comprises a major part of people's diets. Woody perennials often bring to mind sugary fruits or stimulants like coffee or tea rather than staple crops. But, woody perennial plants are staple crops in some parts of the world (for example, avocado, banana, coconut, and many others), providing core nutrition in the form of carbohydrates, proteins and fats. We define perennial staple crops as those that have significant amounts of these three fundamental nutrients (carbohydrates, proteins and fats). This definition distinguishes perennial staple crops from other categories of perennial crops, like sugar-producing crops, industrial crops, perennial pastures, and spices/stimulant/medicinal crops (Box 2.1).

Box 2.1: Perennial crop types

Staple crops: Perennials whose edible products contain high proportions of carbohydrates, proteins, and fats. E.g. nuts, olive, oil palm, avocado, perennial beans, mesquite.

Sugar crops: Perennial crops grown mainly for their sugar content. E.g. cane sugar, date.

Perennial vegetables: Perennials that are used for their leafy greens, shoots, or flowers. These are often rich in micronutrients but not calories. E.g. bamboo shoot, asparagus, Moringa leaf, grape leaf.

Non-staple fruit crops: Typical orchard fruit that do not contain large amounts of carbohydrates, proteins, and fats but are often culturally important and rich in micronutrients. E.g. apples, peaches, oranges, mango, persimmon etc.

Beverage/spice/medicinal: These are non-staple specialty foods that can be economically and culturally important. E.g. cocoa, coffee, spices, medicinal.

Perennial grains (in development): Breeders are currently working on cross-breeding annual staples (grains) with wild relatives to produce perennial grains, but with limited success; most lines are still weakly perennial. The more successful breeding attempt is in the opposite direction: domesticating a wild perennial grass. The Land Institute is currently producing small amounts of Kernza, a perennial wheatgrass bred for improved grain production.

Fodder crops: Perennials grown as animal feed. These overlap with both staple crops (mesquite, chestnuts, honey locust) and non-staple fruit crops (persimmon, mulberry).

Perennial pasture: Many pasture and natural grassland species are long-lived herbaceous (non-woody) perennials, which are either grazed directly or mowed for hay year after year. E.g. perennial grasses, alfalfa.

Industrial crops: Fibre, wood, chemical extracts. E.g. rubber, inedible oil, wax, gums.

We further categorize perennial staple crops into five nutritional categories based on the proportions of carbohydrates, proteins, and fats in the dry, edible portion of the crops. Our synthesis of yields uses this categorization in order to select appropriate annual comparator species. While calorically important perennial staple crops are the focus of this paper, Box 2.1 situates them alongside other categories of perennial crops.

Box 2.2. Nutritional categories of perennial staple crops

Basic starch crops: (0-8 % protein, 0-5 % oil). These crops include crops such as bananas, chestnuts, plantains, breadfruit, air potato, and starchy trunks (Sago palm). Comparable annual crops include cassava, sweet potato, taro, and yams.

Balanced carbohydrate crops: (8.1-15 % protein, 5.1-15 % oil). Carbohydrates can be from either starch or sugar. These crops include crops such as Mayan breadnut, mesquite pods, Tahitian chestnut, and Yeheb nut. Comparable annual crops include maize, wheat, rice, and potato.

Protein crops: (15.1+% protein, 0-15% oil). These crops include perennial beans and honey locust pods, as well as processed leaf protein concentrates of herbaceous perennials like alfalfa and stinging nettle. Comparable annual crops include annual beans, chickpeas, lentils, pigeon peas, and cowpeas.

Protein-oil crops: (over 15 % both protein and oil). These crops include seeds, beans, and nuts such as almonds, Brazil nut, pistachio, walnut, and hazelnut. Comparable annual crops include soybeans, peanuts, and sunflower seeds.

Oil crops: (0-15% protein 16+% oil). These crops are sometimes consumed whole, while some are pressed for oil. They include olive, coconut, avocado, oil palm, pecan, and macadamia. Comparable annual crops include rapeseed (canola).

Some perennial staple crops (almond, banana, coconut, palm oil) are already familiar global commodities (>$ 1 billion USD/year, see Box 2.3). Others are minor global commodities. Many though, are regional crops with fairly limited total production, distribution and trade value. Box 2.3 shows the different categories of crop's cultivation status, market-readiness and commodification.

Box 2.3: Cultivation status of perennial staple crops

Global crop: Crops are grown and traded around the world and have an annual value greater than $1 billion USD. E.g. coconuts, avocado, almonds, bananas.

Minor global crop: Crops are grown and traded around the world, but on a smaller scale than global commodity staple crops, having an annual value lower than $1 billion USD. E.g. breadfruit, sago palm, carob, akee.

Regional crop: Crops have been domesticated and cultivated regionally but adopted elsewhere. Sometimes traded globally, sometimes only traded regionally. E.g. peach palm, yeheb nut, honey locust.

Wild crop: Crops that have strong historic or contemporary use as staples, but are not domesticated and are little cultivated if at all. E.g. monongo nut, Brazil nut, North American pinion pines.

New, in development, and experimental crops: Crops that are under development by breeders to domesticate or perennialize them. E.g. tacay nut, perennial wheatgrass.

2.3 Methods

2.3.1 Categorization of perennial staple crop into nutritional groups

Perennial staple crops were defined as perennial plants producing carbohydrates, proteins, and fats at levels above certain thresholds (Box 2.2). These were assembled based on the perennial staple crops listed in Toenesmeier (2016), only a subset of which are include here due to the availability of adequate data. We grouped crops into five nutritional categories following Toensmeier (2017). However the categories have been updated from Toensmeier (2017) in that they are now based on dry weight values. Though it would be preferable to categorise based on nutrition percentages from the foods as they are eaten (ie. cooked grains, fresh avocado, etc), the nutritional values for most crops that require cooking were not available for the cooked form. We therefore chose to group and compare all crops on a zero moisture (dry weight) basis, so as not to compare some fresh products to other dry products. The disadvantages of this are that some perennial staples are not eaten dry (avocado), while some are mostly eaten as re-hydrated dry products, and some are eaten both fresh and dry (coconut). By using dry weights, crops that are typically not consumed as staples, or not widely known as staples, can be evaluated for their potential as staple crops. Inedible portions like banana peels, avocado pits, and nut shells were also removed from the calculations, resulting in a dry, edible weight that was used for both yield and nutritional comparisons. The disadvantage of using dry edible weights is that farmers are more often paid on the basis of unprocessed (or semi-processed) fresh weight, making our yield estimates less easily converted to financial return.

2.3.2 Yields of perennial staple crops

We used national average data from the Food and Agriculture Organization (FAO) where available, and supplemented with other sources of yield information (often grey literature) to cover additional perennial staple crops. For each crop, we searched for papers, and reports that reported on yields of the perennial staple crops in the 5 nutritional categories. Searches were conducted using the crop name (both scientific and common) and a variety of keywords (yield, harvest, farm, production, productivity, fruit, seeds, nuts) using a Google Scholar and Google proper internet search, and the search results were screened up to page 7. Searches were not exact, since for some crops, results were more readily found than for others, which required more iterations to find relevant results. Studies were included if they contained information on crop production per area, from at least one field. Yield data extrapolated from individual trees or a small number of trees (common for poorly-studied crops) were not included. However, in some cases grey literature reports that lacked robust primary data, but were based on seemingly reliable farmer or expert assessments, were included. Units were converted to tonnes per hectare. Each reported yield was tagged with a data type based on the scale of the observations or experiments they originated from. The following data types were used: 1) research station, 2) on-farm study, 3) multiple sites, 4) farmer/expert assessment 5) regional assessment, 6) national assessment (mostly FAO data), 7) Global average yields (FAO). All categories were plotted with colour-coding and used in descriptive statistics. The category “multiple sites” refers to studies where several on-farm sites were studied, in contrast to regional assessments, which assessed average yields for an entire sub-national region or administrative unit. Global average yields for crops with country-level FAO data were not included in the yield plots with the other data types except for Brazil nut, where country-level information was not available. Due to the dearth of yield information for some crops, we did not require strict peer-review standards for this information, but we did require that the information be traceable to a study location or an author. The data category "farmer/expert assessment" was something of a catch-all category for reports that were from a trustworthy source (such as a government ministry, academic or farmer), but did not contain explicit methods for the area or number of plants assessed.

To minimize large variation in fresh weight yields, we calculated dry weight yields for only the edible portion of each product (ie. no shells, husks etc). Sources and full calculations for yield information and dry edible weights are available in the Supplementary materials available on Figshare: figshare.com/projects/Perennial_Staple_Crops/78756.

2.3.3 Global distribution of perennial cropland

We re-analysed a dataset of global geospatial crop distributions (Monfreda et al 2008) to show the contrasting distributions of herbaceous perennial crops and woody perennial crops, as well as the distinction between staple and non-staple woody perennial crops. The raster dataset on 1750 crops for the year 2000 was assembled as described in Monfreda et al (2008), but we recategorized the crop types for our purposes into three nested layers of categories. First, all cropland was classified into 1) annual crops, 2) annual/perennial grasses, 3) perennial crops. The perennials were further classified into 1) food, 2) fodder/forage, and 3) fibre/raw materials. The perennial food crops were further classified into 1) staples 2) fruit, 3) beverage/spice/medicinal plants. Herbaceous perennials used chiefly to feed animals (alfalfa and clover) were in the fodder/forage category. Most perennial food crops are woody, but two (banana and plantain) are large herbaceous monocots. We produced the maps using the ratio between different categories of interest combined with a colour scheme highlighting high and low ratios.

Data on the harvested area of the 15 perennial staple crops that the FAO reports on was collected and averaged for the years 2013-2017. To supplement these data we also found harvested area data for a few additional crops (pecan, macadamia, sago) in other literature, including the US Department of Agriculture, and the Mexican Secretariat of Agriculture and Rural Development.

2.3.4 Nutrition of perennial staple crops

Nutritional values of each crop were collected from multiple sources in the literature and averaged. Nutritional data for the three macronutrients (carbohydrates, protein and fat) and nine micronutrients (fibre, calcium, iron, magnesium, zinc, vitamin A, folate, vitamin C, and vitamin E) were collected. Two billion people are impacted by traditional malnutrition, a set of nutrient deficiencies with iron, zinc, vitamin A, iodine, and folate most prominent among them (Muthayya 2013). Hundreds of millions of people are affected by deficiencies from highly processed diets, which increase risks of obesity, diabetes, heart disease, high blood pressure, and osteoporosis. Key nutrient deficiencies in these highly processed diets are fiber, calcium, magnesium, and antioxidants like vitamins A, C and E (de Baaij 2015, USDA and USHHS 2010, Suter 2005, Siti 2015). Accordingly, we selected micronutrients that are deficient from either traditional or highly processed diets: fiber, calcium, iron, magnesium, zinc, folate, and vitamins

A, C, and E following Toensmeier (2020). Iodine is not present in most terrestrial foods, so it was not included.

Similarly to the yield calculations, we calculated the nutrient content on the basis of the dry, edible portion of each crop. Error bars (95 % confidence intervals) were calculated. When only one nutrient value was found in the literature, no error bars were calculated. Pigeon peas (*Cajanus cajan)* can be grown both annually and perennially, so nutrient information reported for this species (which did not specify annual or perennial) was used for both. Nutrition information for Leaf Protein Concentrate (LPC) of stinging nettle wasn't available, so nutrition information for blanched nettle leaves was used instead as a rough approximation. Rapeseed, which was the only annual comparator for perennial crops exclusively pressed for oil (and not also consumed as a fruit, seed, or nut), did not have nutrition information available on the basis of the seed (only the pressed oil); there is no annual comparator for nutrition in the oil category for this reason. Data tables with full references for the sources of nutritional data are available on the figshare data repository under the project "Perennial Staple Crops":figshare.com/projects/Perennial_Staple_Crops/78756.

To calculate macronutrient yield per hectare, nutrient content was combined with yield information. For crops with FAO yield data, the FAO global yields averaged from the years 2013-2017 were used. For crops with no FAO data, average yields from our literature review were calculated (regardless of data type). These average yields cannot be considered true estimates because they do not take into account data type or attempt to weight the different yield reports, and are therefore not robust, but merely rough indicators of yield potential. Since uncertainty is not provided from the FAO for their global estimates, and since our own yield calculations cannot provide a true mean and standard deviation, uncertainty was propagated from nutrition data only (not from yield data) by the standard formula for error propagation by multiplication/division (Taylor 1997).

Nutritional values on total carbohydrates were entered as reported in the literature. The challenge is that this value includes not only starch but also sugar and dietary fiber, which are also “carbohydrates” in that they are composed solely of carbon, hydrogen, and oxygen. Thus a value for starch is unavailable for most crops.

Systems for reporting Vitamin A content have varied over the past decades. Here, all values are converted to mg Retinol Activity Equivalent (RAE), the current international standard.

2.6.5 Carbon Stocks

The total carbon stock for a perennial system is the sum of carbon from different pools: above-ground biomass (AGB), below ground biomass (BGB), dead biomass, and soil organic carbon. For above- and below-ground biomass, we looked for mean standing carbon stocks over the lifetime of a crop rather than carbon sequestration rates. This is because biomass (and thus carbon) accumulates over the life of a perennial system in a nonlinear fashion. However, mean stocks can only be reported when biomass measurements for different sizes of trees (or allometric equations that correlate with age) are combined with information about the typical length of a perennial crop’s productive life. Such means were only sometimes reported in the literature. Thus, for crops where we found multiple citations or reports on biomass for multiple ages of trees, these were averaged. For crops for which we could only find a single report from a sample of a certain age, it was used, or if the age was considered mature, the biomass was halved for a conservative estimate of mean standing stock. For crops for which we found no information on biomass, we substituted values from similar crops (for example plantain and banana). Regarding the inconsistency of carbon pools reported for biomass across publications (AGB and BGB and undergrowth/dead biomass), where only AGB was reported we obtained BGB by multiplying AGB with the conversion factor 0.21, which is a conservative BGB:AGB ratio from the range for forest cover from volume 4, chapter 4, table 4.4 of the *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use* (IPCC 2019b). We did not include litter and dead biomass unless these were reported together and couldn't be separated. To obtain values of tonnes carbon/ha we additionally carried out the conversion of C = 0.5*(mass of dry matter) if the publication had not already done so. In addition, we sometimes obtained separate information about typical planting density for a particular crop so that we could use publications that reported on biomass or generated allometric equations from a small number of trees (ie. publications that did not report carbon stocks on a per hectare basis or report planting density).

We used the soil organic carbon stock estimates for 3 climates (temperate, tropical, and Mediterranean) from Ledo et al.'s (2020) meta-analysis of soil carbon under perennial agriculture (Table 1). These soil organic carbon stocks were matched to each crop depending on its growing conditions, and summed with the biomass carbon estimates discussed above. To obtain an estimate of standing stock from perennial staples globally, these per-crop mean carbon stocks were multiplied with the harvested areas of the 15 perennial staple crops reported from the

UN FAO, as well as those for 4 more crops (pecan, peach palm, sago, and macadamia) which were obtained from other references. Standing carbon stock was calculated as follows:

Equation 2.1

$$Carbon\ stock\ perennial\ (Mt\ C)\ =$$

$$\sum \frac{(biomass\ carbon_i(tC/ha) + soil\ carbon_j(tC/ha)) * area\ harvested_i\ (ha)}{1\ 000\ 000(tC/MtC)}$$

Where *i* is the perennial staple crop, and *j* is the climate it matches (Table 2.1). For all the biomass values found in the literature, and how these were applied to the 19 crops, refer to supplementary tables on Figshare: figshare.com/projects/Perennial_Staple_Crops/78756.

Table 2.1. **Soil organic carbon estimates for perennial crops in different climatic regions.** Reproduced from supplementary material, Ledo et al. (2020)

climate	**SOC under perennial agriculture (t/ha)**
Arid	19.15
Boreal	134.7
Mediterranean	71.4
Temperate	116.9
Tropical	143.3

To estimate changes in biomass carbon for several scenarios of land conversion to 2040, data on the adoption of 15 perennial staple crops from 1968-2018 from the FAO Statistical service was used to project harvested area 20 years forward (to 2040) using a linear projection. The changes in biomass of carbon stocks were calculated by subtracting the standing stock of carbon of a comparator comparator land cover type (forest, grassland, or annual cropland) from mean standing stock of carbon for each of the perennial species (calculated above). The carbon stocks of the comparator cover types in different climates were obtained and matched to the climates of each of the perennial crops as follows: the mean AGB carbon stock of various forest types were retrieved from *Volume 4: Agriculture, Forestry and Other Land Use*, Chapter 4, table 4.7 of the *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019b), and multiplied by the ABG:BGB ratios from table 4.4 and matched to the environments where perennial staple crops are grown. These were multiplied with AGB:BGB carbon ratios obtained from table 4.4 to obtain the below-ground carbon estimates for each forest type. These were then summed to obtain biomass carbon estimates that include above and below ground carbon. Biomass carbon stocks (above and below ground combined) for grassland were obtained from *Volume 4: Agriculture, Forestry and Other Land Use*, Chapter 6, table 6.4 of *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Biomass carbon stocks for annual cropland set to 0, as specified in Volume 4, Chapter 4, of the *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019b). For harvested area values from the linear projection and for the values of biomass carbon for the comparison land cover types that were matched with each perennial crop by climate, refer to supplementary tables on Figshare: figshare.com/projects/Perennial_Staple_Crops/78756.

For changes in soil carbon stocks after conversion from other cover types to perennial crops, we used the change in carbon stock/ha over 20 years after conversion from Ledo et al. (2020) (reproduced in table 3). This was summed to the change in biomass carbon stock and multiplied by the change in harvested area for that species (equation 2.2).

Equation 2.2

$$\Delta\ carbon\ stock\ (MtC) =$$

$$\sum \frac{((biomass\ carbon_i - biomass\ carbon_{j,i}) + \Delta soil\ carbon\ over\ 20\ yrs_j) * \Delta area\ harvested_i}{1\,000\,000(tC/MtC)}$$

Where *i* is the specific perennial staple crop, and j the comparison land cover (annual cropland, grassland, or forest). $biomass\ carbon\ _{j,i}$ is thus the biomass carbon land cover type *j*, matched to climate and humidity of perennial *i* as discussed above; this value is set to 0 for *j*=annual cropland. $\Delta soil\ carbon\ over\ 20\ yrs_j$ is the change in carbon over 20 years from the land transition between the comparison land cover, j , and perennial cropland (Table 2.2). $\Delta area\ harvested_i$ is the change in area harvested for a particular crop based based on a subtracting the current area harvested (2013-2017 average) from the linear projection to 2040.

Table 2.2. Soil Organic carbon transitions to 100 cm below the surface over 20 years after transition. Reproduced from table 1 of Ledo et al. (2020)

transition	Change in SOC over 20 years (t/ha)
Annual crop to perennial crop	+ 5.7 (±11.0)
Grassland to perennial crop	−13.6 (±8.9)
Forest to perennial crop	−40.1 (±16.8)

2.7 Results

2.7.1 Characteristics and yields of perennial staple crops

With the literature review, we expanded the set of available yield estimates for perennial staple crops from 15 (records kept by the United Nations Food and Agriculture Organization) to 51 (Appendix A Table S1).

In the basic starch category, two perennial crop species stand out for having high yield potential: sago and enset (Figure 2.1 A). Sago (*Metroxylon sagu*) is a palm grown mostly in Indonesia and Malaysia (Jong 2018) which is used for its starchy trunk. Enset (*Ensete ventricosum*), like banana, is a giant non-woody perennial which is grown in Ethiopia and used for its large, starchy corm and trunk. Both plants are consumed as regional staples, and are similar in that their edible starches are derived from destructive harvest and processing of vegetative parts of the plant after several years of growth as opposed to the harvest of an edible fruit year after year (in the case of sago, only one trunk of the multi-stemmed palm is removed at a time leaving the rest to continue growing; in the case of enset, the corm may be left behind to regrow, or it may be harvested with the trunk, thus killing the plant). While the yield reports we found for these crops had a wide spread, yields exceeding 8 t/ha have been reported, well above typical yields of all the annual staple comparators in this category. Breadfruit (*Artocarpus altilis*), a tropical tree with a starchy fruit that is related to the familiar jackfruit, and carob (*Ceratonia siliqua*), a mediteranean legume tree with edible pods, are additional carbohydrate-rich crops that have similar yield levels to the familiar perennial staples, banana and plantain, and to the annual starchy tuber comparators in this category.

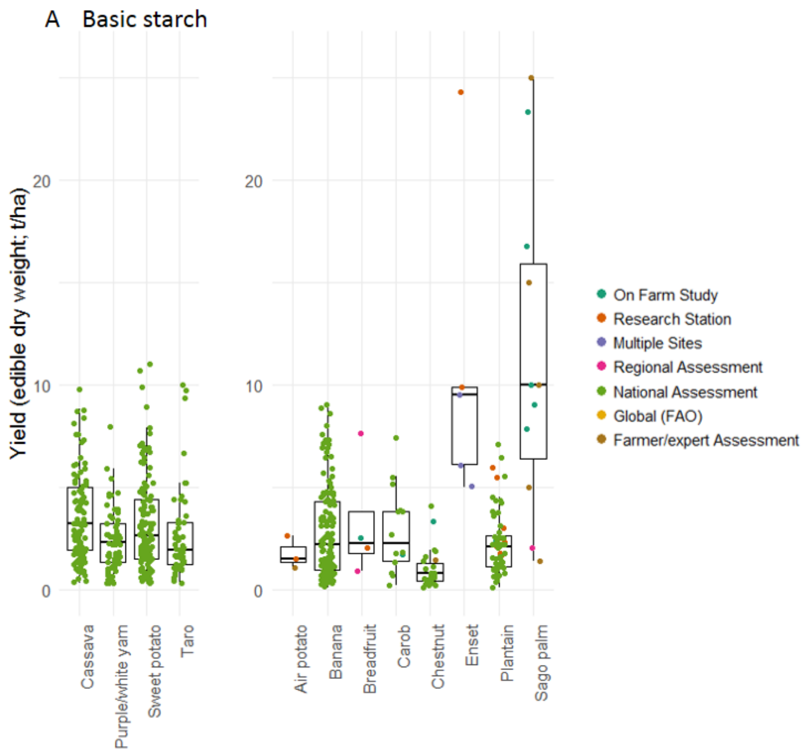
In the balanced carbohydrate category, which contains many of our most familiar annual staples including corn, wheat, potato, and rice, the perennial mesquite (*Proposis spp.*) stands out as a crop with high yield potential, while the other perennials in the category have lower yields than the annuals (Figure 2.1 B). Mesquite is the common name for several species of leguminous tree in the genus *Proposis*, native to the Americas, Africa and Southern Asia and ranging widely in habitat from tropical and hot arid, to temperate climates. The trees have wholly edible pods that can be used for animal fodder or processed as flour for human consumption, and some species can grow in arid and high salinity conditions (Felker et al 1981). Mesquite was used extensively as a staple food by Indigenous peoples in the Southeast of North America, Argentina, and Peru, and also as a fodder crop and fertility enhancer for intercropped annual grains in the Indian subcontinent for centuries (Felker 2005). While Mesquite has been studied as a raw ingredient for the food industry (Meyer et al 1986; Del Valle 1989), and found some success commercially and through community programs that offer milling services (Desert Harvesters 2008), it is still overexploited for timber and charcoal, not yet extensively grown on purpose for commercial food production and could still be improved through trait selection across large parts of its range (Felker 2005).

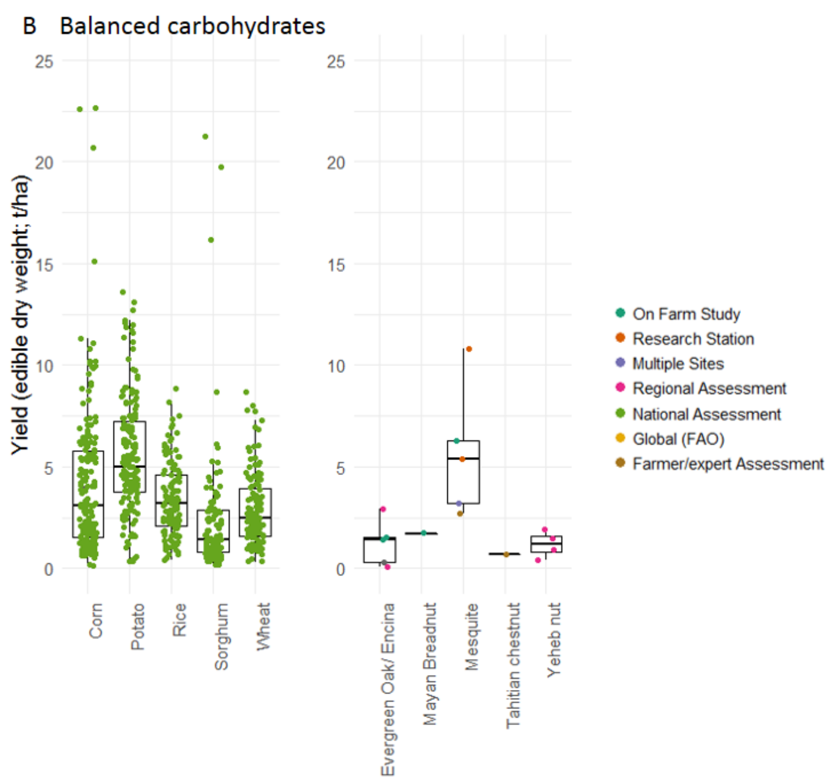
The protein category (Figure 2.1 C), is composed of leguminous species. Some of these are bean trees (Chachafruto, Honey Locust, Edible Acacia), while others are species of vining beans that become woody and persist for many years in warmer climates (vine types of runner bean, lima bean, sword bean). Pigeon pea is a perennial legume bush which is a widespread staple in India. It is chiefly grown as an annual, but has received some attention as a perennial component in annual intercropping systems in place of the non-food producing leguminous trees (like

Leucaena) typically used in arid alley cropping (Daniel and Ong 1991; Waldman et al 2017). The African yam bean is an interesting crop in that it is grown for both its beans (which can be harvested perennially), and its large edible tuber (thus ending its life); this underutilized crop is being studied for traits and genetic markers to assist in breeding (Adewale et al. 2012 & 2014). Finally, the protein category also includes alfalfa and stinging nettle for their leaf protein concentrate (LPC), a tofu-like product created by deriving protein-rich curds from leaf juice or pulp. LPC can be made from a wide variety of palatable leaves, but these are included because of the availability of data. Of the bean trees, vines/bushes, and LPC crops, chachafruto, vining runner bean, lima bean, and alfalfa LPC have the highest reported yields respectively. Honey locust has large variation in reported yields.

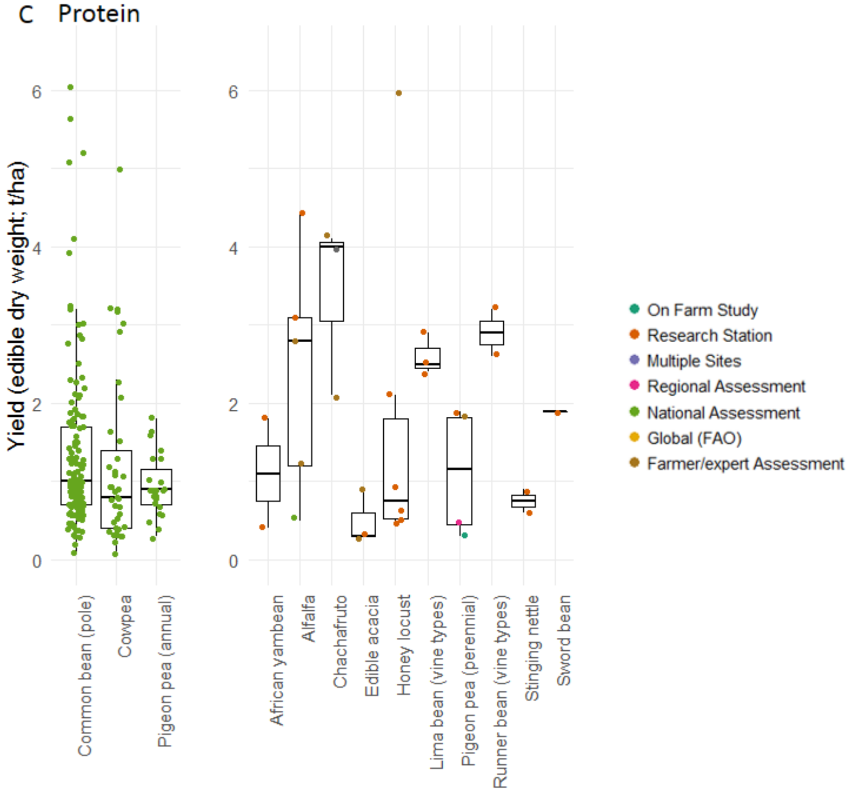
The protein-oil category was the largest of the five nutritional categories, with 18 perennial staple crops including many familiar nut species (Figure 2.1 D). Of these, the species with the highest reported yields are the Asian breadnut (*Artocarpus camansii)*, Inche/ tacay nut (*Caryodendron orinocense*), and Brazil nut (*Bertholletia excelsa)*. Asian breadnut is the wild ancestor of the breadfruit *(Artocarpus altilis)* and is still an important staple in New Guinea. Both its flesh (when immature) and seeds (when mature) are consumed. Inche/ Tacay nut and Brazil nut are both South American nuts that are chiefly still wild-harvested and have not undergone domestication. Tacay nut can be cultivated and grown in plantations, though it isn't clear to what extent it has been planted (Wickens 1995; PFAF 2020). In contrast, Brazil nut requires pollination from wild bees, and attempts at plantations have had low yields (Cavlacante et al. 2010). In summary, all three of these species are essentially undomesticated and partially to largely still wild-harvested, yet they have reported yields significantly higher than the widely domesticated and cultivated species of perennials (such as walnuts, hazelnuts, pistachio and cashew) as well the annual comparators in the same category.

The oil category (Figure 2.1E) is dominated by the intensively produced African oil palm (*Elaeis guineensis)* which boasts high national average yields and is a familiar global commodity ubiquitous in the processed food industry. The crop with the second highest yield, macadamia nut, includes three species from the genus *Macadamia*, all of which are native to Australia, where they are commercially produced along with Australia, South Africa, Hawaii, and elsewhere. Though they are familiar high-value nuts, this crop still lacks official UN FAO data. Peach palm (*Elaeis guineensis)* is the next highest yielding crop in the oil category. Like the African oil palm, it is also a palm tree, but native to the New World. It has many edible uses: its palm heart and flower shoot are eaten as vegetables, while its starchy and oily fruit is cooked and eaten as a staple in many forms (our reported yields relate only to the fruit). The peach palm was domesticated before European colonization, and encompases many landraces with variable genetics and charachteristics (Mora-Urpi et al 1997). While the heart of palm has been commercialized successfully, the fruit is still cultivated mainly as a subsistence crop for local consumption and sale; its use by Indigenous peoples as a staple with many processed products has failed to gain commercial traction and only small amounts are processed and sold internationally (Graefe et al. 2013; Clement et al. 2010). Coconut, avocado, and olive, three important and globally commodified staple perennial crops in the oil category, have generally lower yields than the less ubiquitous perennial staples peach palm and macadamia.

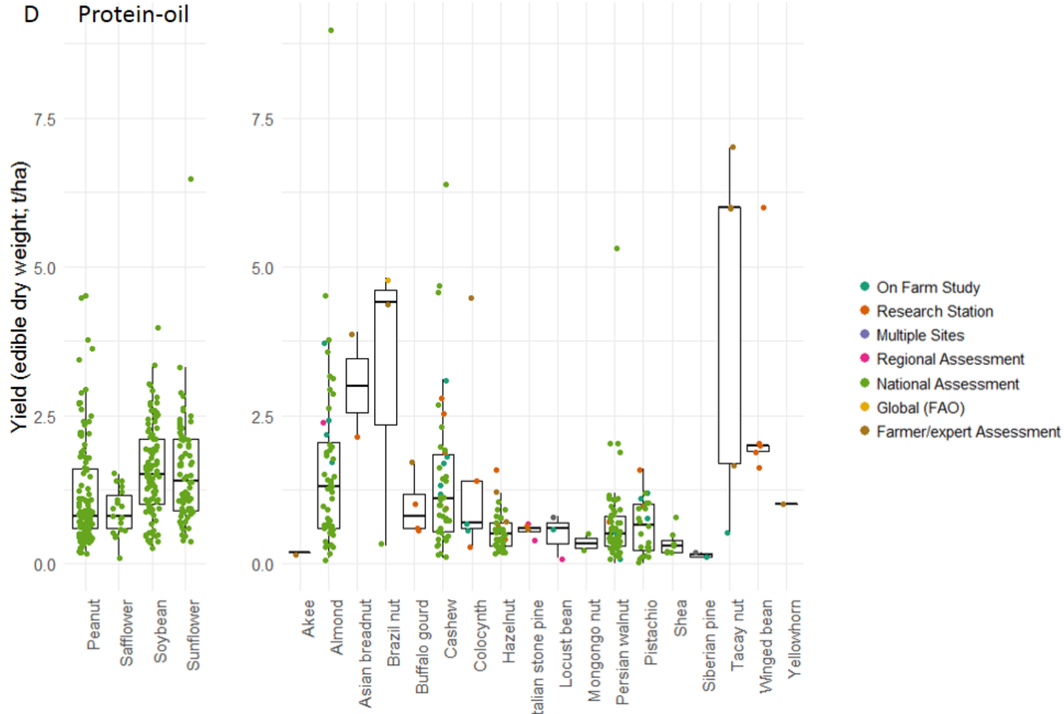

A Basic starch
Yield (edible dry weight; t/ha)
0
10
20
Cassava
Purple/white yam
Sweet potato
Taro
Air potato
Banana
Breadfruit
Carob
Chestnut
Enset
Plantain
Sago palm
On Farm Study
Research Station
Multiple Sites
Regional Assessment
National Assessment
Global (FAO)
Farmer/expert Assessment


B Balanced carbohydrates
Yield (edible dry weight; t/ha)
0
5
10
15
20
25
Corn
Potato
Rice
Sorghum
Wheat
Evergreen Oak/ Encina
Mayan Breadnut
Mesquite
Tahitian chestnut
Yeheb nut
On Farm Study
Research Station
Multiple Sites
Regional Assessment
National Assessment
Global (FAO)
Farmer/expert Assessment

C Protein



D Protein-oil



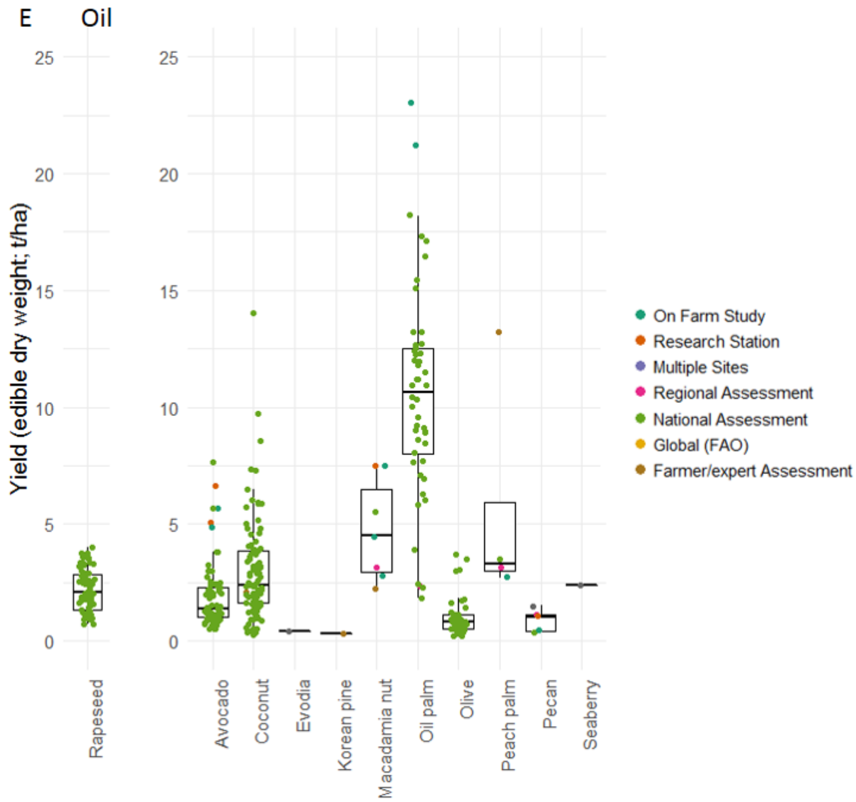
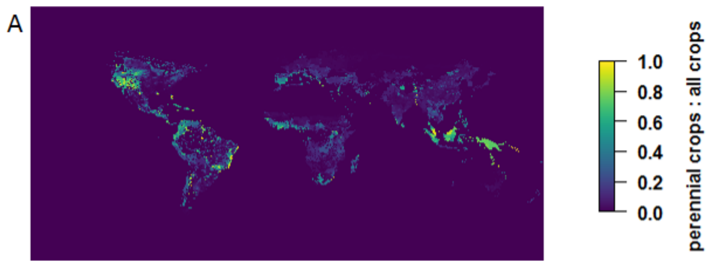


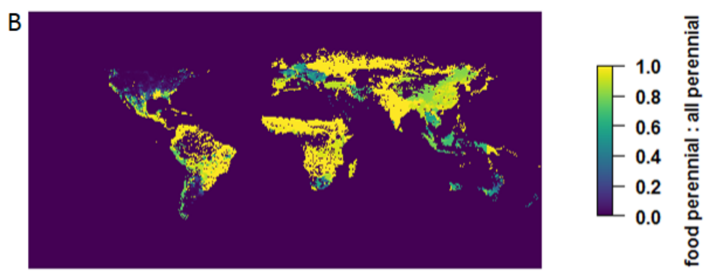
Figure 2.1 Yields of perennial staple crops. Left panels contain annual crops, right panels contain perennial crops. Each point represents one data point (t/ha of dry, edible portion) from the literature, colour coded by data type (see methods for full reference list). Box plots show the mean (line through box), 25th and 75th percentile (top and bottom of box), largest and smallest value within 1.5 times of interquartile range (top and bottom of whiskers). Green points (National Assessments) are mainly FAO data. A: basic starch crops. B: balanced carbohydrate crops. C: protein crops D: protein-oil crops E: oil crops.

2.7.2 Global distribution of perennial staple crops

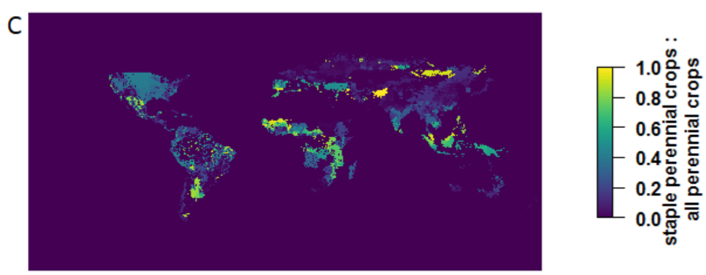
While yield information is crucial for understanding the intensity of production, the geographic distribution and harvested areas of these crops are necessary to understand their current extent. Based on Monfreda et al (2008), perennial crops comprise 12 percent of global cropland (Figure 2.2). Of this, 80 percent produces food, while the remaining 20 percent produces forage and fiber/raw materials. Previous spatial analyses have investigated tree cover on agricultural land, but haven't distinguished between different classes of food-producing perennials (Zomer et al 2009). We therefore distinguished between perennial staples and other food-producing perennials. Out of all food-producing perennial croplands, 34 percent is in perennial staple crops. The remainder is devoted to non-staple perennial crops: fruit (46.7 percent) and beverages, spices, and various medicinal plants like coffee, cocoa, kola nut, cardamom, etc (18.5%). The spatial analysis of area harvested only includes the 15 perennial staple crops included in the Monfreda dataset, which are the same as those with UN data (supplementary table 1).



All cropland	Harvested area (Million ha)	Percent total cropland
Annual crop	1017.9	80.7
Annual/perennial grasses	91.5	7.2
Perennial crop	152.5	12.1



Perennial cropland	Harvested area (Million ha)	Percent perennial cropland
Food	121.2	79.5
Forage	22.2	14.6
Fiber/raw material	8.9	5.9



Perennial food cropland	Harvested area (Million ha)	Percent perennial food cropland
Staple	42.1	34.8
Fruit	56.6	46.7
Beverage/spice/medicinal	22.4	18.5

Figure 2.2. **Land in perennial production.** A: Perennial cropland as a ratio of total cropland. B: Food-producing perennial cropland as a ratio of total perennial cropland. C: Staple crop producing perennial cropland as a ratio of

total food-producing perennial cropland. Data categorized and re-analysed from EarthStat database (Monfreda et al. 2008). Figures and table results were produced in R using the raster, rasterVis and maps packages.

The estimate of 42.1 million hectares, or 4.2% of total cropland in perennial staple crop production (Figure 2.2) is an underestimate for two reasons: first, the Monfreda et al. (2008) dataset is more than a decade old; more recent UN FAO data gives a total of 65.4 million ha, or 4.7% of total cropland in perennial staple crop production (FAO, average of 2013-2017). Second, as mentioned, both the UN FAO and Monfreda et al. (2008) datasets are based only on 15 perennial staple crops. For example, pecan, macadamia, and sago palm are three perennial staple crops with at least some accessible harvested area data that are not included in these global datasets. The area of pecans harvested from the US and Mexico (which dominate world production) in 2019 totalled ~320 000 ha (USDA 2020, SIAP 2020). The area of macadamia harvested in 2018 is around ~65 000 ha (calculated by dividing global production in pounds by Hawaii yields; USDA 2020; AgriOrbit 2018). The area of sago palm harvested is as high as 6.5 million ha according to Bintoro et al. (2018), though some of this area overlaps with diverse smallholder polycultures. These estimates, together with the minor global and regional crops that have limited or no available area data indicate that even the more recent UN FAO estimates are low. Nonetheless, the geographic distributions and overall ratios between the different crop types summarized in Figure 2 are likely to be similar given that underreporting in the UN FAO data may be occurring for both minor perennial and annual crops.

Of the 51 perennial staple crops in our dataset, 62% are subtropical or tropical, 19% are temperate or Mediterannean, and 19% span across temperate to tropical ranges (Table 2.3; Appendix A Table S1).

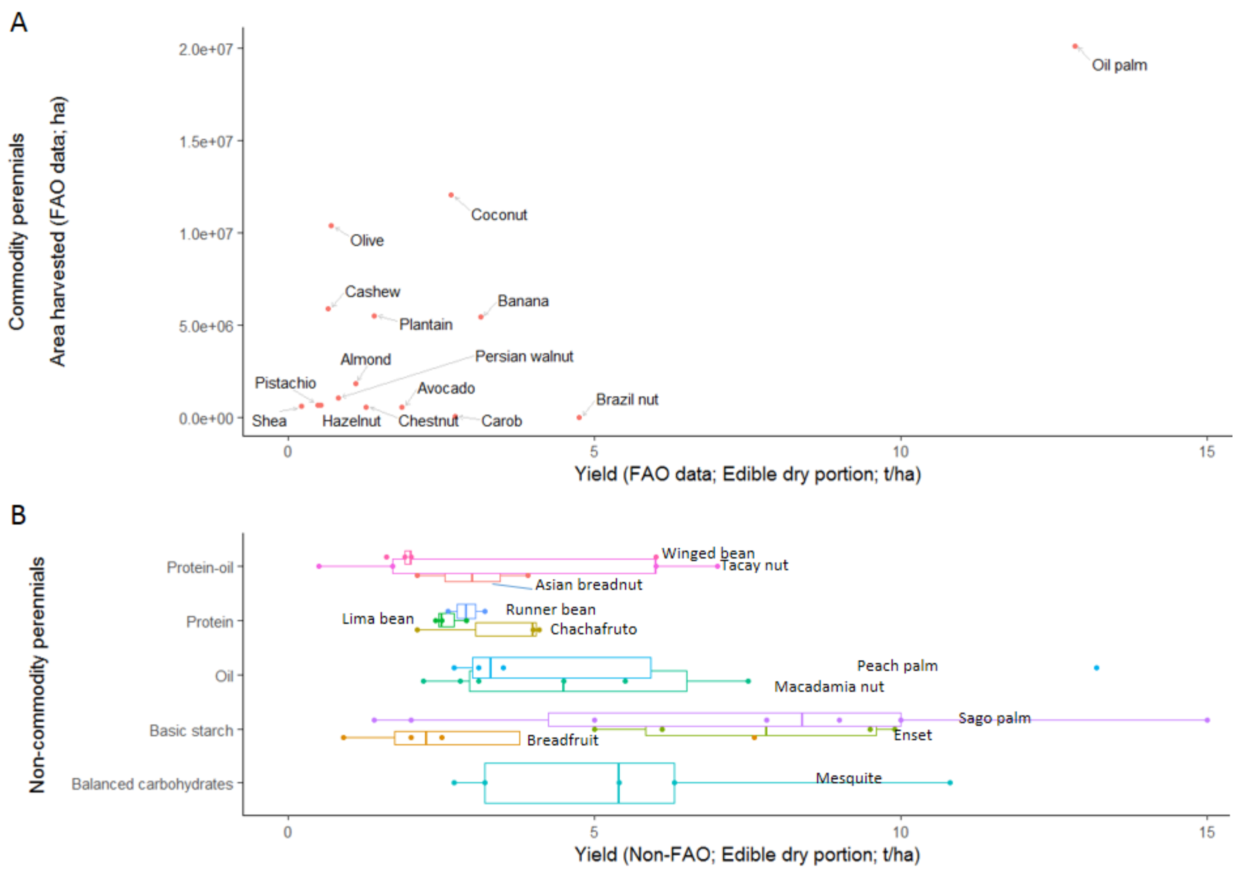


Figure 2.3 Yields and areas harvested. A: Perennial staple commodity crops with both yield and area harvested data from the UN FAO. Yields and area harvested are not significantly correlated if oil palm is removed from the data (P=.94). B: Top-yielding perennial staple crops (>2.5 t/ha on average) that do not have FAO production data, plotted on the same scale.

Whether in the tropics or in temperate climates, the current area harvested of perennial crops does not necessarily correspond to yields (i.e. production per unit area; Figure 2.3 A). Oil palm is an outlier in that it far outcompetes the other crops in both the yield and area of production, but if this crop is left out of the data, there is no correlation between the yield and area in production of perennial staple crops for which production data is available (P=0.94). This is not unexpected in a system that optimizes for profitability rather than food production, but it highlights the potential gains in food production that are possible under differently regulated market conditions.

Indeed, many perennial crops with potentially high yields are not global commodity crops (Table 2.3), and therefore their total production and harvested areas are not known. These high-yield potential non-commodity perennial staples (those with a mean yield of > 2.5 t/ha; Figure 2.3 B) have comparable or potentially higher yields to many global commodity crops. Indeed, only 29% of the perennials in our wider dataset of 51 crops were defined as global crops, while the remaining 71% were minor global, regional, or new/historical/wild/experimental crops (Table 2.3; Appendix A Table S1).

Table 2.3. Region and cultivation status of perennial staple crops. Includes 51 crops (52 in this table because hardy and tropical Mesquite were separated) for which yields were obtained. The climate/region category "both" means that these crops range across or between the two other categories, for example, Mediteranean to subtropical. See supplementary table 1 for detailed information on climate and cultivation status of each crop.

		Climate/region			
Cultivation status		Subtropical to tropical	Temperate to Mediterranean	Both	Total
	Global crop	7	4	4	15
	Minor global crop	7	3	4	14
	Regional crop	14	3	2	19
	Historical/new/ wild/experimental crop	4	0	0	4
	Total	32	10	10	

2.7.3 Nutrition of perennial staple crops

The three macronutrients on which we based our categorization (carbohydrates, proteins, and fats) fulfil people's basic caloric needs, while micronutrients (vitamins and minerals) provide essential additional components of nutrition. Figure 4.4 shows the crops with the highest proportion of the three staple nutrients on the basis of dry edible weight (Figure 2.4, A-C). For carbohydrates, sago palm, cassava, and enset have the highest proportion of starch. This is unsurprising since both sago palm and enset's nutritional data pertain to a processed product which is extracted from the tree trunk. Breadfruit, chestnut, mesquite and plantain also rank in the top 85 percentile for carbohydrate content.

For protein content, alfalfa LPC ranks first; this nutritional information pertains to a processed tofu-like extract, not the raw leaf. A variety of legumes as well as less familiar perennial crops (yellowhorn, oyster nut, colocynth) make the top 85th percentile of protein content along with the annuals soybean and peanut.

The crops with the highest concentration of oil were all perennials. Rapeseed, an annual which is chiefly grown for oil, was not included because its nutrient content was not available in raw form (only as a pressed oil), but other annuals which are regularly pressed for oil (sunflower, safflower, soybean, corn etc) were included.

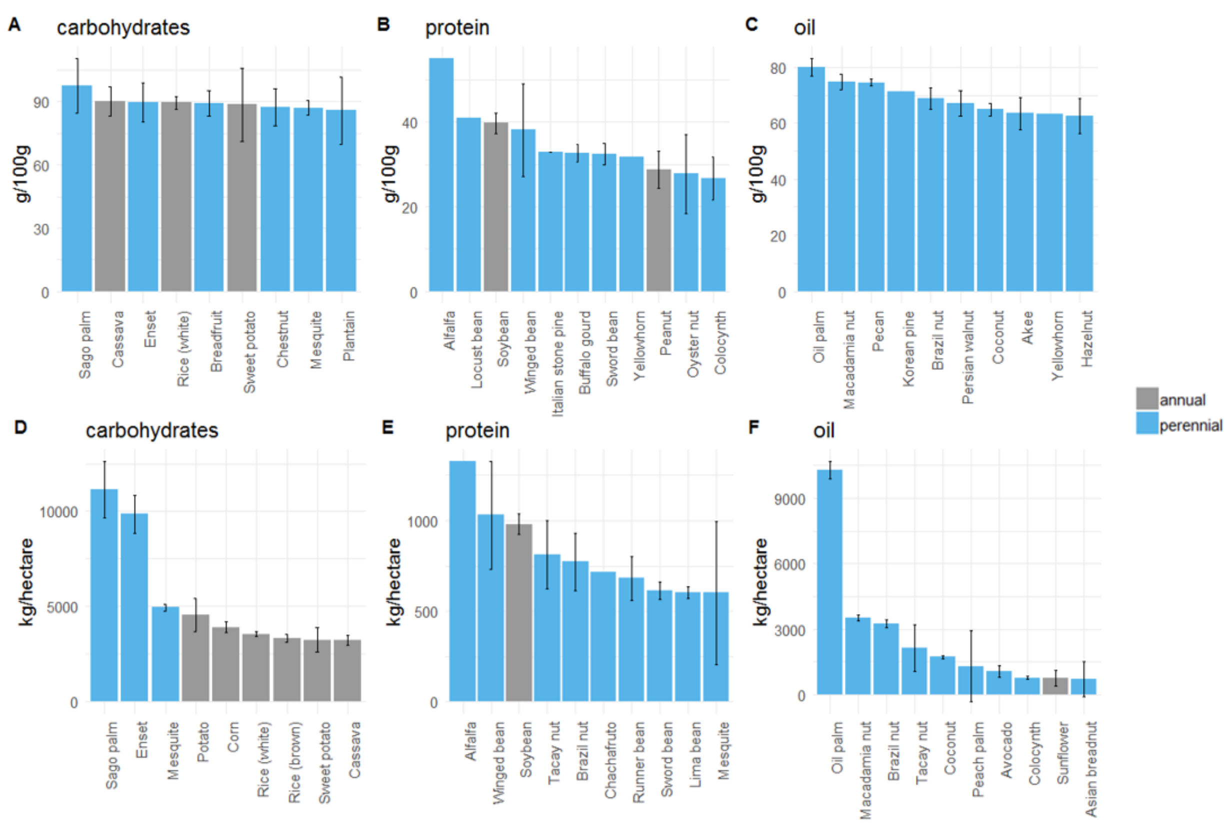


Figure 2.4. Macronutrient content and yields of perennials relative to select annuals**.** Panels A-C show staple nutrient content (g/100g) for leading crops (those in the 85th percentile and higher for that nutrient). Nutrient content is based on the dry, edible portion of each crop. Panels D-F show estimated yields of each staple nutrient (kg/hectare) for leading crops (those in the 85th percentile and higher for each respective nutrient yield). If available, yields from the UN FAO were used; for crops without UN yield data, we used a mean yield estimate from our literature review. Error bars are 95% CIs based on distribution of nutrient data only; if absent, only one source of nutritional data was available for that nutrient of that crop.

Based on the combination of nutritional density with yield estimates, perennial crops can produce large amounts of macronutrients per unit area (nutrient yield; Figure 2.4 panels D-F). These macronutrient yields provide several insights: for example, mesquite, a perennial we classified in the "balanced carbohydrate" category could produce more carbs per unit area than other perennial crops in the "basic starch" category like plantain and banana (these two do not appear in the top 85th percentile of carbohydrate production per unit area). Thus, crops with a lower proportion of a particular nutrient might still produce more of that nutrient per unit area if their yields are high. This analysis shows that for all three categories, the top crop for nutrient content (sago palm, alfalfa LPC, and oil palm Figure 2.4 A-C) is also the top crop for nutrient production per unit area (Figure 2.4 D-E). The presence and rankings of subsequent crops differ variously in each category. In all three categories, nutrient production per unit area (Figure 2.4 panels D-F) dropped off faster than nutrient content (Figure 2.4 panels A-C), indicating that yields are more variable than the staple nutrient content of top staple crops, particularly for carbohydrates and oil.

Perennial staple crops also provide other micronutrients, which are important for addressing both traditional and industrial malnutrition (see methods), including fiber, calcium, iron, magnesium, zinc, folate, and vitamins A, C, and E. We found that specific perennial staples are abundant in specific micronutrients, indicating that they can be a nutrient-dense part of diets, unlike the most ubiquitous annual staple crops in people's diets (corn, wheat, rice) that do not appear in the top 85th percentile for any of the 9 micronutrients (Figure 2.5).

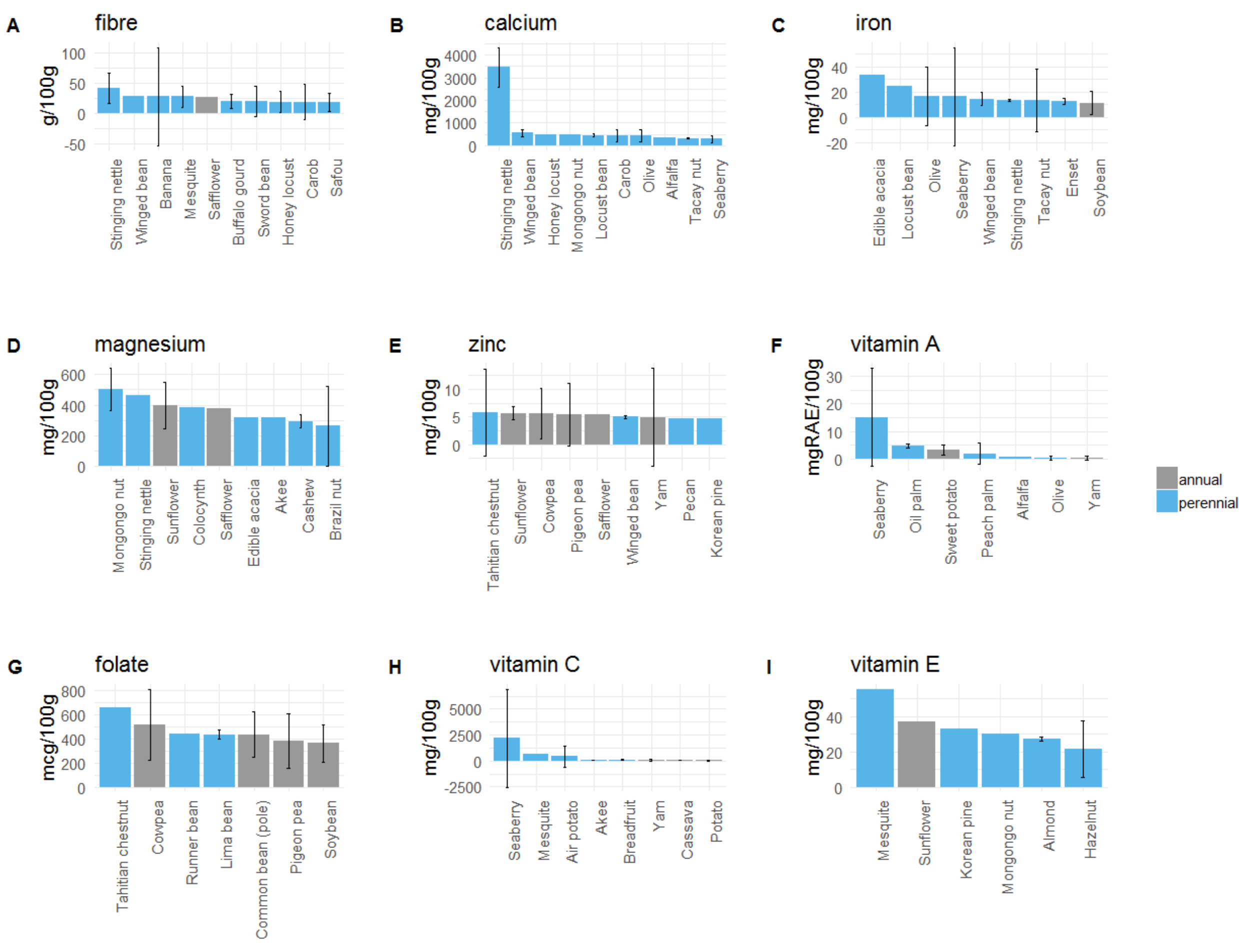


Figure 2.5. Micronutrient content of perennials. Plots A to I show the crops in the 85th percentile and higher for micronutrient content (g/100g). Error bars are 95% CIs; if absent, only one source of nutritional data was available for that nutrient of that crop. Nutrient content is based on the dry, edible portion of each crop. Note that pigeon pea can be grown as an annual or perennial, but there isn't separate nutritional information for each. Error bars reflect wide nutrient composition variation reported in the literature, and may reflect different crop varieties, soils, and growing systems. For example, there are hundreds of varieties of bananas, seaberry is a new crop with a wide genetic base, and Tahitian chestnut is grown on hundreds of Pacific islands, with populations that have been isolated by thousands of miles for millennia.

2.7.4 Carbon sequestration of perennial staple crops

Perennial staple crops, like other perennial land cover types, accumulate and hold carbon in their biomass and soils over their lifetimes. From biomass carbon and soil carbon estimates with harvested areas for 19 of the most commercialized perennial staple crops (see methods), we found that perennial staple crops are currently holding ~ 11,386 MTC globally (Table 2.4), less than one third of the annual annual anthropogenic emissions from all sources for 2018 of 37 Gt CO_2 equivalents (Le Quéré et al. 2018). These stocks do not take into account the fate of stored carbon at the end of a typical growing cycle, which could differ significantly depending on how biomass and soil are managed during clearing and replanting, but rather represent mean standing stock.

Based on a linear projection of the increase in land under perennial staple production for 15 crops, this standing stock would grow to 14,389 MTC in the year 2040. The land cover that is replaced by perennial staple crops in this projection determines whether this standing stock is likely to represent a net increase or decrease in stored carbon: conversion from annual cropland

and grassland would likely increase sequestered carbon (Table 2.4). The opposite is true for land transition from forested land to perennial staple crops, as the latter generally hold substantially lower carbon stocks than do intact forests (Lasco 2002). For carbon stocks and projected changes in carbon per crop, see Appendix A Table S2.

Table 2.4. Global carbon stocks and changes from perennial staple crops. Carbon stocks and changes include both biomass carbon (above ground and below ground) and soil carbon.

Carbon stock perennial staple crops	MegaTonnes C
present	11,386
2040 projection	14,389
Change in carbon 2040	
annual cropland to perennial	+ 965
grassland to perennial	+ 132
forest to perennial	- 3,145

While these simplified calculations of 100% conversion from one cover type (annual cropland, grassland or forest) to perennial staple crops do take into account the climate in which the conversion takes place (see Methods) they do not represent more realistic scenarios where increases in harvested area for each perennial staple crop replaces a geographically-informed amount of cropland, grassland, and forest. Our estimates are conservative in that they only include crops for which we had harvested area data at present (19 crops) and historically (15 crops) (Appendix A Table S1).

2.8 Discussion

2.8.1 Agronomy of and nutrition from perennial staples

Our collation of yield data indicates that numerous perennial staple crops have yield ranges that are competitive with familiar annual staples. The extent of perennial staple crop production is currently modest covering 4.2-4.7% of total cropland. In addition, specific perennial staple crops have high macronutrient and micronutrient content necessary for fulfilling people's dietary needs.

The yield ranges we found in the literature were often wide. This reflects the diverse climates, soils, and management practices under which crops are cultivated, as well as different levels of maturity of crops in various studies. The yields reported here for non-FAO crops should be interpreted as the range of potential yields, not as actual estimates of global yields. Indeed, even some global crops (macadamia and pecan, two highly commercialized crops in the oil category), do not have FAO yield and production data. Nonetheless, the ranges of yields collected here highlight crops with high yield potential. Eleven of the twelve perennial staple crops with the highest yield potential (estimated yields above 2.5 t/ha) are subtropical to tropical crops (Figure 2.3b). Perennial staple crops in the temperate North and Meditteranean are certainly not to be disregarded, but the variety of perennial staples with high yields in the tropics and subtropics justifies particular research and policy attention.

As this study only includes perennial staple crops for which we could find yield estimates with adequate evidence, many interesting crops were not included here at all. Crops with no available yield information, or those without citable yield information, should not be neglected; on the contrary, they require more scientific attention. For example, oyster nut, safou/butterfruit, African breadnut, and souari nut are all crops that are used as regional staples, but for which we could not find citable yield information. Toenesmeier (2016) has assembled comprehensive lists of perennial staple crops, most of which lack yield information, which could be the basis of further study. Other clearinghouses for information on plants such as Plant Resources of Africa (PROTA) should ensure that the information they provide is cited to its source. Nutritional information was generally more available than information on crop yields.

2.8.2 Perenniality and growth form

While most of the plants discussed here are woody trees and shrubs, some are perennial vines, some are perennial herbs (alfalfa, stinging nettle), and some like banana, plantain and enset, are giant tree-like herbs. The range of lifespans among the crops is large: from just two to three years (pigeon pea) to many hundreds or up to a thousand years (Brazil nut, olive).

Most of the crops in this study produce edible fruit (including soft fruits, nuts, beans, and capsules) that are harvested year after year without damaging the plant. In contrast, the edible content of sago palm and enset, two of the highest yielding crops in this study, is stored in their trunks or underground corm, and are harvested at the end of a multi-year growth cycle. For sago, the individual trunks are destroyed when they are harvested, but the plant is a multi-stemmed palm that continues to produce new trunks for many years, and will have multiple trunks of different ages present in each clump at any given time. Enset can be harvested for its trunk only, in which case stems will regrow, but also for its corm, in which case the harvest is terminal. African yam bean and air potato are interesting in that they produce staple foods on an ongoing basis perennially (beans and aerial bulbils respectively), but also have edible tubers that can be harvested at the end of the plant's productive life or when they are needed. The destructive, terminal harvest of vegetative parts of perennial plants can serve as a "famine buffer" in times of scarcity.

For example, enset ensured greater food security for millions of people in Ethiopia's Southern highlands during the famines of the 1970s and 1980s (Brandt et al 1997). But, enset stands are sometimes being harvested earlier than the full 4-11 year cycle, thereby depleting stands before they mature (Borell et al 2020). Thus, while the harvest of stored calories in enset trunks and corms can mitigate food shortages for a time (Brandt et al. 1997), the depletion of enset stands or their loss due to other reasons reduces their subsequent ability to mitigate further disruptions in the food supply and they take longer to recover (Quinlan et al. 2015). This example demonstrates how perennials with edible vegetative parts that are destructively harvested can serve as food 'insurance' but cannot do so indefinitely. If they are used as a line of defence when annual food supplies diminish, they must be accumulated ahead of time and replenished during times of plenty.

2.8.3 Climate regulation and ecology of perennial adoption

Perennial staple crops hold a relatively modest amount of carbon within the global carbon budget, comprising less than one third of the annual emissions from the year 2018 (Le Quéré et al. 2018). Our estimates indicate that land transition from annual crops to perennials will increase these carbon stocks by approximately one additional GtC over twenty years, while transition from mature forests to perennials will reduce carbon stocks by over three times as much

(Supplementary Table 1). When perennial staple crops replace grassland, there is carbon sequestration globally, but whether carbon is sequestered or emitted is highly context dependent, and is determined by the crop and the climate of the grassland that is being replaced (Supplementary Table 1). The relatively modest amount of carbon held in perennial staple crops, and the small but positive sequestration from transitioning land from annual to perennial food crops indicates that such land transitions can only be one small part of the transformational change necessary to avert climate and ecological disaster (IPBES 2019; IPCC 2019).

This analysis was exploratory and did not include several important factors, including 1) a comparison to grasslands degraded by excessive grazing, which are likely to benefit more from a transition to perennials in terms of carbon and soil health (including dust-reduction) than the grasslands represented in this analysis; 2) non-CO_2 emissions like nitrous oxide and methane resulting from fertilization regimes and livestock occupation, and 3) management of perennial staple crops together with a grassy understory, in which case the carbon sequestration of woody perennial crops and grassland may be additive, rather than the former replacing the latter.

Future work using more spatially explicit scenarios of land transitions to perennials for each crop would improve the rough global estimates presented here. This work is particularly important because many of the high-yielding crops assessed here are tropical, where forest conservation is of critical importance to biodiversity and climate regulation (Wilcove and Koh 2010). However such modeling work will need to confront a lack of available data: the climate regulation services provided by long-lived perennials is well documented for perennial grasslands, forest cover, and timber plantations (IPCC 2019), but the same is not the case for tree crops: current IPCC carbon estimates for tree crops only include *two* perennial staple crop species (olive and oil palm) out of a total of only *six* tree crop species (volume 4, chapter 5 table 5.3; IPCC 2019). This dearth of information about tree crops in the most updated and world-class dataset available is troublesome, and will hamper planning and policy making efforts. We have improved on available data by collecting biomass carbon data and typical life spans from the literature for an additional 17 crops (freely available on Figshare figshare.com/projects/Perennial_Staple_Crops/78756). These estimates are still limited samples that hinder robust calculations of the mean and maximum carbon stocks (above and below-ground) for various species over the course of their productive lifetimes from available literature. The management-dependent nature of these properties of perennials means that there will always be considerable variability within one crop, yet even with this caveat, the literature on the carbon sequestration capacities of tree crops is still underdeveloped compared to forestry and agroforestry systems.

From a biodiversity and ecosystem services perspective, research has shown that tree crops that are managed with permanent or diversified understory vegetation can boost ecosystem services including pest control (Simon et al. 2009), increased root infiltration of beneficial mycorrhizal fungi (Ishii et al. 2008; Cruz & Ishii 2012), soil carbon content (Xi-rong 2005; Merwin et al. 1994), and water retention (Huai & Lin 2005; Merwin et al. 1994), as well as decrease nutrient loss from soil (Gómez et al. 2009). In addition, diversified perennial systems in the tropics harbour higher biodiversity compared to simplified perennial plantations and annual crops (Perfecto et al. 2003; Frishkoff et al. 2012). Following studies in the tropics and meta-analyses of non-food producing agroforestry systems in temperate climates (Torralba et al 2016) it is likely that temperate tree crops with greater complexity also support more biodiversity. But, the magnitude and context dependence of other benefits from diversified management, particularly in the temperate North, are largely unknown due to a lack of synthetic meta-analysis on understory management practices of tree crops for various services (apart from pest control, covered in Simon et al 2009).

Taken together, the expansion of perennial staple cropland (as well as non-staple perennial cropland and agroforestry practices like silvopasture) into existing annual cropland or existing pasture land represents a potential win-win scenario between environmental benefits and sustained food production, especially if done with environmentally friendly management practices like continuous diversified groundcover/cover-cropping, or mulching (see references in paragraphs above).

2.8.4 Societal aspects of perennial adoption

Crop adoption and land transition is a multifaceted process that involves market demand, land tenure, environmental regulations (or lack thereof), farm subsidies and incentive programs, need for and availability of capital, insurance and labour, and other local and regional political dynamics. But if there are so many perennial staple crops with good yields, abundant nutrition, and environmental benefits, why are they not already a larger part of the global food system?

Before discussing barriers, it is important to recognize that many of the crops discussed here (and ones that are not included in this study), while not heavily commercialized and unfamiliar in the West, *are* already important products locally and regionally. While some of these are being developed through research and business enterprises (peach palm, tacay nut, sago) some of these crops are declining in production, and losing valuable genetic variation in the process (enset, yeheb nut; Tsegaye and Struik 2002; Yusuf et al 2013).

Perennial crops face several barriers. In the developed world, the economics of investing in perennials are not well supported. Perennial enterprises entail a delayed return on investment due to the length of time between planting and bearing; moreover, the relative permanence (i.e. lower flexibility to convert) of perennial crops gives them a lower option value, thereby lowering farmers propensity to adopt these practices even if they are profitable on paper (Frey et al 2013). This reality means that perennial farmers and businesses need access to capital years in advance. Given price volatility and/or undeveloped markets for many perennial staples such enterprises may be risky and harder to capitalize than shorter term enterprises (Wolz et al. 2017). Crop insurance programs and futures markets help mitigate agricultural risk, but these are not available for many perennial staple crops, even ones that are already global commodities. In addition, access to land for long-term farming enterprises is unusual (outside of land ownership). Farmers that do not own their land need to have access to long-term leases with terms that ensure their investments if land is sold, and other long-term provisions. This issue has begun to receive some attention in the US midwest (for example, the nonprofit organization Savanna Institute offers a long-term lease workbook for farmers and landowners), but such long-term arrangements are still highly unusual. Third, research and breeding development devoted to perennial staple crops is lacking compared to annual crops, and more difficult due to longer generation times (Mehlenbacher, 2003; Molnar et al., 2013). A research and development agenda laid out nearly a century ago by the scholar J Russel Smith in his book *Tree Crops, A*

Perennial Agriculture (1929) to accelerate breeding of tree crops for food and fodder in order to replace tilled agriculture on hilly landscapes is just as relevant today and largely unfulfilled.

In areas of the developing world that are vulnerable to food insecurity, the agendas of aid agencies have concentrated heavily on improvement in cereal production at the expense of other crops including perennials that are grown traditionally (Brandt et al. 1997, Chifamba 2011). Such an approach may be counterproductive for both local food security as well as cultural values.

Finally, perennial crops are vulnerable to war and other social upheavals. Some cultures have established protections for perennial crops, such as the laws of war in the Hebrew Bible that dictated that food-producing trees were not to be cut down during siege and warfare (Deuteronomy 20:19), Nevertheless, perennial crops have fallen victim to conflicts throughout history, including in this century (Orians and Pfeiffer 1970), and unlike annual crops which can be replanted the next season, take years or decades to recover.

Despite these barriers, in-demand global perennial staples like oil palm, avocado, and almond have become highly lucrative commodities. For example, oil palm production has replaced large tracts of rainforest (Guillaume et al. 2018), the Mexican avocado industry has been taken over by gangs (Flannery 2017), and almonds in California exert unsustainable water demand on the state (Wilson et al. 2016). Thus, expansion of perennial staple cropland is not a solution divorced from specific environmental and social contexts, which can be exploitative and unsustainable. Nevertheless, unlike these rapidly-expanding crops, some perennial staples (for example olives in the Mediterranean basin, chestnuts and evergreen oak in Corsica, Portugal and Spain, mesquite in the American Southeast, and a large variety of perennial staples in tropical homegardens) have been sustained in ecologies and ways of life for millennia (e.g. Michon 2011; Uylaser and Yildiz 2014).

Policy solutions that aim to promote tree-planting are often fraught with difficulties and can even be counterproductive for carbon sequestration and wildlife if they result in the replacement of native vegetation with plantations, as has occurred in Chile and other locations (Heilmayr et al. 2020). However, while incentive programs like Payments for Ecosystem Services (PES) can backfire, they can also have substantial positive effects if designed well (Rode et al. 2015, Chan et al. 2017). Reviews show that effective PES incentive programs also provide technical expertise and co-payments (rather than covering the entire cost), recognizing that farmers often have non-monetary incentives to manage their lands in environmentally benign ways (Wilcove & Lee 2004; Chan et al. 2017; Rosa et al 2004; Clot et al. 2017). Designing and implementing tree crop programs to reflect local relationships and cultural values regarding species and practices is a key for uptake and program success (Chapman et al. 2017; Chapman et al. 2020). Despite this opportunity, there may be little use in creating additional boutique incentive programs if underlying policies still lend conventional practices disproportionate favour (for example, large subsidies or the lack of crop insurance for annual crops; Chan et al. 2019).

Considering the various social and ecological dynamics we have discussed, the most prevalent global perennial staples may or may not be the best candidates for further production increases. Other high-yielding crops (sago, enset, breadfruit, mesquite, peach palm, Asain breadnut, perennial vining beans, tacay nut) that are currently only regional or experimental crops, could be candidates for production increases. However, if such increases occur under a business-as-usual model, they would likely fall prey to similar problems that other “superfoods” that have experienced a rise in popularity have driven, namely carbon and environmental impacts from land clearing, use of chemicals, and transportation, coupled with a boom-and-bust dynamic that causes social problems for communities (Magrach and Sanz 2020). Whether production increases of perennial staple crops and land transitions are geared towards export, or local consumption, whether they are fuelled by smallholders or highly capitalized enterprises, and whether they are governed using ecological as well as economic priorities will ultimately dictate their outcomes. If implemented to replace existing agricultural land rather than natural land cover and while prioritizing local values and equitable access to nutrition rather than absolute yields, transition of land and diets to perennial crops can play a positive role in global food systems.

Chapter 3: Biodiversity and ecosystem services indicators of perennial polycultures in the US Midwest

3.1 Introduction

Agriculture is currently contributing to the unsustainable overshoot of multiple planetary boundaries (Campbell et al. 2017) including 10-12% of greenhouse gas emissions (IPCC 2015), nutrient pollution, (Withers et al. 2014), erosion of soils, (Lal 2003), and the pervasive decline of life on Earth (Foley et al. 2005; IPBES 2019; Díaz et al. 2019). Thus, the need for solutions to growing food that also provide multiple ecosystem services and conserve biodiversity is paramount. The teachings of ecology and complex adaptive systems suggest that agriculture will be more productive (in all aspects over the long-term, though not necessarily in agricultural yield) more resilient, and less leaky of nutrients, soil particles, etc. if plants and associated organisms are allowed to grow to form stable interactions over years. Such systems should provide the foundation for food production that also nourishes biodiversity including various ecosystem functions (Chapman et al. 2017). Perennial agriculture, particularly if designed for multiple woody crops is a potential solution that embodies these understandings from ecology, and contrasts with the simplified agroecosystem of industrialized annual agriculture (Wolz et al. 2017). However, our understanding of the benefits and tradeoffs involved in perennial polycultures compared to conventional agricultural systems is limited, especially in the temperate North (Lovell et al. 2018). Systematic and comprehensive studies of the differences between these types of cropping systems are needed to begin to make informed decisions that can shift food production towards more sustainable and multifunctional practices. This chapter, which explores a regional scale of the US Midwest, uses original data collection to explore multiple environmental and food production outcomes of woody perennial polyculture systems in a temperate climate.

Tree-based perennial systems are fundamentally characterized by long-lived woody plants with permanent root and shoot systems. They therefore provide more structurally complex vegetation structure compared to annual systems, and can be managed to provide continuous ground cover which is theoretically consistent with a host of ecosystem services and biodiversity benefits (Jose et al 2009; Asbjornsen et al. 2014). Structurally complex vegetation and ground cover provide habitat and allow for movement of organisms (Bailey et al. 2010; Brady et al. 2011), as well as slowing down and absorbing erosive forces (wind, water) and mitigating the leakiness of nutrients (Teshager et al. 2017). Understanding from agroforestry and herbaceous perennial forage studies indicate that perennialization is linked to improvements in soil carbon sequestration (Young et al. 2009; Cates et al. 2016), pollination (Morandin and Kremen 2013; Bennett and Isaacs 2014), pest regulation (Landis et al. 2000), water quality (Gao et al. 2004), and soil erosion (Zuazo and Pleguezuelo 2008; Brady and Weil 1986).

Studies of perennial tree crop systems often focus on the presence or diversity of the pasture or ground cover mix beneath a woody perennial canopy, not on diversification involving the tree crops themselves or a combination of the two. This literature indicates that the presence and/or diversification of vegetative ground cover in tree crop systems can result in increased pest regulation (reviewed by Simon et al. 2010), root infiltration of beneficial mycorrhizal fungi (Ishii et al. 2008; Cruz and Ishii 2012), soil carbon (Merwin et al. 1994; Xi-rong 2005), and water retention (Merwin et al. 1994; Huai and Lin 2005); decreased nutrient loss (Gómez et al. 2009); and opportunities for income generation from secondary products like mushrooms and forage (Baptista et al. 2007; Martins et al. 2011). Some studies have shown that understory vegetation competes with trees for available nutrients, particularly in the first few years (Huai and Lin 2005; Xi-rong 2005). These studies show that permanent and diversified ground cover in perennial agriculture can contribute to pest control, soil fertility, mitigate soil and nutrient loss, and even allow production of income-generating secondary products.

Empirical studies from systems that include multiple species of food-producing woody perennials and vegetative groundcover (here called woody perennial polycultures)support these findings in part, but are mainly limited to tropical homegardens (e.g. Méndez et al. 2001) and coffee plantations (e.g. Perfecto et al. 2003; Gordon et al. 2007; Philpott et al. 2008; Vandermeer et al. 2010; Briggs et al. 2013). These studies explore pest control, biodiversity of many taxa, food web dynamics, as well as yields and farmer livelihoods. However, similar studies are exceedingly sparse in temperate climates. Except for one study that examined yields and pest control in a system of three interplanted fruit species (Brown 2012), we are not aware of temperate studies that look beyond pest control to a more holistic assessment of woody perennial polycultures.

Thus, the study of diverse food-producing perennial agriculture is currently underdeveloped (Lovell et al. 2018), given the ecological theory suggesting its promise. While non-food producing agroforestry practices such as buffer strips, hedgerows, and alley cropping with leguminous trees that supply regulation services have received considerable scientific attention, little is known about the practices and outcomes for food-producing tree crops, especially if grown as diverse polycultures (Lovell et al. 2018). Informal knowledge about woody perennial-based agriculture held in some traditional farming societies and in the grassroots permaculture movement has largely been disregarded by science (Ferguson and Lovell 2013). In both, perennial crops are not only used for timber, shade, and fruit, but as providers of staple nutrition that is integrated with both animals and annual production under polycultural management. In recent years, modern examples of such systems on a commercial farm scale are emerging in the US Midwest: one of the most industrialized food systems in the world.

In this study, we compared the environmental and agronomic outcomes of on-farm woody perennial polyculture agriculture with conventional annual agriculture and hay (composed of herbaceous plants only, many grown perennially) in the US Midwest. Specifically, we set out to answer two questions: 1) what are the effects of establishing perennial polyculture systems on a broad range of indicators relevant to biodiversity and ecosystem services? and 2) how do perennial systems vary among themselves as a function of field age/maturity? To this end, we conducted a natural experiment (Diamond 1983) directly comparing a broad range of indicators relevant to biodiversity and multiple ecosystem services between woody perennial polyculture fields and adjacent conventional annual (soy and corn) and perennial hay fields. We hypothesized that woody perennial polyculture fields would support higher levels of biodiversity and ecosystem services than annual and hay fields and that these differences would increase with the age of the woody perennial fields.

3.2 Methods

3.2.1 Study system

Our study took place in the US Midwest. One important ecosystem of the pre-colonial US Midwest was the fire-maintained oak savanna (ie. a mixed woodland and grassland without closed canopy; Karnitz and Asbjornsen 2006). While historical baselines for the vegetative structure are not straightforward to establish since this ecosystem has been all but eliminated from the landscape (Asbjornsen et al. 2005), archeological findings indicate that it supported a high density of ungulates including bison, deer, antelope, and elk (Shay 1978; Abrams and Nowacki 2008). Unlike drier savanna ecosystems where net primary productivity (NPP) peaks at an intermediate (~40%) level of canopy cover (Battles et al.), the NPP of midwestern oak savanna increased consistently with tree cover along the grassland to forest continuum (Reich et al. 2001), and the region's wet climate could have supported forests. However, in many cases Indigenous peoples preferred tallgrass prairies and savannas and actively maintained them through fire to promote ungulate grazing habitat and the many species of mast trees and berries (acorn, nut & fruit) that were staples of their diet (Abrams and Nowacki 2008). After settlement by Europeans, these prairies and savannas were replaced by tilled agriculture, were altered by domestic livestock pasture, or underwent succession to closed canopy forest due to fire suppression (Karnitz and Asbjornsen 2006). The oak savanna ecotype preferred by Indigenous peoples during the Holocene is mimicked in our perennial study sites, including through the use of livestock in the understory of the trees on some farms.

3.2.2 Study design

Fourteen farms located in four states (Minnesota 2, Iowa 3, Illinois 3, Wisconsin 6) were selected (Figure 1) based on the criterion that each was growing multiple species of perennial crops in the same field for commercial purposes. Each woody perennial polyculture field was paired to a neighboring corn, soybean, or hay field, chosen to be as adjacent and similar as possible in terms of soils. The three types of comparison fields reflect the most common crop covers in this region of the US Midwest. The cover type "hay" was composed of one or more herbaceous perennial plants; therefore, if grown as a mixture of species, it is also a perennial polyculture. In this study, the four fields classified as "hay" were on a continuum of age and number of species, ranging from a field that had been recently cultivated and replanted with alfalfa, to a mature alfalfa field in a 4-year rotation with corn, to a rarely-mowed field that was left fallow (see Appendix B, Table S1). I therefore chiefly use the term "woody perennial polyculture" to refer to the fields with multiple tree species and herbaceous understory plants, not the hay fields. The term "perennial" on its own used in plot labels or occasionally in the text is a shorthand to refer to "woody perennial polyculture", and does not refer to the hay fields, which are labeled as such. Paired sites were within 500 meters of the woody perennial polyculture fields (most were immediately adjacent). The study is therefore composed of 14 perennial-conventional annual or perennial-hay pairs. On a few farms, an additional woody perennial polyculture or comparison field was added if there was a separate field that was of interest due to age, management, or crops (sup. Table 1). Many of the woody perennial fields were established on land that was recently under conventional annual management, providing a direct comparison to their paired conventional fields. However, a few woody perennial fields were established on pasture or fallow fields that were not recently under conventional annual management. Each farm was visited twice during the spring (May/June) and summer (July/August) of 2018. Farm visits were sequenced south to north, to mirror south-to-north spring plant phenology shifts.

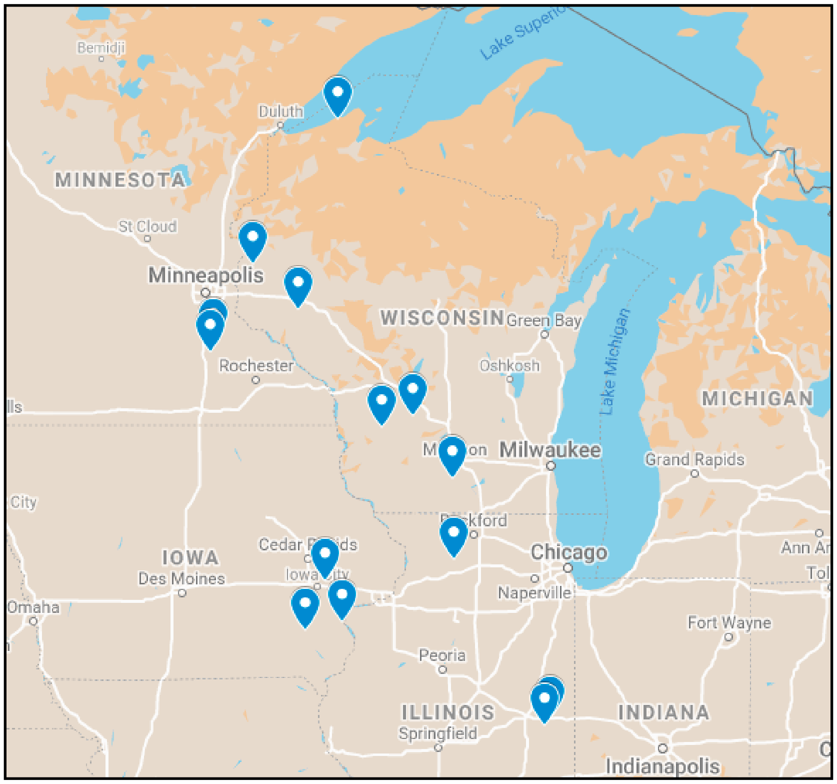


Figure 3.1. Field sites. Fourteen farms in the Upper Midwest were included in the study.

Each field (woody perennial polyculture, corn, soy, or hay) was divided into 4 quadrants, to serve as subsamples. Corn, soy and hay fields, which were often larger than the perennial fields, were sampled on a sub-section equivalent to the size of the paired perennial field. In each quadrant a random point was marked that served as the central sampling point for insects, soil, and vegetation within each quadrant (Appendix B.1 Figure S1). Insect sampling was completed on both visits. Most of the soil sampling was completed on the first visit (unless wet conditions delayed us to the second visit). Vegetation observations were completed on the second visit.

3.2.3 Overall approach

We completed a natural experiment measuring several biodiversity and ecosystem service indicators (Table 1). Abundance and diversity were measured for several taxa: soil bacteria and fungi, plants, arthropods, and birds. Ecosystem service indicators were of two types: some were directly measured physical and chemical properties (e.g. soil structure, soil fertility, soil organic matter). Others were measures of organisms that supply ecosystem services but not of the services themselves (e.g. pest regulation, pollination, erosion control). The service of nutrient cycling has one measure of each type (active carbon, and presence of nutrient cycling species of arthropods). We also collected data on the food production from the woody perennial polyculture farms (though, many of these farms are young, have not yet reached maturity, and are therefore not at full production).

Table 3.1. Biodiversity and ecosystem service indicators used in this study.

Ecosystem service & biodiversity indicators	**Metric**	**Relationship between indicator and service supply**
Biodiversity		
Alpha diversity	Shannon diversity index Species richness	positive positive
Beta diversity	Bray Curtis dissimilarity Turnover Nestedness	positive positive negative
Soil structure		
Bulk density	mass soil/ volume	negative
Carbon storage		
Soil organic matter	% organic carbon in soil	positive
Soil carbon	% total carbon in soil	positive
Soil fertility		
Nitrogen	% total nitrogen	positive
Phosphorus	phosphorus (mg/kg)	positive
Erosion control		
Plant cover density	% ground cover	positive
Nutrient cycling		
Active carbon	active carbon (mg/kg)	positive
Detritovore presence	Species richness Abundance of individuals	positive positive
Pest regulation		
Predator presence	Species richness Abundance of individuals	positive positive
Herbivore presence	Species richness Abundance of individuals	negative negative
Pollination		
Pollinator presence	Species richness Abundance of individuals	positive positive
Crop production		
Crop yield	Edible fresh weight/ ha Calories/ ha	positive positive

For each species group that we measured, we assessed both alpha diversity (number and abundance of species) and beta diversity (differences in species composition across sites). These additive components of gamma (landscape level) diversity are useful to study together in order to capture distinct patterns of species presence across different scales in a landscape. In our case, alpha diversity indicates the diversity at one sampling site, while beta diversity indicates the additional diversity within a cover type greater than the average per sampling site (Shahabuddin 2013)

Soil carbon metrics represented both nutrient cycling and carbon storage, via active carbon and total organic carbon, respectively. Active carbon is a portion of the organic carbon in the soil which is relatively easily metabolized by soil fauna and microorganisms and is therefore readily available as an energy source for them (half life of a few day to a few years); it is therefore linked to the ecosystem service of nutrient cycling. Total organic carbon in contrast is all carbon in organic compounds in the soil, from those that are quickly decomposing, to those that are complex and stable (e.g. humic compounds); it is therefore linked to the overall carbon storage in the soil.

3.2.4 Soil chemical and physical properties

We studied basic soil properties related to soil quality and carbon sequestration including bulk density, pH, organic carbon, active carbon, nitrogen (N) and phosphorus.

For bulk density, an intact soil core was taken at each quadrant's sampling point at 0-15 cm and 15-30 cm depth using a metal ring 7.5 cm in diameter and 7.5 cm in height. The soil core was air dried until it was bone dry in the field, and then oven-dried for 24 hours before weighing.

For the analysis of the other properties, one soil sample per quadrant was collected by combining 10 auger sub-samples into a bucket, mixing, and taking an approximately 500 g sample of the mixed soil (Appendix B.1 Figure S2 A). This was done separately for 0-15 cm and 15-30 cm depths. The 10 sub-samples were collected in a spiral transect around the central sampling point, with 3-5 steps between each point. In woody perennial polyculture fields the sub-samples were distributed between rows and alleys at a ratio that represented their relative distribution across the field (e.g. two auger samples in the row and 8 in the alley for 2 foot rows and 8 foot alleys). In the annual and hay fields, no permanent alleys or rows were present, so sampling points were evenly distributed along the spiral transect. All equipment was cleaned with water and wiped down with 70% ethanol between quadrants. Air-dried soils were sieved (2 mm) and analyzed for pH, active carbon, available phosphorus, and texture, and analyzed for total C and N by combustion (see Appendix B.1 for details).

3.2.5 Soil microbes

The microbial communities in soil facilitate its nutrient cycling processes and are thus both drivers and indicators of soil fertility. To better understand the species richness and diversity of soil bacteria and fungi between the two cropping systems, we used our soil samples for DNA sequencing of two regions of ribosomal DNA (16S for bacteria, Internal Transcribed Spacer (ITS) for fungi). These regions are sufficiently conserved while containing enough variation to be able to estimate unique sequence variants, construct phylogenetic trees, and thus estimate composition and variation of sometimes unknown bacteria and fungi in soil communities using microbiome methods.

A sub-sample of the soil from each quadrat was taken from the 10 combined 0-15 cm auger samples described above. Samples were stored in sterile bags and kept frozen on dry ice in the field and in transit until they could be stored in a -20 freezer. They were transferred to a -80 C freezer at the end of the collection period. DNA was extracted using the Qiagen PowerSoil kit.

I6S and ITS sequencing and sequence analysis

Two target libraries were constructed per sample, one for 16S (bacteria) and one for the internal transcribed spacer (ITS; fungi). These were then sequenced using a single illumina miSeq run. See Appendix B.1 for details.

We quantified the diversity of microbial communities using Operational Taxonomic Units (OTUs) since individual microbial species are largely unknown. We used the dada2 pipeline to identify sequence variants in the 16S and ITS sequences (Callahan et al. 2016). Sequence variants that did not start with known primer sequences were removed. Since fungal and bacterial sequences were mixed within libraries, they were separated after the taxonomic identification stage. Taxonomy was assigned (to species level) for the fungal and bacterial sequence variants using the Silva (for bacteria) and UNITE (for fungi) references using dada2's native bayesian assignment algorithm. A community matrix (known as an OTU table in microbial ecology) was constructed for bacteria and fungi separately with rows as sites, and columns as species (or in this case, unique sequence variants). Sequences were aligned to each other and these alignments were used to construct trees using the 'mafft' and 'fastree' programs in Unix. The community matrices and trees were combined to construct a distance matrix using weighted UNIFRAC distance, which takes phylogenetic similarity as well as the number and magnitude of sequence differences into account to plot the ordination (function ‘distance’ with method ‘wunifrac’ in R package ‘phyloseq’).

16S and ITS qPCR assay and analysis

Because microbiome community analyses based on sequencing are carried out using relative abundances (i.e., percentage of read counts) of sequence variants or taxonomic units within a single library (representing one sampling point), they do not account for differences in amounts of organisms *between* sampling points. To understand the relative amounts of total bacteria and total fungi between samples, we carried out a quantitative PCR analysis on similar (but not identical) 16S and ITS primers to those used in the sequencing described above (see Appendix B.1). This resulted in relative bacterial or fungal load per gram of soil which is comparable across samples. This was calculated using the following equations:

Total DNA (ng/g soil) = stock concentration (ng ul^{-1}) *50 (ul $extraction^{-1}$) / mass soil (g soil $extraction^{-1}$)

Relative bacterial load g $soil^{-1}$ = relative amount($2^{\Delta Ct}$) / DNA used in qPCR (ng) * total DNA (ng g $soil^{-1}$)

$2^{\Delta Ct}$ (threshold cycle, Ct, is a relative measure of the concentration of target in the PCR reaction) is the formula used to quantify each library in relation to the first library on the qPCR plate, where ΔCt is the difference in Ct between each library on the plate and the first library on the plate.

3.2.6 Vegetation

Vegetation was sampled on the second farm visit only, in July and August. Two sampling methods were used. 1) Understory vegetation cover: three 75 x 75 cm quadrats were placed around each random sampling point three meters away from the point. For woody perennial polyculture fields with distinct row/alley management, quadrats were placed in alleys, not in rows, in order to get a representative sample of the vast majority of understory vegetation. Plant cover was estimated as percent cover for each different species of plant. Percent cover for each quadrat did not necessarily add up to 100% due to overlapping vegetation. 2) General diversity: we scouted and recorded all plant species within a 4 m radius of the sampling point in each quadrant of the field. This includes plants in both rows and alleys that were not included in the plant cover quadrats.

3.2.7 Insects and non-insect arthropods

In order to capture the diversity of arthropods in different habitats within the fields, we deployed three collection methods: pit traps, pan traps, and sweep nets. One pit trap and pan trap were set up per quadrant at the random sampling point. We used unbaited Vernon Pitfall Traps (Appendix B.1 Figure S2 C; Van Herk et al. 2018). Pan traps with three plastic coloured bowls (blue, white, yellow) were nested in a plate fixed to a 5 foot tall post (Appendix B.1 Figure S2 D). Pit and pan traps were filled with soapy water and were deployed for 48 hours. Collected insects were stored in propylene glycol. Two sweep net transects were completed per field in randomly selected quadrants, which were consolidated (resulting in one consolidated sweep net sample per field originating in two out of the four quadrants). Each sweep net consisted of 25 figure-8 sweeps going away from the central sampling point and 25 figure-8 sweeps coming back. Insects from the sweep net transects were suctioned out using a simple aspirator, and stored in ethanol. Setup and collection of pit traps and pan traps and sweep netting were carried out as closely as possible in time on woody perennial and adjacent comparison fields, and collected in the same order that they were set up.

Insects were sorted into morphospecies and counted, preserving all information about the quadrant, collection round, and trap type they were found in. Voucher specimens of each morphospecies were given a unique number and stored in ethanol. After counting and sorting of morphospecies was complete, each collected morphospecies was identified according to a prioritization scheme that assigned trophic function to each unique specimen. For example, insects were identified to the largest clade (i.e., order or family) that would allow for approximate assignment to an ecological function. Thus, arthropods were only identified to genus or species if these more granular levels of identification had distinct, known trophic functions (see insect identification framework in Appendix 1).

In order to provide some insight regarding services and dis-services associated with arthropods, we classified each trophic functional group into categories of ecosystem service (pollination, pest control, or nutrient cycling), dis-service providers (plant pests), or into a category for unknown functions. For example, for the service of nutrient cycling, we included detritivorous, scavenger, and mycophagous arthropods; the pest control service included predatory and parasitic trophic groups (see Appendix B.1 Table S3 for details).

3.2.8 Statistical analysis

<u>Linear models</u>

We used linear mixed-effects models using standard normal distributions to estimate many of the response variables in this study: soil bulk density, nitrogen, phosphorus, and pH, alpha diversity of soil microbes, vegetation cover, plant diversity, and insects, as well as functional diversity and ecosystem service supply from arthropods, and fungal and bacterial load (see Appendix B.2 Table S2 for the model syntax for each variable). All the models used field cover type as the fixed effect and farm as the random effect in order to account for the study design which paired a perennial and conventional field at each farm. We divided the cover type into woody perennial polyculture, corn, soy, and hay in the models.

For active carbon, organic carbon, and total carbon, the percentage of silt was also used as a fixed effect, since soil texture is known to be a predictor of carbon content. Hypothesis tests were carried out using categorical Anova on the model estimates. For the quadrat-based metrics (plant cover and bare ground) we used the quadrant as a nested random effect within the *farm* factor to account for repeat sampling within quadrants. For the invertebrate related variables (alpha diversity, functional diversity, and ecosystem service supply), we added trap type and visit number as fixed effects to the models, enabling us to retrieve separate estimates for trap type or average over the trap types to get estimates for the cover types .

Hypothesis tests on linear model estimates were carried out using categorical Anova on the model estimates using the ’trt vs ctrl’ parameter of the emmeans package in R, which allows multiple treatments to be compared with just one treatment. Tests of differences between means (using the function ‘contrasts’ in emmeans) includes a Dunnet multiple-test adjustment for cases where there are more than two categorical levels. Note that statistical tests of the differences between means may be significant even with overlapping confidence intervals of the means themselves. Means, and differences of means, being different statistics, have different standard errors distributional properties, particularly in mixed effects models that include random effects (i.e. blocking factors). In this case some sources of variation may cancel out when differences are taken meaning that overlapping confidence intervals for means themselves do not indicate a lack of a significant difference between means (Schenker and Gentleman 2001).

Alpha diversity

Alpha diversity metrics for all taxa (Shannon diversity index or species richness) were calculated per sampling point using the ‘vegan’ package in R (Dixon 2003) For crop and non-crop plant richness, the numbers of unique species were aggregated per field (i.e., from all four quadrants per field) and averaged within each field cover type, and 95 % CIs were calculated based on the standard deviation of the mean.

Beta diversity

As is typical for many biodiversity studies, we created standard plots illustrating compositional differences by ordinating pairwise distances between all the sites using non-metric multidimensional scaling (NMDS). The distance metrics used differed slightly among taxa. For the microbial analysis, we used weighted UniFrac distance (Lozupone et al. 2011), which incorporates presence and abundance of species with phylogenetic dissimilarity derived from sequence-based trees; for plants and arthropods we used Bray Curtis dissimilarity (Beals 1984), which incorporates presence and abundance of species. For arthropods, the data from both visits were merged so that each sampling point represents one quadrant. For tests of compositional differences on each individual farm, the community matrix (and resulting distance matrices) were subsetted by farm and tested using PERMANOVA (function ‘adonis’ in the R package ‘vegan’) on the distance matrix.

However, recent research has shown the shortcomings of using pairwise-dissimilarity to estimate multisite beta-diversity (Baselga 2013). Therefore, we estimated multi-site dissimilarity, which represents the dissimilarity across the entire set of communities, instead of averaging across pairs of communities (Baselga, 2013). The contrast between pairwise distance based NMDS plots and multisite beta diversity metrics is important for some of the taxa, and highlights the different abilities of these statistical methods for species composition.

Moreover, research has also shown that standard beta diversity metrics (e.g., Sorensen, Jaccard, Bray-Curtis, UniFrac) conflate two distinct components: nestedness and turnover. Turnover represents the replacement of a species in one site with another species on another site, an important contributor to gamma diversity. In contrast, nestedness represents species-poor sites being a strict subset of the species in species-rich sites which does not contribute to gamma diversity (Baselga and Orme 2012; Leprieur et al. 2012; Baselga 2017). We used the ‘beta.multi’ and ‘beta.multi.abund’ functions in the 'betapart' package to decompose beta diversity into its nestedness and turnover components (Baselga and Orme 2012) for the various taxa.

Cover-types with more samples will likely have higher gamma diversity, and this can lead to artificially higher beta diversity. Thus, in order to compare estimates for different cover types that contain different numbers of samples (i.e., woody perennial polycultures n=14, corn n=7, soy n=4, hay n=4), we carried out a subsampling procedure (Baselga 2010). For bacteria, fungi, plants, and arthropods, we sampled 50 sets of data for each cover type. Each of these 50 samples was obtained by randomly selecting 4 farms out of the total farms for that cover type, and then randomly selecting one quadrant per farm (for arthropods, data from both visits were merged; for plants, data from the three 75 x 75 cm quadrats in each field quadrant were merged). We sampled sets of 4 farms to match the hay and soy cover types, which were only present on 4 farms. Furthermore, to ensure that our beta diversity metrics represented dissimilarity between farms, and not merely between samples from a farm, we included only one sampling point (=quadrant) per farm in each subsample. Both presence/absence-based metrics (Sorensen and its nestedness and turnover components) and abundance based metrics (Bray-Curtis and its nestedness and turnover components) were calculated from these 50 sets, and their means, standard deviations, and 95% confidence intervals were calculated.

3.2.9 Food

Each farmer answered a questionnaire that included information about food harvested from their woody perennial polyculture enterprises in the previous (2017) season. For each woody perennial enterprise (including animals grazing in the understory), the land in production, the products harvested and their amounts were recorded. Each food product was then converted to an edible portion (i.e., excluding shells, pits, cores, and so on) using information from the Canadian Nutrient File (Health Canada 2012). The edible portions (in weight and in Calories [Kcal]) were then converted to edible yields by dividing by the area harvested. In woody perennial polycultures, several species are often grown in the same fields, so the total perennial harvested area was used for all crops, and the yields of the crops were then summed to obtain an overall yield per farm. Eggs from farms 11 and 14 were omitted because while egg-laying hens foraged among the perennials, large external inputs of feed were used (so we wished to avoid suggesting that the perennial fields ‘produced’ the eggs). For annual comparisons, the 2017 yields of corn and soy for the 13 counties in 4 states where our study sites were situated were obtained from the USDA 2017 Census of Agriculture.

3.2.10 Synthesis plot

To synthesize the benefits and costs of woody perennial polyculture across all of the biodiversity and ecosystem service indicators measured, we plotted comparisons from the various indicators and taxa on the same axis. Comparisons that included model estimates were assembled for all of the indicators measured, and log response ratios were calculated (perennial/control). For one comparison (bulk density), where lower estimates are “better”, the response ratio was reversed so that ratios above 1 could be read coherently on the summary plot as positive. The log of the response ratios was taken so that a wide range of response ratios could be plotted together more easily. The ratios were calculated by comparing the woody perennial polyculture values to corn. as it is the most dominant conventional crop in the Midwestern landscape.

3.3 Results

3.3.1 Biodiversity

3.3.1.1 Soil Microbial and Fungal Communities

Alpha diversity, measured as the Shannon diversity index, did not differ significantly between perennial and conventional cover types for either fungal or microbial communities (Figure 3.2). Using a quantitative PCR assay, we likewise found no difference between the amounts of total fungal and bacterial sequences (expressed as relative bacterial/fungal load per gram of soil) between any of the cover types (data not shown).

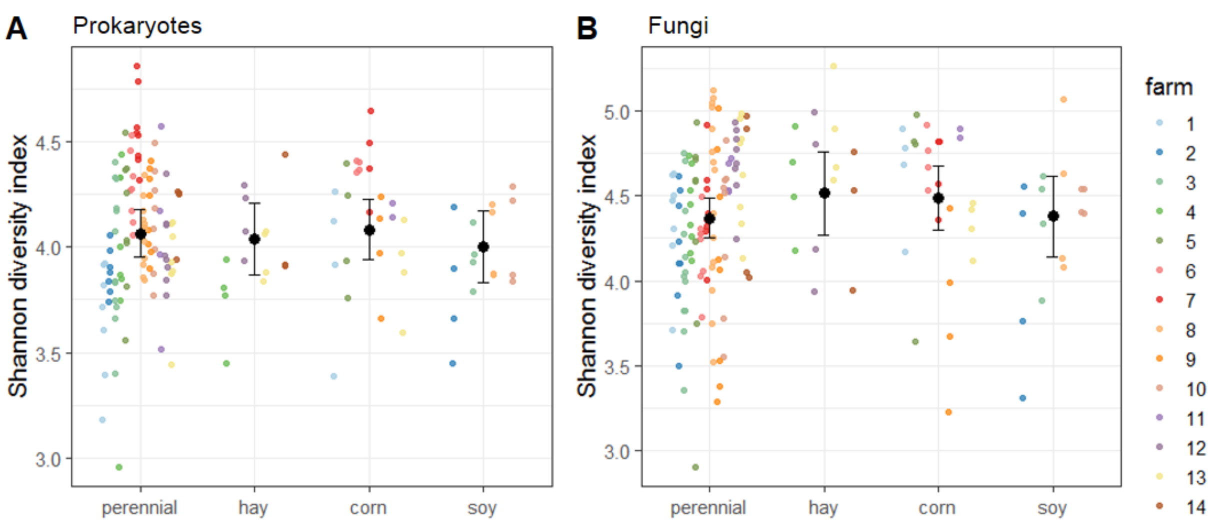


Figure 3.2. Prokaryotic and fungal alpha diversity. Shannon diversity index for prokaryotes (A) and fungi (B). Each point represents a 16S (prokaryotes) or ITS (fungi) DNA library originating in a composited sample made up of 10 auger samples. Black points and error bars represent model estimates and 95% CIs.

Ordination plots using pairwise distances showed no clear separation of communities between the different cover types for bacteria, but somewhat distinct but overlapping communities for fungi (Figure 3.3 A and B). Looking at each farm individually, 50% had significantly distinct prokaryotic community composition compared to its paired conventional field while 93% had significantly distinct fungal community composition (Appendix B.2 Figure S3 B). Overall (within treatment) beta diversity was mostly composed of species turnover, as opposed to nestedness for both prokaryotes and fungi (Figure 3.3 C and D). For fungi, overall beta diversity was higher in the perennial and hay fields than in corn and soy fields. This higher beta diversity was composed of more turnover and less nestedness than the corn and soy fields. This was true for both abundance-based and presence/absence-based metrics and their turnover and nestedness components (Figure 3.4 D)

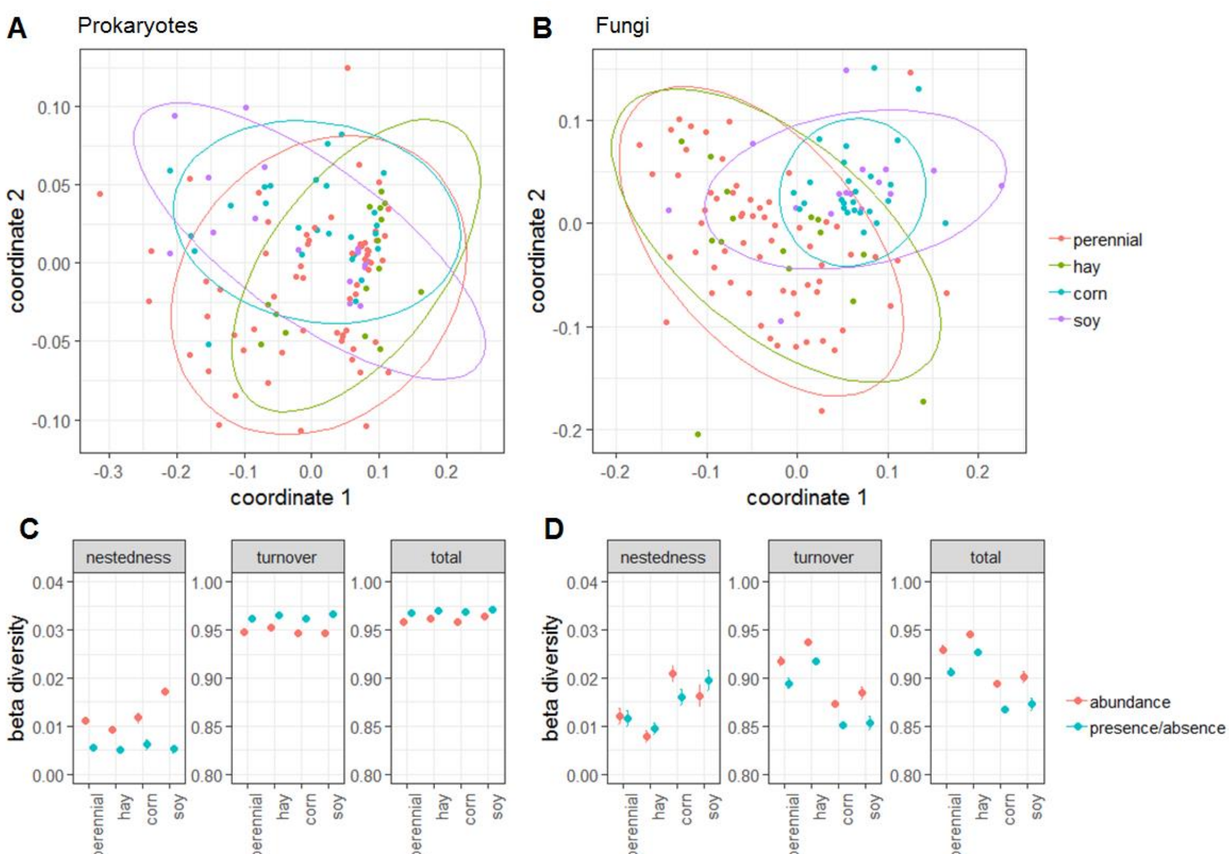


Figure 3.3. Prokaryotic and fungal beta diversity. Non-metric multidimensional scaling (NMDS) of weighted UniFrac distance (taking into account phylogenetic similarity) derived from 16S (A; prokaryotes) or ITS (B; fungi) sequences between all sites. Each point represents a soil sample (aggregated from 10 auger samples) from one quadrant of a field. Panels C (prokaryotes) and D (fungi) show the groupwise beta diversity and its components, nestedness and turnover, calculated using both abundance-based and presence/absence-based metrics (Bray-Curtis and Sorensen, respectively).

3.3.1.2 Vegetation

From plant cover sampling, we found that perennial fields had equal Shannon diversity compared to hay fields, but higher Shannon diversity and abundance compared to corn and soy fields (Figure 4A). From scouting, we found that perennial fields were also characterized by higher general species richness than the other field types, including higher planned (crop) and unplanned (non-crop) species richness (Figure 4B and 4C respectively). The age of perennial and hay fields were significantly positively correlated with general species richness (Figure 4D). Interestingly, richness calculated only from the plant cover data (only plants within quadrats) was not significantly correlated with field age (not shown), indicating that less abundant plants that do not cover significant surface area are correlated with maturity of perennial fields while more abundant ground covering plants are not.

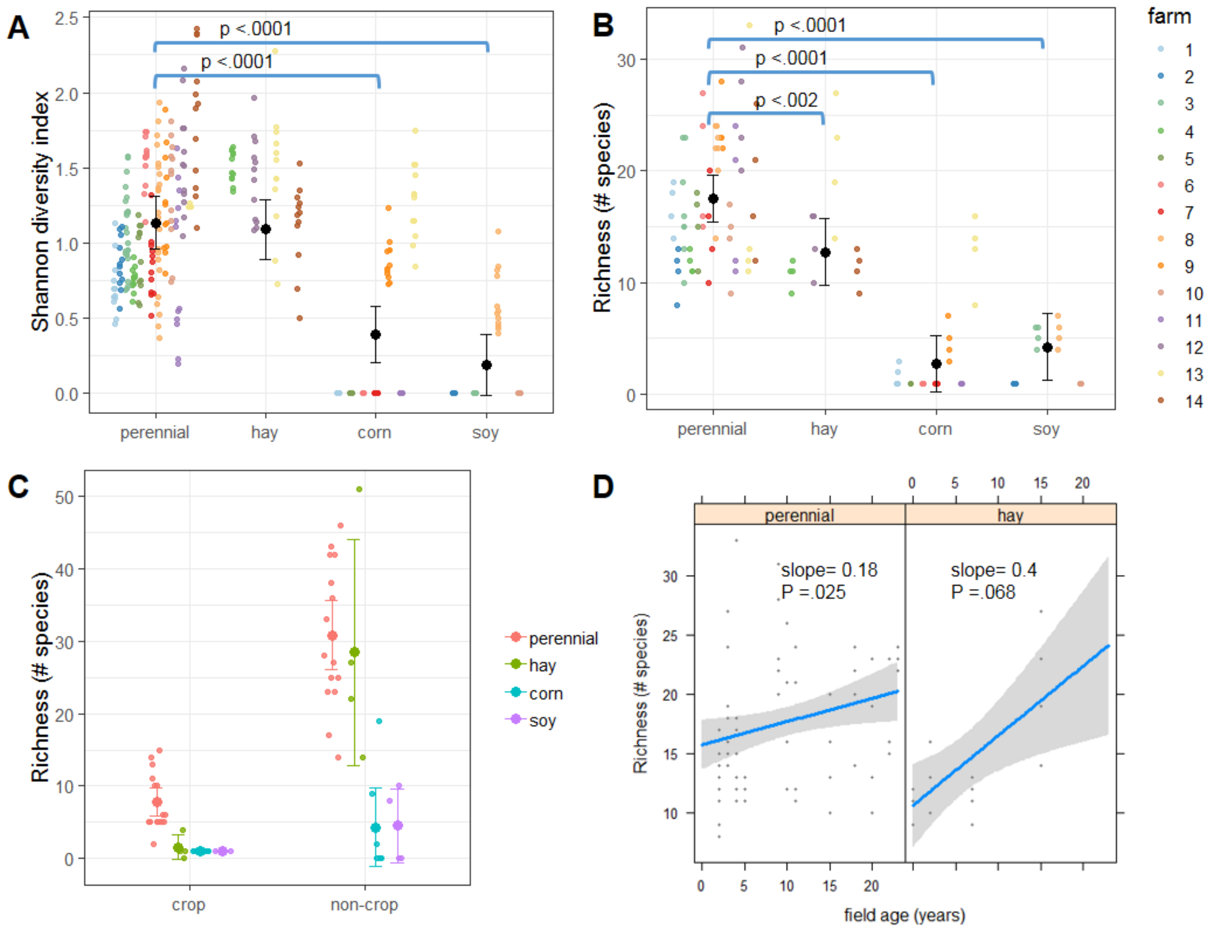


Figure 3.4. Plant alpha diversity for woody perennial, corn, soy, and hayfields. A) Shannon diversity index for each sampling point (one 0.75m^2 quadrat). B) Species richness of plants based on scouting a 4-m radius around each sampling point. C) Estimated richness for planned (crop) and unplanned (non-crop) species using aggregated unique species per field. D) Richness as a function of crop type and field age. The large points and error bars represent model estimates and 95% Cis (A-C). P-values include Dunnett adjustment.

Ordination plots using pairwise distances (based only on quadrat samples, not including perennial crop species or scouted species) showed strong overlap in hay and perennial plant communities, and separation between these and the corn and coy plant communities (Figure 3.5A). In addition, the composition of plants between annual and perennial fields were distinct on all 14 farms (Appendix B.2 Figure S4). Overall (within treatment) beta diversity was higher in perennial and hay fields than in corn and soy fields for both abundance-based and presence/absence-based metrics. Overall beta diversity was mostly composed of species turnover, for perennial and hay fields, but mostly composed of nestedness for corn and soy fields (Figure 3.5 B). This was true for both abundance-based and presence/absence-based metrics (Figure 3.5 B)

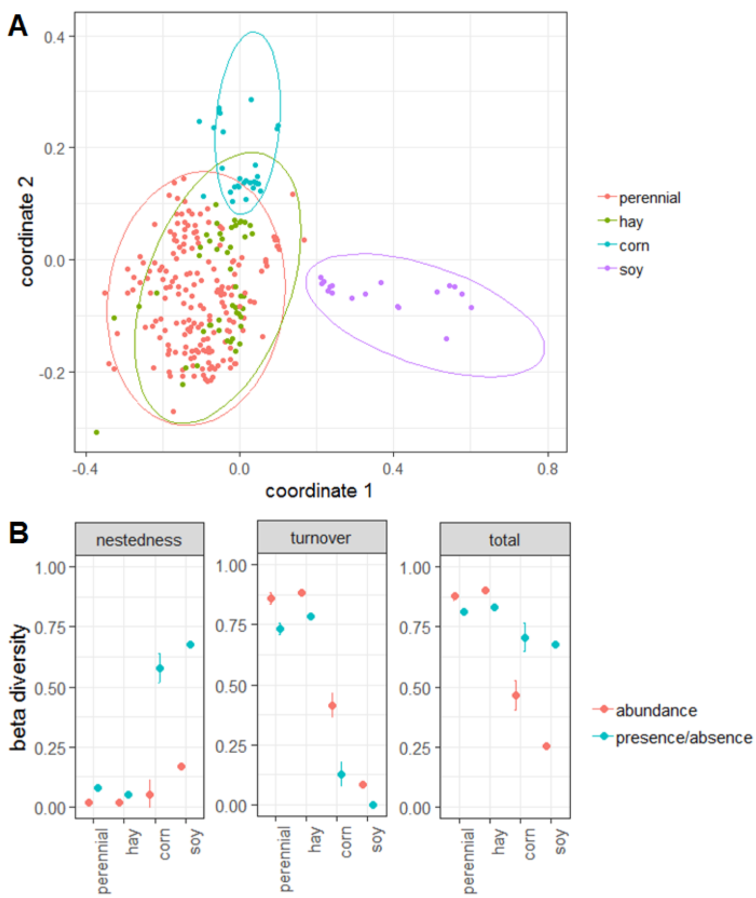


Figure 3.5. Plant beta diversity for woody perennial, corn, soy, and hay fields. A) Non-metric multidimensional scaling (NMDS) of Bray-Curtis distance between plant communities. Each point represents one sampling point (one $0.75m^2$ quadrat). B) Groupwise beta diversity and its components, nestedness and turnover, using both abundance-based and presence/absence-based metrics (Bray-Curtis and Sorensen, respectively).

3.3.1.3 Insects and non-insect arthropods

Alpha diversity and abundance of arthropods differed according to trap type. For pan traps, alpha diversity of perennial sites was 21% and 23% (P=.015 and P<.001 respectively) higher than that of hay and corn. For pit traps and sweep nets, alpha diversity of perennial sites was no different than hay but 20% and 22% (P=.027 and P=.012 respectively) higher than corn and soy for pit traps, and 71% and 60% (P<.001 for both) higher than corn and soy for sweep nets (Figure 6). The total abundance of arthropods (number of individuals) was only significantly higher in perennial fields for sweep nets compared to the corn and soy cover types (p<.0001 for both; Figure S5). There were no differences for pan traps or pit traps. There was no significant relationship between the alpha diversity of perennial or hay fields with the age of the field (data not shown).

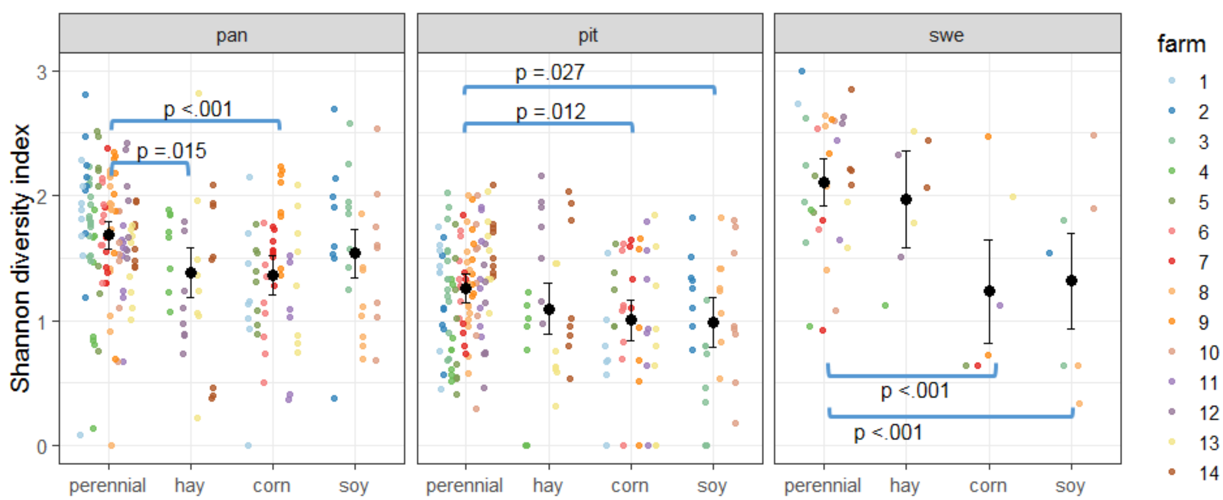


Figure 3.6. Invertebrate alpha diversity for woody perennial, corn, soy, and hayfields. Shannon diversity index cover type and trap type. Each point represents one trap, of one trap type, on one quadrant, on one farm visit. Black

points and error bars represent model estimates and 95% CIs wit estimates are averaged over the levels of visit; P-values include Dunnett adjustment.

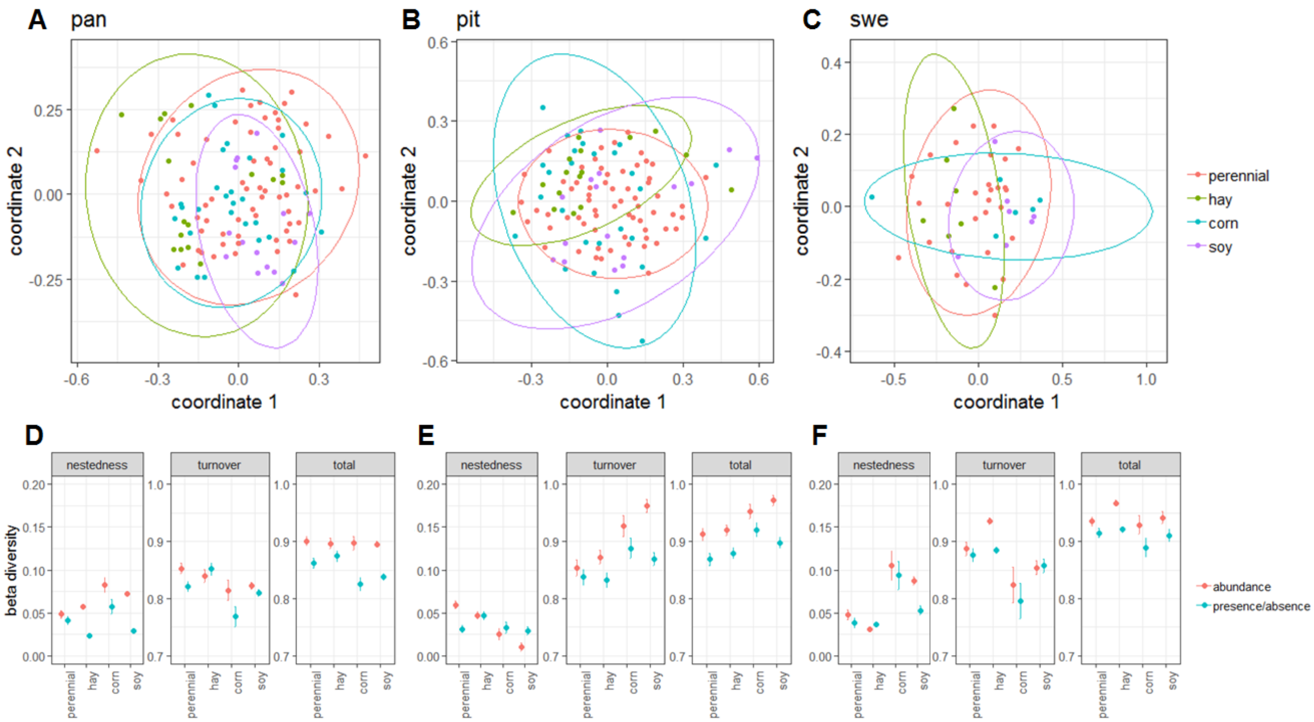


Figure 3.7. Arthropod beta diversity for woody perennial corn, soy, and hay fields. A-C) Non-metric multidimensional scaling (NMDS) of Bray-Curtis distances between invertebrate communities at each site. Each point represents an invertebrate community from one trap type in one quadrant on a perennial or conventional field. D-F) Groupwise beta diversity and its components, nestedness and turnover, using both abundance-based and presence/absence-based metrics (Bray-Curtis and Sorensen, respectively).

Ordination of the arthropod collection sites did not show visually distinctive communities for any of the trap types (Figure 3.7 A-C). Overall beta diversity and its components for insects and non-insect arthropods depended significantly on the trap type (Figure 3.7 D-F). Flying insects (caught in pan traps) and those found on ground-cover vegetation (caught in sweep nets) had similar overall beta diversity compared to corn and soy fields, but a larger portion of this was due to turnover (Figure 3.7 D,F). Ground-dwelling insects (caught in pit traps) had lower beta diversity in perennial fields compared to corn and soy fields, and this smaller total was comprised of more nestedness and less turnover than the conventional cover types (Figure 3.7 E).

3.3.2 Ecosystem Service Indicators

3.3.2.1 Soil structure

Woody perennial fields are characterized by less soil compaction than conventional fields at both 0-15 cm below the surface and 15-30 cm below the surface (Figure 3.8). Perennial fields are 11%, 17%, and 11% (P= .049, P<.001, P=.045) less dense than hay, corn, and soy fields respectively at 0-15 cm below the surface, and 8% (P= .005) less dense than soy fields at 15-30 cm below the surface. Note that for comparison of means calculated using linear mixed effects models (i.e. including blocking factors) overlapping confidence intervals do not indicate a lack of significance in the difference between means.

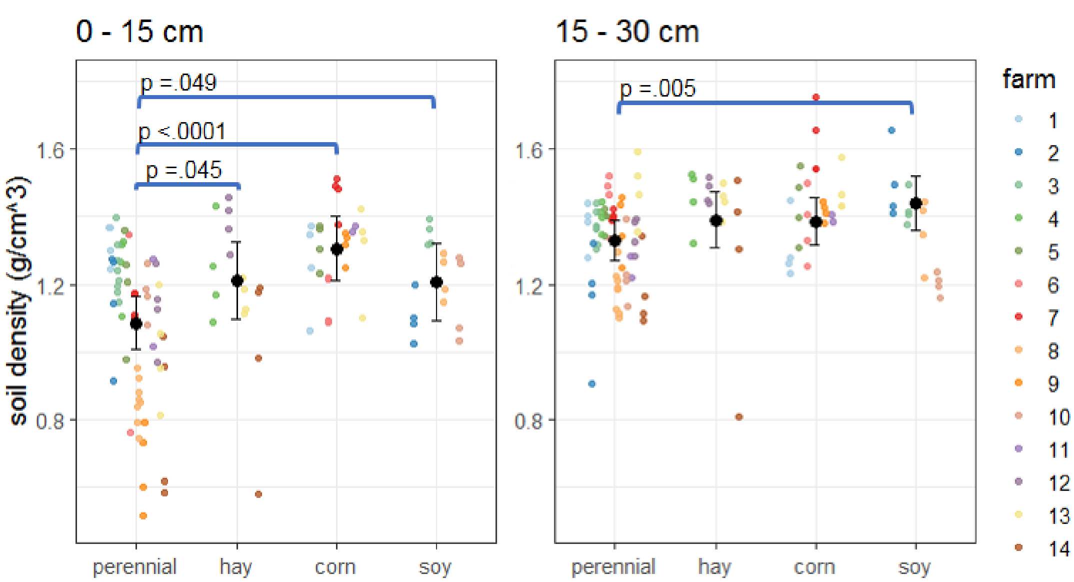


Figure 3.8. Soil bulk density. Each point represents an individual sub-sample from one quadrant within the field. Black points and error bars represent model estimates of means for each field with 95% confidence intervals; P-values include Dunnett adjustment.

3.3.2.2 Soil carbon storage

For soil organic carbon, perennial fields were not significantly different than any of the conventional cover types individually (Figure 3.9). Soil organic carbon did not increase significantly with the age of the perennial field.

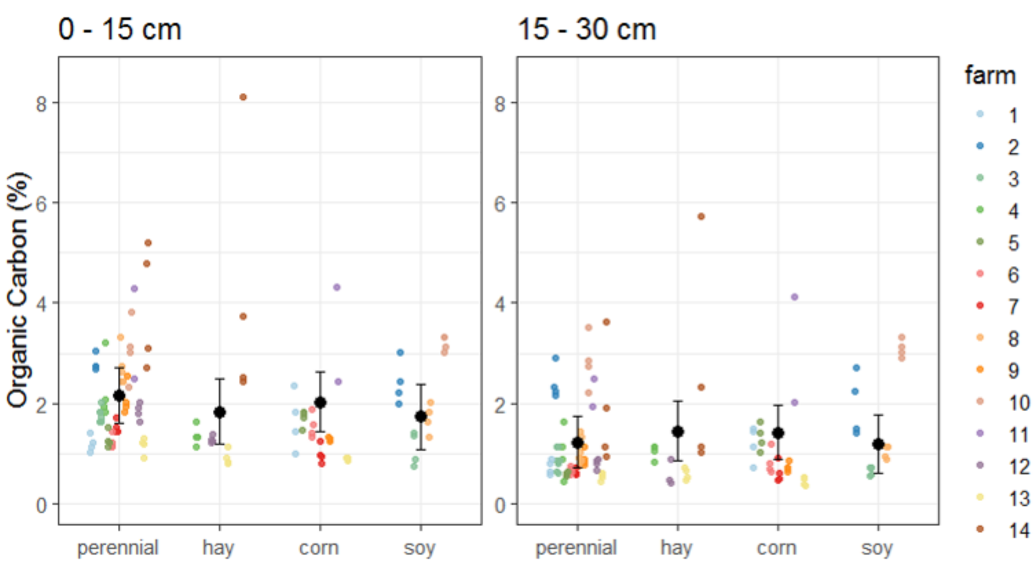


Figure 3.9. Soil organic carbon. Each point represents a composited sample made up of 10 auger samples. Black points and error bars represent model estimates and 95% CIs.

3.3.2.3 Soil fertility

Nitrogen and phosphorus are essential nutrients for plant growth, and are supplemented heavily through chemical fertilizers in conventional corn/soy rotation systems in the US Midwest. Woody perennial fields have 16% and 15% (P= .037 and P=.042) more total nitrogen than hay and soy fields respectively at 0-15 cm below the surface, but not different than any conventional cover type at 15-30 cm below the surface (Figure 3.10 A). Available phosphorus was not significantly different at either depth compared to any comparison cover type (Figure 3.10 B).

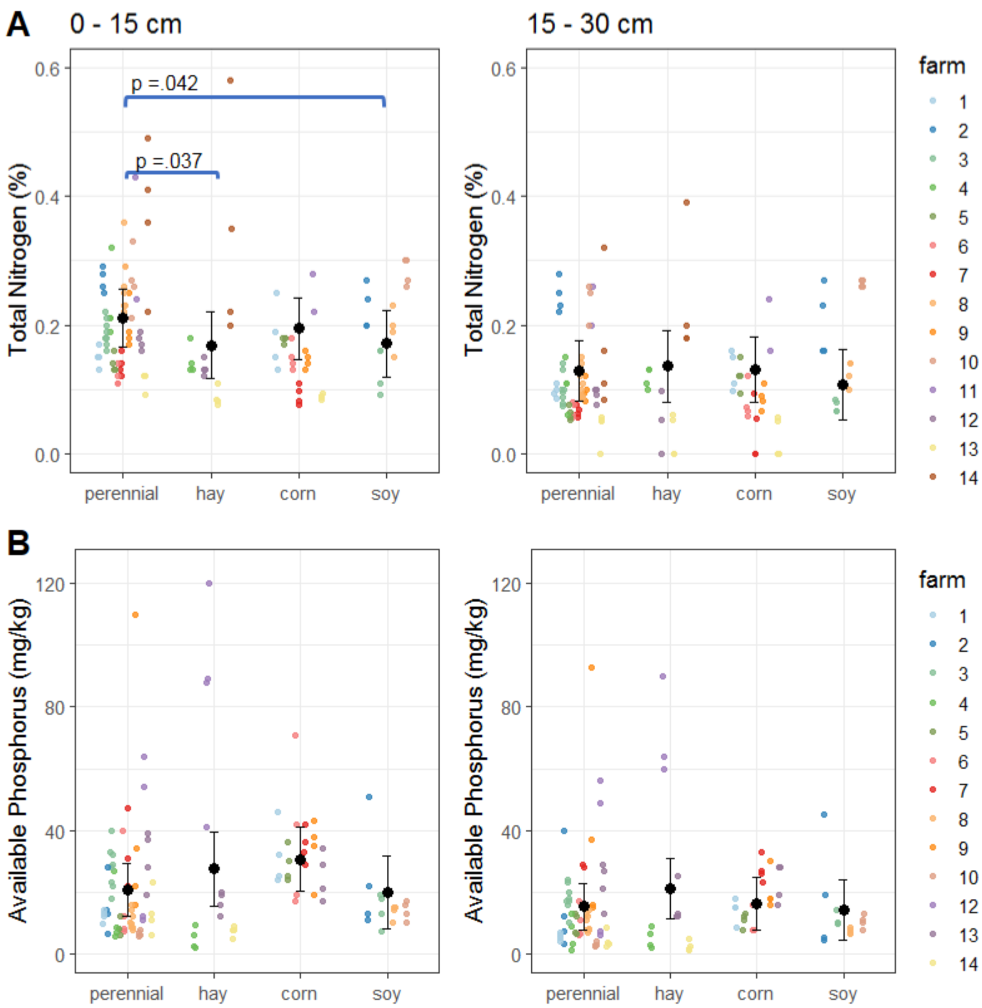


Figure 3.10. Total nitrogen and available phosphorus. Differences in total nitrogen (A) and available phosphorus (B). For phosphorus analysis, farm 11 was an extreme outlier due to the presence of chickens and was excluded. Each point represents a composited sample made up of 10 auger samples. Black points and error bars represent model estimates and 95% CIs; P-values include Dunnett adjustment.

3.2.2.4 Erosion control

We looked at the density of total plant cover as an indicator for vulnerability to erosion. Woody perennial polyculture fields had 31% and 55% ($P < .001$ for both) denser ground cover compared to corn and soy fields (Figure 3.11), but no different than hay fields. These measurements were taken in mid-summer and include the cover of the annual crops themselves; the data do not reflect extensive bare ground on annual fields outside of peak growing season, when the benefit of perennial fields might be considerably larger.

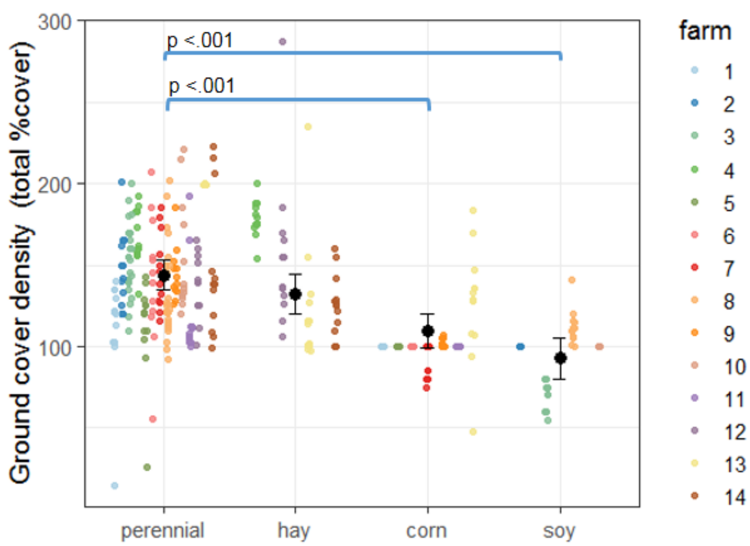


Figure 3.11. Ground cover. Ground cover can exceed 100 % due to overlapping leaves. Black points and error bars represent model estimates and 95% CIs; P-values include Dunnett adjustment.

3.2.2.5 Nutrient Cycling

For the ecosystem service of nutrient cycling, we looked at both the readily metabolized carbon (active carbon) in the soil, and the presence of arthropods that decompose organic matter, which included detritivorous, scavenger and mycophagous arthropods.

Perennial fields have 31% (P<.001) more active carbon than hay fields at 0-15 cm below the surface, but 23% less active carbon than soy fields at 15-30 cm below the surface (Figure 3.12 A). Comparison between perennials and other individual crops types are not significant.

The pattern of active carbon in the top layer of soil was mirrored in both the species richness and abundance of arthropods involved in nutrient cycling (Figure 3.12 B). Compared to hay fields, perennial fields had 76% (P=.003) more nutrient-cycling species and 3.4-fold (P=.002) more nutrient-cycling individuals. Interestingly, the presence of nutrient cycling arthropods did not differ significantly between woody perennial fields and corn or soy fields.

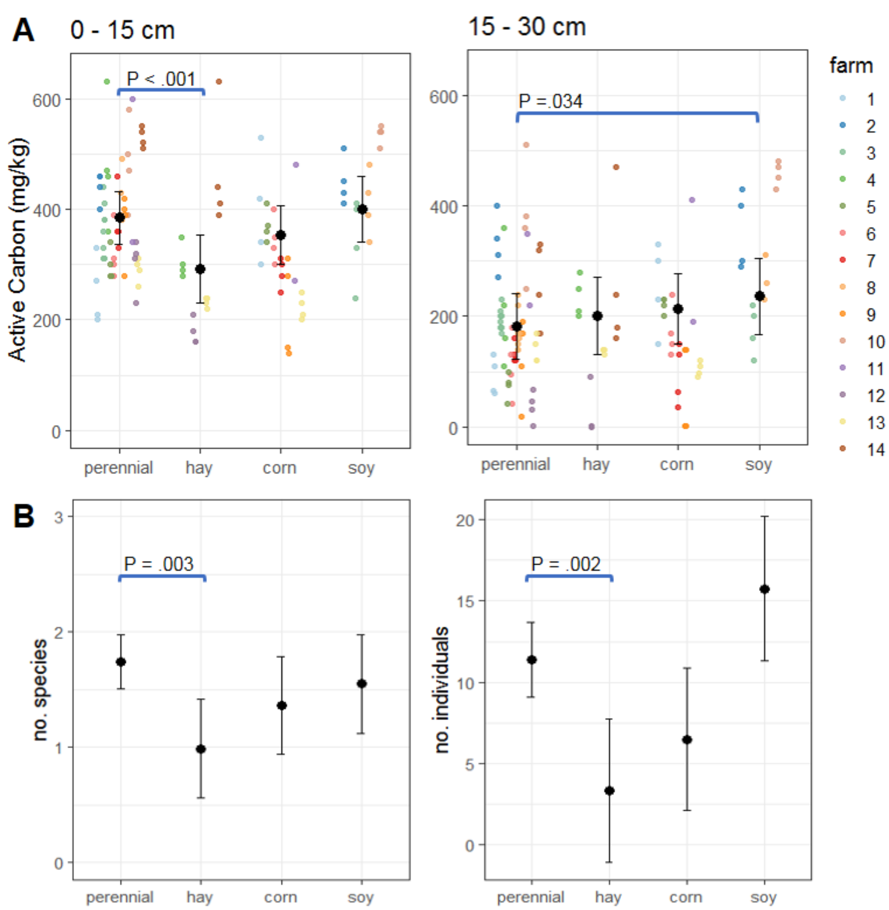


Figure 3.12. Nutrient cycling indicators. A) Active carbon; each point represents a composited sample made up of 10 auger samples. B) Nutrient cycling arthropods present at each sampling site; both species richness and abundance are shown. For all panels, black points and error bars represent model estimates and 95% CIs; P-values include Dunnett adjustment.

3.2.2.6 Pest regulation and pollination

We found that perennial fields had 2.3-fold and 2-fold ($P<.001$ for both) more species potentially supplying pest control to corn and soy fields respectively. This was mirrored for plant damaging species, where perennial fields had 3-fold and 1.8-fold ($P<.001$ for both) more species than corn and soy fields, respectively. Abundance was 4.6-fold and 3.5-fold ($P<.001$ for both) higher in perennial fields than corn and soy fields for plant damaging species but there was no difference for pest control species (Figure 3.13 A).

For pollination, perennial fields had 73% ($P=.003$) more species than corn fields, while there was no significant difference in the abundance of pollinators between the perennials and any conventional cover type (Figure 3.13 B).

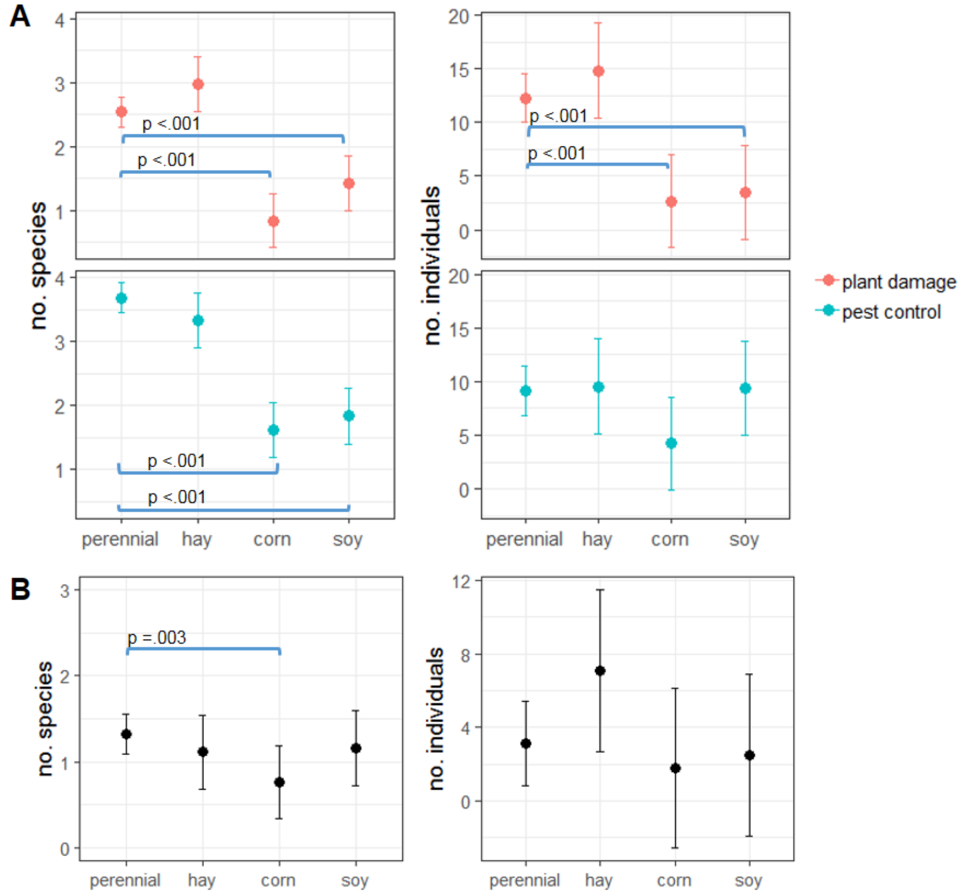


Figure 3.13. Pest regulation and pollination species. Estimated species richness and abundance belonging to (A) pest regulation and (B) pollination functions. Ecosystem services were classified by trophic group (see Appendix B.1 box 1). Points and error bars represent model estimates and 95% CIs. Estimates are averaged over the levels of trap type and visit; P-values are adjusted using the Dunnett method.

When all the ecosystem services provided by arthropods were grouped together, perennial fields had the highest number of service-providing invertebrate species, while corn fields had the lowest. Soy fields had the largest number of service-providing individuals, while corn had the lowest (Appendix B.2 Figure S6).

3.2.2.7 Crop production

The woody perennial polyculture farms in our study had very low food production yields compared to the corn and soy typical of the US Midwest (Figure 3.14). As mentioned, many of the farms in our study were young, and have not reached full production (or even started producing at all). We therefore compared only the oldest half of woody perennial polyculture farms in our study to corn and soy average yields from the region (Figure 3.14). It is important to keep in mind that the vast majority of food produced on perennial farms is consumed by people, and uses minimal or no fertilizer and pest-control inputs (see methods). This is in contrast to much of the corn and soy produced in the region, which is used for biofuel or animal feed.

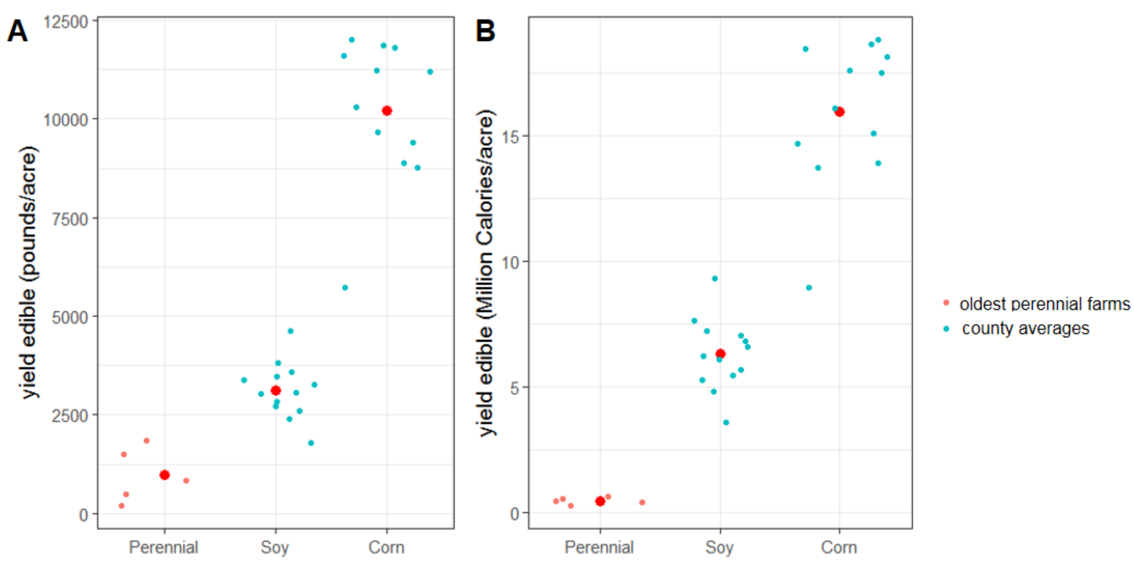


Figure 3.14. Yields of midwest conventional annuals and woody perennial polycultures**.** Yields from woody perennial polyculture farms and midwestern row crops in (A) edible pounds/acre and (B) million calories/acre. 2017 Yields of the top 5 yielding woody perennial polyculture farms in our study (out of 14) are plotted (pink) with their mean (red). 2017 soy and corn yields from the 13 counties where our study took place (blue) and their means (red) (data source USDA).

Woody perennial polyculture farms produced a variety of different food types, ranging from high energy density crops (like nuts) to specialty crops with low energy density but important nutritional or medicinal properties (like seaberry and aronia berry), to perennial vegetable crops like asparagus (Figure 3.15). Appendix B.2 Table S1 lists the crops being grown on each of the farms, though not all of these had corresponding yields (for example in the case of young trees not yet yielding, or yielding in minor amounts that the farmers didn't keep records of). Particularly within the fruit category, there were a wide variety of foods produced including many different berries and a variety of familiar and less familiar fruit. Farm # 10, the youngest of the farms in our sample, was using chickens in their young perennial fields to generate cash flow while their trees matured. Food production generally increased with age of the farm.

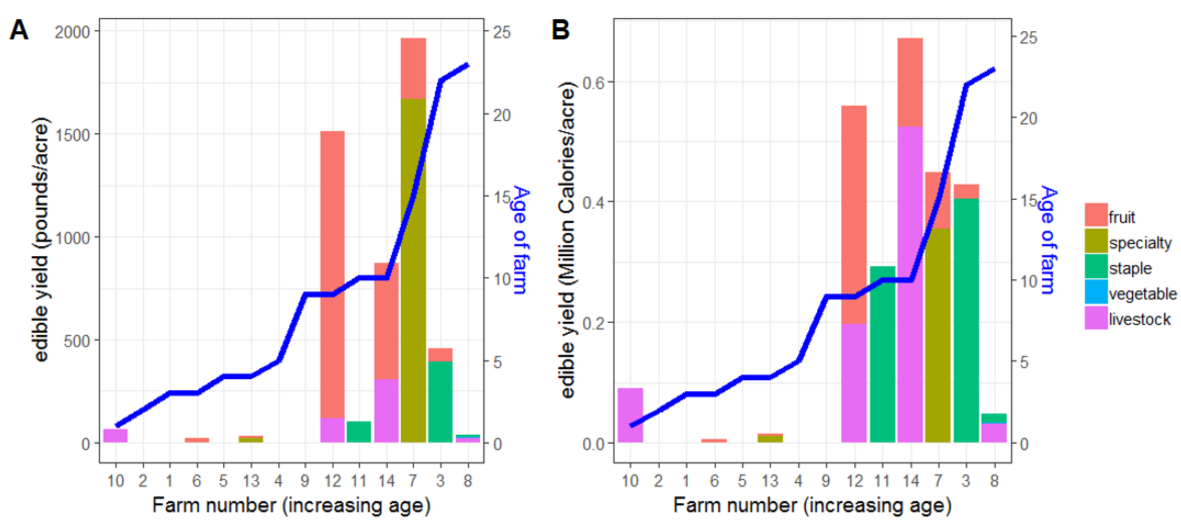


Figure 3.15. Yields of 14 woody perennial polyculture farms**.** Yields in (A) edible pounds/acre and (B) calories/acre. Each farm's total yield is colour coded by food type; farms are sequenced by the age of the plantings (blue line). Eggs were removed (see methods). Farm 9 had no data available.

3.2.3 Synthesis of Indicators

On 14 farms with perennial crop polycultures and in nearby monoculture control fields, this study measured several aspects of the biophysical environment using diverse methods. Figure 3.16 shows log response ratios and the significance levels of the statistical tests carried out on each parameter we measured (the magnitude of response ratios do not necessarily correspond to the significance of the hypothesis tests because of the nature of the underlying properties they are representing).

One challenging aspect of the experimental design was that not all the perennial polyculture farms had the same type of conventional comparison field. At times, the trends for individual cover types were distinct in such a way that they were not significant when compared to the perennial sites together, though some were individually (Figure 3.16, e.g. abundance-based beta diversity for fungi). Other times, individual control types behaved similarly to each other (Figure 3.16, alpha diversity and ES metrics), and/or the combined comparison was more significant due to increased power than the individual comparisons (Figure 3.16; soil fertility metrics).

In addition, there was a range of crop assemblages (Appendix B.1 Table 1) and management practices in the perennial farms themselves (and also the hay fields), unlike annual crop fields that are often managed to similar industry standards. The presence of a signal for several indicators from this group of young and heterogeneous perennial polyculture farms is therefore significant in itself.

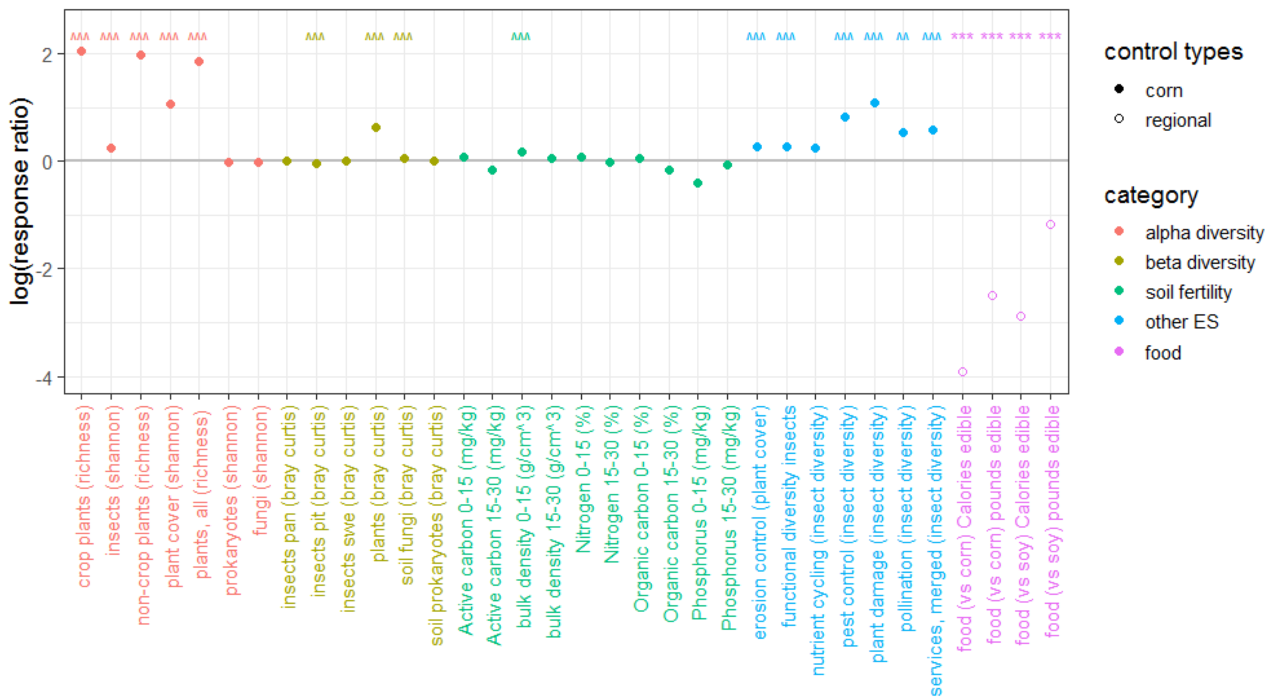


Figure 3.16. Synthesis of comparisons. Each point represents the log of a response ratio (perennial/control). Response ratios were created from model estimates of the different variables. Solid circles represent response ratios of woody perennial polyculture sites compared only to corn fields and the significance of these comparisons is denoted by carets (^=<0.05; ^^=<0.01; ^^^=<0.001). Open circles represent response ratios of woody perennial polyculture sites compared to food production from county averages, not from the control fields in our study (see methods), and the significance of hypothesis testing on these comparisons is denoted by stars (*=<0.05; **=<0.01; ***=<0.001). The response ratio for soil bulk density was inverted such that lower density in the perennials shows up above the 0 line. .

3.4 Discussion

3.4.1 Woody perennial polycultures differed from conventional monocultures in flora and fauna

The soil bacterial and fungal communities in this study showed distinct patterns: the fungal community was both compositionally more distinct from annual controls and internally more variable from itself (i.e., higher beta diversity and higher turnover component of beta diversity) than prokaryotes were. The observation that fungal community composition differs more than prokaryotic communities between perennial and annual fields is consistent with other published literature citing the sensitivity of some fungi (especially beneficial symbiotic traits of mycorrhizal fungi) to N fertilization, tillage and monoculture (Verbruggen and Kiers 2010; Jach-Smith and Jackson 2018).

Plant diversity had, perhaps unsurprisingly, some of the largest differences between perennial and corn and soy fields, both based on plant cover quadrats and overall diversity from scouting. From our field notes, the corn and soy fields that had some diversity of weedy undergrowth had visibly less vigorous/healthy corn and soy crops than the fields that had no weeds, while a diverse understory was seen by many of the perennial farmers in this study as an advantage. Hay fields were as diverse as perennial fields in the plant cover quadrats, but less diverse than the perennials for overall plant diversity from scouting. This indicates that perennial fields contain more low-abundance plants that do not show up in quadrats than hay fields do. In addition, overall plant diversity increased over the age of the farms while diversity from plant cover quadrats did not, indicating that lower abundance plants take longer to appear and establish after perennialization. Not only did woody perennial fields have more species of plants than conventional fields, a greater portion of this diversity was due to turnover and less due to nestedness than conventional fields. The more nested nature of conventional field communities means that they are homogenous and provide habitat for a fundamentally limited number of species (habitat filtering). In contrast, the perennial fields provided habitat that is potentially amenable to many species, and each farm hosts a different set of these species. Taken together, the perennial fields hosted a large number of species, whereas control fields do not provide this same additionality.

Woody perennial fields had consistently higher insect alpha diversity for all trap types and in comparison to all control cover types. In contrast, the abundance of insects (i.e., total number of individuals) was only different in the sweep nets, where abundant understory vegetation in the perennials provided more habitat for the types of insects caught in sweeps than the nearly bare ground of the early season visits to the annual fields and the tall corridors of corn where sweep netting was impossible of the late season visits. The changes in insect composition seem to be apparent over a short time after perennialization, with field age of perennials seemingly not linked to insect diversity (though it is linked to plant diversity).

Patterns of beta diversity and its components in arthropods varied by trap type. This is indicative that the variability of species across a landscape depends on their movement through the matrix and their unique habitat niches and modes of life. Perennial fields showed more turnover and less nestedness than corn and soy fields for pan traps and sweep nets, but the opposite for pit traps. The more nested nature of ground-dwelling arthropod communities in perennial fields means that they are homogenous and provide habitat for a fundamentally limited number of species (habitat filtering). In contrast, for flying and vegetation-dwelling arthropods, the perennial fields had higher turnover indicating that they provide habitat that is potentially amenable to many species, and each farm hosts more different sets of these species. Taken together, the perennial fields were home to a larger number of species than conventional fields for all trap types, but provided greater additionality for flying and vegetation-dwelling communities caught in pan traps and sweep nets. Replacing traditional corn and soybean farms with perennial farms would help conserve rich and varied communities of insects in these niches compared to ground-dwelling arthropods which are more homogeneous in perennial fields.

3.4.2 Woody perennial polycultures increased the supply of ecosystem service indicators

The presence of more active carbon in the top layer of perennial field's soil likely reflects that much organic material is not removed in perennial systems, and is accumulating as leaf litter from trees and under-story plants and roots contribute dead plant material. Unlike the perennial systems, in annual systems, soil is turned down to 30 cm, perhaps distributing active carbon from surface residues to the deeper layer of soil. The result that nitrogen was higher in the top layer of perennial fields and that nitrogen in the deeper layer and phosphorus were no different is interesting considering that corn and soy control fields are fertilized extensively. Some of the perennial enterprises in the study were fertilized with compost and/or bark mulched, while others were not actively fertilized.

While we did not observe a significant temporal trend with farm age for active carbon, organic carbon, N or P, it would be interesting to follow up with these properties as the perennial fields mature. The small effect sizes of the soil chemical properties when they were significant are perhaps not surprising given the fairly small sample of mostly young perennial plantings. In addition, farmers at three of the sites specifically mentioned that perennials were planted on land that was marginal for annual row-crops (chiefly because of slope and subsequent erosion), and therefore may have had inferior fertility properties initially. Taken together though, these results indicate that nutrient availability and overall soil fertility may not be the bottleneck hampering increased food production from perennial farms.

The higher density of plant cover we found in woody perennial polyculture fields compared to corn and soy fields is directly linked to reduction in nutrient pollution in the US Midwest (Blesh and Drinkwater 2013). Our analysis was based on plant cover in mid-summer, so it is certainly a severe underestimation of the difference in soil exposed to leaching and erosive forces on a year-round basis. While we did not conduct direct measurements of nutrient runoff, water retention, or soil erosion, the density of plant cover (and presence of bare ground) can function as a proxy for these functions based on previous studies.

The higher number of invertebrate trophic levels/diets observed in the woody perennial polyculture fields indicate that the increase in alpha diversity is accompanied by an increase in the types of niches these species occupy, and presumably in the complexity of the resulting food webs. When invertebrate morphospecies were assigned to service and dis-service categories based on trophic functions, different trends were apparent for each. Clearly, diversity and abundance of service providers are indicative only of rough supply of certain services; they do not reflect the magnitude of the resulting service nor how these services are actually used and by whom, which would require additional studies and metrics of actual pollination of crops, insect damage on fruit, and so on. Interestingly, pollinating insects did not differ in either richness or abundance between any of the cover types. The supply of pollination services correlated to perennial landscapes is (relative to other services) quite well studied, and generally the presence of diverse perennials is beneficial to pollination of neighboring monocultures (Morandin and Kremen 2013). It is therefore interesting that when diverse perennials are themselves the main occupants of the fields (rather than being planted as pollination enhancers on fields margins as in most pollination studies), we only observed a significant difference in the number of pollinating species between perennials and corn. Woody perennial fields (as well as hay) had both more plant damaging insects and pest controlling insects than corn and soy fields; this agrees with literature that has found both more beneficial and more damaging trophic functions within a complex food web in multistory coffee plantations and in multi-species fruit orchards (Vandermeer et al 2010; Brown 2010), and in a meta-analysis which found higher abundance of natural enemies in habitats with more complex structure (Langelloto and Denno 2004). The nutrient cycling service was perhaps the most unusual because while for pest control and pest damage, perennials and hay were more similar to each other, for nutrient cycling (which involves detritivorous and scavenger trophic groups), soy fields had both the most richness and abundance, while hay fields had the least. With this exception, corn had the lowest richness and diversity for all the other ecosystem service/disservice categories (including a catch-all category for omnivores and arthropods of unknown function) indicating that the intensive pest management of corn fields is effective in reducing both species and numbers of arthropods across the board whether beneficial or damaging.

Yields from woody perennial polycultures in the Midwest are very low at this time compared to average corn and soy yields in the 13 counties we visited, even when only the oldest half of farms were considered. Older perennial enterprises generally produced more food than younger ones, as expected given the long maturation times of most tree crops. Farm 8, one of the two mature farms in the study was an exception to this, but from our discussion with the farmer, this low yield is at least in part the result of lack of harvesting effort due to preoccupation with breeding and consulting enterprises, not because the crops themselves are not yielding. Indeed, experimentation and learning was one of the main goals of many farmers, in part from a recognition that the systems to scale up perennial production in the region are still underdeveloped (see chapter 4). In addition, as mentioned above, a few of the perennial plantings were established on land that was considered marginal for annual agriculture, a scenario for land transition that is more palatable to midwestern landowners than transition of prime cropland (Mattia et al. 2016; Stanek et al. 2019), but may limit the productivity of land until fertility is reestablished. Importantly, the nutrient and energy inputs into the perennial polycultures in this study were minimal compared to the conventional crops that dominate the region meaning that the yield comparison is not simply between food production from crops with differing physiognomy, but between radically different farming systems with many contextual differences (further elaborated in Chapter 4).

It is important to elaborate that, although we carried out a rough caloric comparison here, the foods compared in annual and perennial systems in this study are not equivalent nutritionally. The uses of conventional corn/soy agriculture are chiefly animal feed and biofuels, while the food produced on the perennial farms was nearly all for human consumption. The caloric comparisons we made are fair through the lens of land use in a particular geography, but they do not take into account the different levels of inputs, the non-equivalence of all calories, and the actual food needs of midwestern and international communities (Cassidy et al. 2013). Studies are increasingly showing that food security is dictated by accessibility and affordability of food rather than its absolute production or availability, which is currently in surplus globally for all major macro and micronutrients (Ritchie et al. 2018). Yields therefore must be considered alongside information about the end use, nutrient density, and accessibility of the food being produced, as well as the inputs needed.

3.4.3 Implications of perennialization and diversification for ecosystem services from agriculture

This study shows that planting perennials on formerly conventional annual cropland or marginally used fallow land in the American Midwest has several diversity and ecosystem service benefits. Many of these benefits are likely the product of a favorable comparison to the low bar of the largely annual conventional agriculture which is adjacent to our study sites (and which often occupied these fields before the transition to perennial agriculture). Perennial monocultures that provide staple foods but are unsuited to the environment (almonds in California), or that replace forest cover instead of already-cleared land (avocados in Central America, palm oil in Indonesia) cause enormous environmental harms despite being perennials. Nonetheless, some of the benefits we observed are, if not unique to woody perennial systems, especially suited to them. For example, the increase in total plant diversity over time indicates that lack of soil cultivation and herbicide management over time, not just its initial cessation, is necessary for less abundant plants to establish. The higher abundance of sweep net arthropods directly reflects the presence of continuous ground cover in the perennial systems. Taken together, the permanent ground cover combined with trees provided benefits that annual crops (which require constant soil disturbance and do not have permanent 3-d vegetation structure) did not.

Due to the natural-snapshot experimental approach of this study, the specific mechanisms contributing to various ecosystem functions and services cannot be clearly interpreted. Controlled experiments (such as those being conducted at the University of Illinois at Urbana Champaign; Lovell et al. 2018) are necessary to more clearly delineate which functions and biodiversity patterns in perennial polycultures stem from understory composition and management relative to the composition and diversity of tree crops themselves. It is possible that some ecosystem services and species benefit equally from more simplified perennial systems or only from specific components. The perennial systems included in this study (multiple perennial crop species in the same field, sometimes with hay harvest and grazing livestock) exist towards the more complex and integrated side of the spectrum of perennial management possibilities, and they were contrasted with neighboring annual agriculture rather than more conventional types of perennial agriculture (which could not be studied side by side with this study design). In addition, the perennial fields we studied included a variety of crop species and employed different management, though none used intensive repeated chemical fertilization, pest or weed control (some did use organic sprays, occasional application of chemical weed or pest control, and compost). For all these reasons, our findings are more relevant to the process of diversified perennialization than to questions of specific management practices and outcomes among perennial systems.

The farm-scale perennial polycultures in the US Midwest included in this study mimic savanna ecosystems in that they combine mast trees with continuous grassy ground cover and often incorporate livestock that graze the understory during certain times of the year. The (re-)introduction of woodland-based agricultural practices to this region therefore relates to both its natural history and pre-colonial management by Indigenous peoples, who actively maintained savanna ecotypes in mid-succession along the grassland to forest continuum. The data presented here was in some ways prematurely collected since only two of the perennial farms could be said to be mature (over 20 years). Plant diversity and food production increased with the age of the perennial fields, but the other variables we looked at did not significantly correlate with field age. Following up as more farms mature would allow for better assessment of their food production and other variables at maturity, including an analysis of carbon stocks. Basic data about the environmental and agronomic outcomes of these systems is a necessary first step for future modeling work that can evaluate the role of more widespread transition to perennial food systems (for example, see Figure 6 in Wolz et al. 2017).

As the world faces accelerating ecological crises, the need for agricultural systems that minimize negative impacts while providing people access to nutrition is paramount (Campbell et al. 2017). Our findings suggest that—in line with fundamental ecological theory—woody perennial polycultures provide several environmental and ecosystem service benefits in the US Midwest. How to weigh the public interest in these benefits against caloric and financial output of conventional row crops has become an increasingly important and challenging question for public policy (Atwell et al. 2010). As unexpected weather events increase with climate instability and the need for locally resilient food systems becomes more pressing, perennial systems that provide food for people could become more politically attractive. For example, 2018 was a good year for corn and soy, but 2019 was a difficult year with lower yields due to heavy spring floods that waterlogged fields all over the US Midwest. Further research that models scenarios for the transition of annual cropland to perennial crops is necessary to better understand the magnitude of ecological and agronomic shifts such transitions might drive (Asbjornsen et al. 2014; Wolz and DeLucia 2019). This paper, which studied 14 farms that have actually begun this transition, is a first step towards policy relevant landscape level work.

Chapter 4: Local knowledge and relational values of Midwestern perennial polyculture farmers

4.1 Introduction

Agricultural producers, academics, and policy makers are increasingly interested in multifunctional tree crop systems as a solution for maintaining ecosystem services and producing food (IPCC 2019; Hawken 2017; Mattia et al. 2016), as these systems can sequester carbon, support biodiversity, provide nutrition and support livelihoods (Lovell et al. 2018; Wolz et al. 2017; Smith et al. 2012; Martins et al. 2011). While most diverse tree crop systems are in the tropics, the US Midwest is emerging as a region of the temperate North where such systems are also developing in a community of practice as a radical alternative to the region's prevalent annual monocultures. This development is in the form of research sites (Lovell et al. 2018), farmer networks, and farm-scale enterprises. Here called woody perennial polycultures (or simply "perennial polycultures" for the purposes of this chapter), these systems are a type of agroforestry that produce multiple species of perennial tree crops in the same field, sometimes integrating herbaceous perennial crops, livestock, hay or annual production in the understory. Woody perennial polycultures are a good example of a component of diversified farming systems (DSF) which intentionally include functional biodiversity on spatial or temporal scales to sustain production and ecosystem services (Kremen et al. 2012). The complexity that woody perennial polyculture systems embody on multiple scales raises the questions: how do farmers resolve tradeoffs and dilemmas arising from this valuable complexity? What are the practices that enable such enterprises to exist and thrive in the shadow of the industrialized annual agriculture that dominates the region (Lovell et al. 2018)? And what does this mean for the prospect of the wider application of this type of farming? This study collects and synthesizes the valuable local knowledge of the people who are already designing, planting and nurturing perennial polyculture systems on the regional scale of a particular geography: the US Midwest.

The ecological context for perennial polyculture systems comes from applied ecological literatures (agroecology and agroforestry) as well as the grassroots permaculture movement, which have long advocated for the integration of long-lived perennial species in diversified agricultural landscapes (Asbjornsen et al. 2014, Jose 2009; Mollison and Slay 1995, Ferguson and Lovell 2014). Understandings from agroforestry and perennial forage studies indicate that perennialization is linked to improvements in soil carbon sequestration (Young et al. 2009; Cates et al. 2016), pollination (Morandin & Kremen 2013; Bennet & Isaacs 2014), pest regulation (Landis et al. 2000), water quality (Gao et al. 2004), and soil erosion (Zuazo & Pleguezuelo 2008; Brady & Weil 1986). In the tropics, diverse multi-strata tree crop systems are a common type of agroforestry both for commodities (coffee and cocoa) and in homegardens (where a large diversity of tree crops are grown), and have been thoroughly studied (eg. Gordon et al. 2007; Scales and Marsden 2008; Mendez et al. 2001). In contrast, most agroforestry studies in the temperate North investigate the environmental outcomes of integrating non-food producing perennials into the edges of annual agricultural landscapes (as buffers, hedges etc), or using timber trees in alley-cropping systems with an annual grain. As a result, there is a lack of knowledge about both the ecological and social aspects of temperate perennial polycultures where woody plants are themselves the primary food-producing crop (but see Wolz et al. 2018; Lovell et al. 2018, Kreitzman et al., in prep for biophysical approaches).

The application of local knowledge-based scholarship to agricultural research and development began in anthropology and rural sociology about (and in partnership with) marginalized agrarians (Thrup 1989; Kloppenburg 1991; Bentley 1994). The benefits of including and understanding farmer knowledge have become apparent, particularly in the prioritization/diagnostic/design stage of agricultural development initiatives (Oliver 2012; LeGal et al. 2011), but also in ongoing collaboration and monitoring, though examples of truly collaborative work are fewer (Bentley 1994; Cardoso et al. 2001). In the context of perennial systems in the US Midwest, several studies have engaged landowners and farmers about the adoption of perennial grass strips (Atwell et al. 2009; Atwell et al. 2010) and woody perennial polycultures (Trozzo et al 2014; Stanek et al. 2019; Mattia et al 2018), articulating demographics, barriers and structures involved in limiting interest in these seemingly beneficial practices. However, these studies involved gauging the interest of participants who had not adopted these practices, rather than investigating the successes and needs of people who already had (but see Blesh and Wolf 2014 for an example of work that integrates barriers with practices post-adoption). In particular, we were interested in how the farmer's practices (and the values that manifested therein) allowed them to not only transition to, but continue maintaining, a high-diversity complex adaptive system like a woody perennial polyculture.

The adoption of agricultural practices has been studied using a wide variety of different theories of human action, grounded in various academic disciplines, from psychology to conservation (reviewed in Meijer et al. 2014). Recently, the concept of relational values, which draws from the qualitative social sciences, has sought to break down the divide between instrumental framings that emphasize nature's material benefits to people, and intrinsic/moral framings which emphasize the existence value of the other (in this case nature) in its own right (Chan et al. 2016). This concept, which draws on Indigenous relational ontologies articulated by Indigenous scholars previously (e.g. Datta 2013), recognizes that many aspects of people's relationships to nature cannot be well understood by the stock and flow model of ecosystem services (instrumental values) or through the lens of universal and abstract moral, intrinsic, or held values (Chan et al. 2018, Himes and Muraca 2018). Rather, people can express values (preferences, principles, and virtues) through meaning-laden relationships. The relationship with a particular object situates the benefits of that relationship (e.g. nature's benefits to people), together with other values that emerge from the relationship like respect, care, and duty. While in an instrumental framing, these would be seen as costs (Jax et al. 2018), in a relational framing their fulfillment can contribute to wellbeing by embodying notions of a good life that go beyond the satisfaction of one's preferences to include living in accordance with one's principles and virtues (Jax et al. 2013; Chan et al. 2016).

The relational values construct is a useful one in an agricultural context, where farmers are deriving instrumental benefits from the land, while also living out other more nuanced values (Jones and Tobin 2018). For example, restoring nature for its own sake would generally be considered intrinsic, whereas restoring nature purely for better farm performance (e.g., via ecosystem services) would be instrumental; doing so for the sake of a sense of connection with the land would be relational. These values constructs often overlap - within a single 'feeling' about what motivates a person there might be a strong relational thread, an instrumental thread, and maybe also a hint of an intrinsic one (Chan et al. 2018). The application of a relational values framing to the themes that emerged from the present study is therefore useful in that it allows the analysis to embrace a multifaceted partnership (Knippenberg et al. 2018) rather than dualism between objects.

Unlike studies that investigate what would or could motivate people to use new practices or programs based on the failure to do so (Chapman et al. 2019, Meijer et al. 2014), this study investigates how people who have already taken considerable and contextually radical action explain, reflect, and describe their experiences. As perennial polycultures begin to appear in the US Midwest, scaling up will require a better understanding of both the praxis (including management practices, land uses, finances, and challenges), and the theories (including the values and motivations) of the farmers leading this land-use transition (Blesh and Wolf 2014). To this end, in the present study we ask a) how do perennial polyculture farmers use their farmland and generate their livelihoods? b) what motivates them to initiate these enterprises? c) what is their local expertise the management of perennial polyculture systems and how does this relate to complex adaptive systems? d) what are their community relationships and knowledge networks? and e) what are the challenges and barriers to thriving/expansion that they face and how do these intersect with existing policies? We synthesize the themes that emerged from these topics using a relational values framing, and connect our findings to both mainstream agricultural science and permaculture. Finally, we set an agenda for policy and program development in the private, non-profit, or government sectors that emerges from this local knowledge.

4.2 Methods

4.2.1 Study System

The study was conducted in 4 four states (Minnesota, Iowa, Illinois, Wisconsin) in the upper Midwest of the US. Farmer owners and/or operators were selected based on the criterion that their farms included a perennial polyculture enterprise, i.e., one on which they grew multiple species of perennial crops (not including pasture or hay) in the same field for commercial purposes. These were chiefly tree crops and woody shrubs, but also included perennial vegetables and medicinal plants that were interplanted or grown in alleys, and hay or pasture mixes in the understory of the trees or shrubs that were either mowed and left in place, mowed for hay, or grazed. Access to participants was facilitated through the Savanna Institute, a non-profit organization that conducts research and education about agroforestry and perennial agriculture in the US Midwest. The Savanna Institute partnered on this study by recruiting participants through their informal network of farms practicing perennial polyculture. Of the farms invited to participate in this study, the Savanna Institute had cooperated on research previously with some, some had participated in the Institute's educational programs, and some were part of the social network but had not previously participated in Savanna Institute research or education.

The study took place in the US Midwest, in the heart of the US Corn Belt. The agriculture typical of the region today is high-input corn/soybean rotation and cattle production, as well as an increasing density of concentrated animal feed operations (CAFOs) in three of the four states we visited (Walljasper 2018). In the pre-colonial US midwest, one of the important ecosystems was the fire-maintained oak savanna (i.e. a mixed woodland and grassland without closed canopy;

Karnitz & Asbjornsen 2006) which historically supported a high density of ungulates including bison, deer, antelope, and elk (Shay 1978; Abrams & Nowacki 2008). While the region's wet climate can support forests (Reich et al. 2001), in many cases Indigenous peoples preferred tallgrass prairies and savannas and actively maintained them through fire to promote ungulate grazing habitat and the many species of mast trees and berries (acorn, nut & fruit) that were staples of their diet (Abrams & Nowacki 2008). After invasion and settlement by Europeans, these savannas were replaced by tilled agriculture, were degraded by domestic livestock pasture, or underwent succession to closed canopy forest due to fire suppression (Karnitz & Asbjornsen 2006). The oak savanna ecotype preferred by Indigenous peoples during the Holocene is mimicked in our perennial study sites, including through the use of livestock in the understory of perennials on some farms. The appearance of perennial polyculture farms in this industrialized food landscape provides a case study for land transition in a region heavily dominated by conventional agriculture.

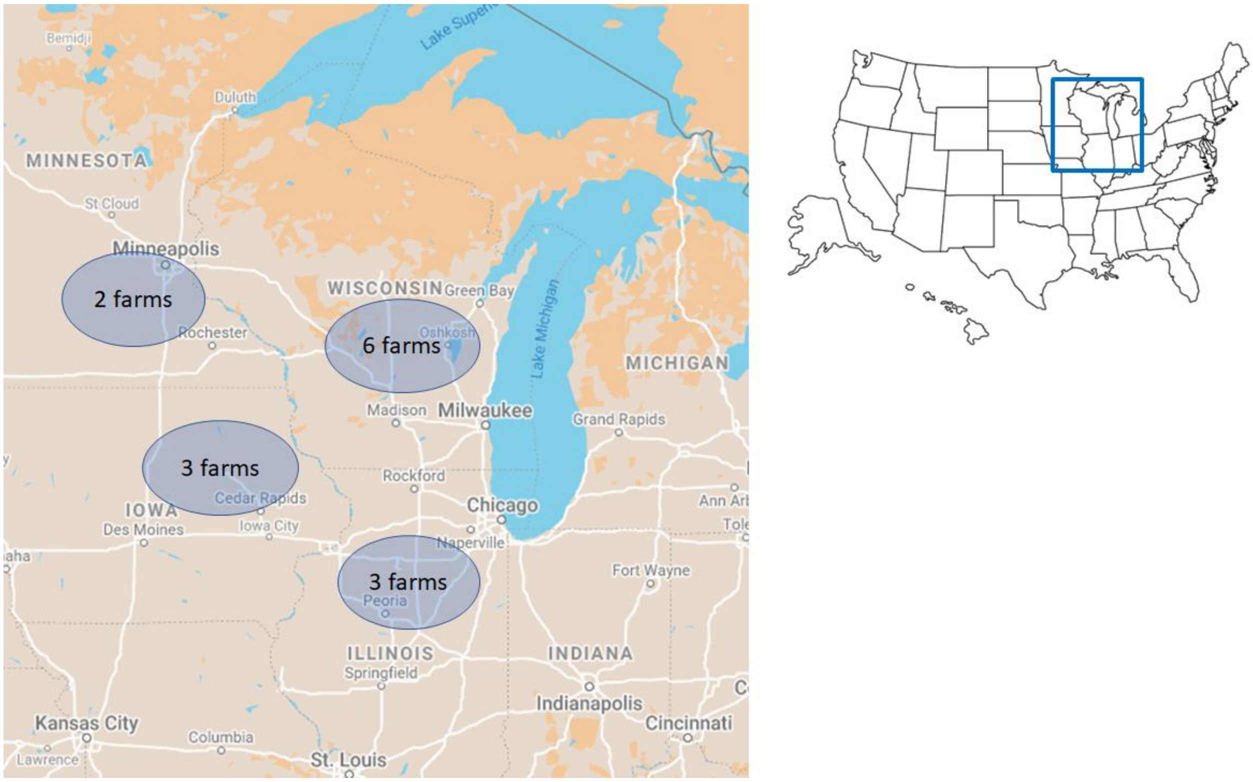


Figure 4.1. Fourteen farms in four states in the upper Midwest were owned or operated by the study's participants.

<u>Interviews</u>

We conducted 13 semi-structured interviews with 18 farm operators (including 5 farming couples or business partners) in the summer of 2018 (table 4.1). All but one of the participants were also the owners or part owners of the farms they operated. The 39% of female participants in this study is in line with the 39% of female farmers in the United States (USDA 2019). Our participants were slightly younger than the US average at a mean age of 50.1 compared to the US mean age of 57.5 (USDA 2019). One farmer managed two farms. Four of the interviews were conducted with couples who managed their farms as a team, and one interview was conducted with two business partners. The interviews were one to two hours in length, and took place on the farms. They were all conducted by the first author.

Table 4.1. Study participants

Gender	# participants (total 18)
women	7
men	11
other	0
Age	
25-35	3
36-45	5
46-55	5
56-65	2
66-75	2
76-85	1

The interview protocol was developed in conjunction with the research team prior to the lead author conducting interviews. Interview questions involved participants' general views on farming, management practices, wellbeing, motivations, and barriers (see Appendix C for full protocol). The interview questions drew from the sustainable livelihoods framework (Scoones 1998), on motivations through the lens of stewardship practices (Bennet et al. 2018) and on survey questions developed for Australian farmers by Maybery et al. (2005), but also drew on the the team's knowledge and specific interest in the perenniality of these enterprises.

The lead author (MK) met the farmers twice during the spring and summer while also conducting biophysical sampling on their properties, where the lead author and field team also camped, occasionally sharing meals, conversation, and enthusiasm with farm families about their perennial enterprises. As a result, MK's relationship with the participants was familiar when she conducted the interviews on the second farm visit. The participants knew that MK and the research team were studying environmental aspects of their practices in the biophysical part of the research on their farms.

4.2.1 Coding

Interviews were transcribed, and then coded by the first author using NVivo 12. Coding followed a hybrid deductive-inductive approach involving a combination of pre-defined and emergent codes. We used predefined codes for larger thematic categories that reflected the interview instrument/protocol. These included codes for general views on farming, motivations for perennial farming, management practices, community and mentorship relationships, challenges and barriers to expansion, and government programs. Emergent coding allowed for a greater diversity of topics to be included (e.g. values, succession, priorities for reform). This hybrid approach allowed us to integrate new themes that emerged from the data, particularly ones that did not easily fit within or that cut across the topics laid out in the protocol.

Values were one of the cross-cutting themes that were not the result of direct prompts in the interview, but rather came from statements across the whole of the interview that involved a sense of rightness, appropriateness, virtue, principle, or preferences, or through contrasting statements that indicated dislike, worry, and rejection. For example, in the following quote the farmer is speaking about the design of multiple levels of shade and canopy from the management practices portion of the interview, but s/he goes on to speak about all the wildlife that has appeared and how it makes them feel happy.

Well, for example by incorporating multi-levels of shade and canopy in this space, we went from seeing just basic crickets and very little life to having turtles, and crawdads. And, I think when *you see reptile life and stuff like that in an area where food's growing that's kind of a cool feeling. And all of the pollinator insects that we see here, that makes me happy. [12]*

This would be seen as a value statement in the category of connection to nature and wildlife (mention of seeing reptile life in an area where food is growing), and eudaimonia, i.e. notions of thriving or a good life (mention of a "cool feeling" and "that makes me happy" express a notion of a good life). Apart from the values present, the statement would also be coded for the management/design practice of multi-level canopy. Though they are presented in different sections, this overlap of practice and value was common in the interviews.

4.3 Results

4.3.1 Land and livelihoods

4.3.1.1 Land uses on farms

In speaking to participants about their land access arrangements, we found that the farms and perennial farm enterprises were mainly owned by individuals or farming families who had acquired their land by purchasing it. The three enterprises which were owned by businesses involving silent partners/investors rented their land in long-term leases; these farms were young, run by younger farmers, and oriented towards mechanization and eventual expansion. The two largest farm properties included (at least in part) land that was inherited and co-owned with siblings, and in both cases, siblings were co-owners of the perennial polyculture enterprises (Table 4.2).

Table 4.2. Land tenure and management of participant's farms

Ownership of land	# farms (total 14)
rented	3
purchased	8
inherited	3
Ownership of perennial enterprise	
owned with business partners/investors	3
owned by nuclear family/ individual	9
owned with siblings/family members	2
Farm manager	
couple, nuclear family	6
individual	5
business partners, employees	3
Age of perennial enterprise	
1-5	7
6-10	3
11-15	2
16-22	2

The perennial polyculture enterprises on all but three of the farms occupied a modest proportion of the farm property, and ranged in size from just 1 acre to 110 acres. (Figure 4.2). Half of the perennial polycultures were 1-5 years old, and four were not yet bearing, while only two could be considered mature at over 15 years old (Table 4.2). The woody perennial plantings on 9 of the 14 farms occupied space that had previously been under annual row crops (corn/soy or small grain) representing a direct transition from annual to perennial systems; the remaining ones were planted into unmanaged pasture or fallow representing the diversification of a grass-based perennial system to include woody species. The perennial plantings generally consisted of a canopy layer of fruit and/or nut tree crops (e.g. chestnuts and hazelnuts, apples, pears, plums, cherries, pawpaw, persimmon), a perennial shrub layer (aronia, black currant, elderberry, saskatoon berry, other berries), and an understory layer of hay or pasture mixes that were either mowed and left in place, mowed for hay, or grazed. Sometimes perennial vegetables and medicinal plants were interplanted or grown in alleys as well (rhubarb, asparagus, comfrey). The number of perennial crops (not including hay) in the fields ranged from 2-15 (average 8), though not all the crops were necessarily sold commercially. In addition, six of the farms had at least one type of animal (pigs 3, chickens 5, sheep 2) grazing among their perennials for part of the year. In two cases, these animals were owned and managed by external parties because the farmers saw benefits of grazing but weren't interested in managing livestock. Except for two farms that were basing their businesses off fairly intensive poultry production while their trees matured, the livestock were not very numerous (7- 15 pigs; 50-100 chickens, 15-30 sheep), but were still sold commercially.

The management style and intensity on the farms varied. For example, some used small amounts of herbicide in the few years after planting their trees, while others relied solely on mulch and mowing for weed control. Likewise, some used Integrated Pest Management which includes chemical pesticides when required, while others used only organically certified pest-control substances, while others did no chemical pest control at all. The farms were designed for different levels of automation, ranging from being managed with small hand tools and entirely hand-harvested to being managed with larger mowers and designed for machine harvest. Four of the fourteen farms were certified organic.

Other land uses on the farms included hay, pasture with livestock, forest/unmanaged timber, annual vegetable, monocrop berries, annual row crops, and conservation reserve program (CRP) set-asides. Several of the farms pointed out that they chose their worst land for the perennial polyculture enterprise, thereby mitigating the cost of taking it out of annual crops or hay production, while others used their prime land for the perennials. Two of the farms were growing conventional corn and soy on part of their land as well as perennials. Explaining the logic of initiating a perennial polyculture enterprise while growing conventional row crops on most of their land, one of the farmers said:

Conservation doesn't mean new-age green. Conservation means preserving and maintaining, and improving what's there for the future. For generations now that has been more and more productive corn and soybean soil. And I do know that's labor intensive and environmentally kind of, not very diverse at all. Which is why we tried this experiment on 17 of those acres to see what we might do that would be different, that would still grow food and fiber and not have to be replanted, or fertilized, or high intense input of chemicals to keep it going. Which corn pretty much does require all those things.

But practically, we can't just stop growing corn and soybeans and let it all go. Nobody would pay us for that, and that's how we're paying the taxes and the acquisition of the farmland, and our entire dietary system in this country is based upon successful growth of corn and soybeans, more than anything else, and wheat. And we, so I think we're experimenting with a responsible job of conservation in both of those land uses. [5]

Thus, this farmer held a moderate view that they could conserve and improve their land both under corn and soybean production while at the same time experimenting with perennials. In contrast, other farmers had transitioned all of their land out of annual row crops (or would not have countenanced having any in the first place) to a combination of hay, pasture, vegetable, and perennials plantings, and some did not use chemical inputs on any part of their land out of concern for health and safety. Thus there was a diversity of views among our respondents on the appropriateness of land uses and the speed of land transition that was right for them.

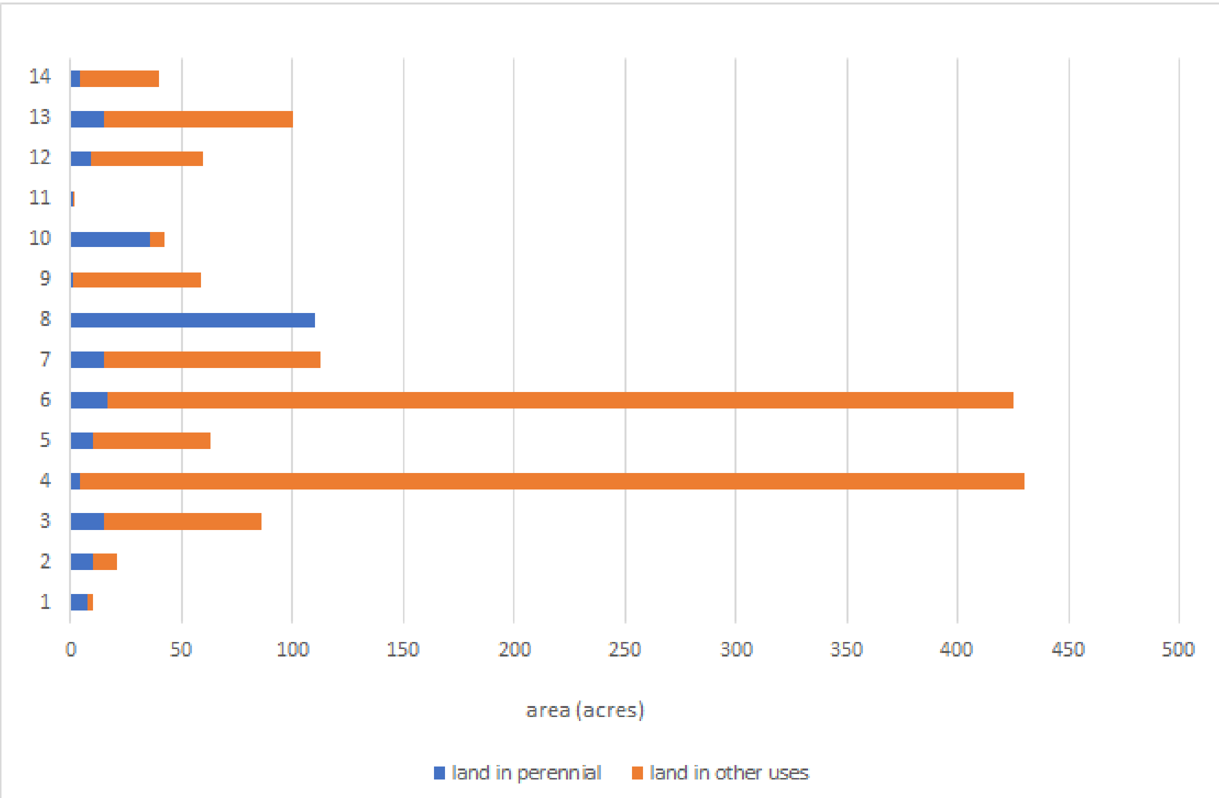


Figure 4.2. Farm land use relative to total farm size (in acres).

4.3.1.2 Farmer livelihoods

The participants in our study did not receive the majority of their gross income from their perennial enterprises, and 5 of the farms (4 of which were young and not yet bearing) reported no income at all from their perennial enterprises (Figure 4.3). We reported gross income rather than net profit: because the farmers sometimes carried debt, had depreciation on buildings, and/or transacted earnings and expenditures through companies rather than personal accounts, net earnings were sometimes negative or hard to calculate. All the farmers had other sources of revenue: other farming enterprises, (including annuals, tree nursery operations, and livestock), government programs, consulting, and off-farm work. Income from perennial enterprises was increasing in some cases, and many farmers projected further increases as their perennial plantings were quite young and not yet bearing. However, the importance of planning for revenues while the perennial enterprises were maturing was critical, particularly since only three of the 14 farms were leveraged by capital investment from outside the family. Thus, long-term financial planning was particularly important for these perennial farmers.

For some people, especially the younger ones, the financial success of the business was very important and the businesses were expected to pay off their investments and become profitable. For example, this farmer spoke about how it was important to them to increase the part of their income that comes from farming, not just to become commercially successful, but because they "want to be farmers" (more on this in the discussion under "Eudaimonia and connection to identity"):

I mean, we're mostly trying to be a commercially successful farm. And I think that's like our, maybe our primary motivation.[...] It doesn't, you know, it doesn't constitute a huge portion of our income right now, but we'd like to get to where it does. I think we'd like to get there because we want that. We want to be farmers. [11]

In contrast, there were participants, (including three older participants) for whom perennial enterprises were experimental at their outset, and were not necessarily expected to turn a profit, though they were still being harvested and sold commercially on a small scale. For these participants, their family's financial security did not depend on their perennial enterprises, even if the enterprises turned out to be successful (refer to quotes in Appendix C Table 1). The farmers used a variety of typically smaller scale marketing avenues including direct to consumer (CSA or u-pick), selling through local grocery stores, restaurants and farmer's markets. Access to wholesale markets and regional processing capacity was limited (discussed below in the section "challenges, barrier and policy priorities").

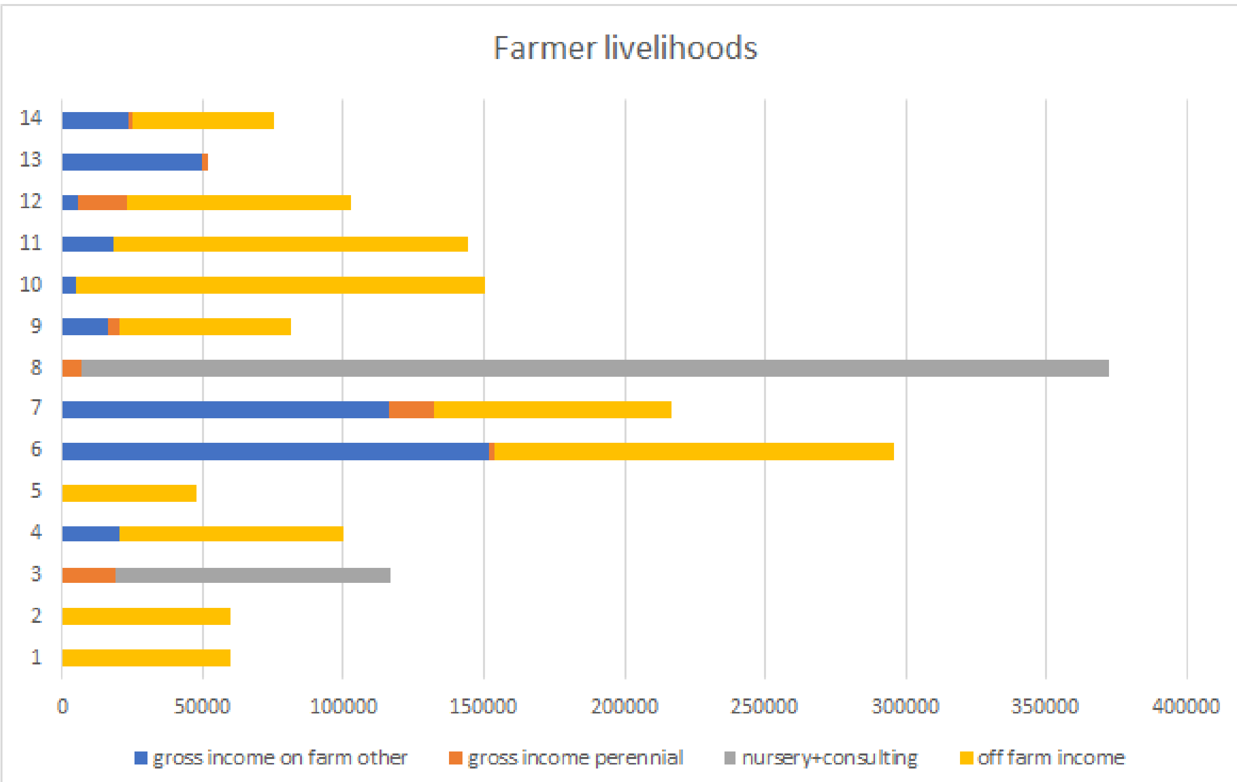


Figure 4.3. Farmer Livelihoods. Figures in USD for 2017.

4.3.1.3 Rural and community livelihoods

While most participants' comments about livelihood and financial management related to their own enterprises, several brought up the connection between their farms or similar farms to rural livelihoods more generally. They identified the poverty and the population decline in their rural neighbourhoods with their perceived decline in the health of the land and the number of people who were earning a living from the land. Several participants said that the success of their enterprises and similar enterprises could boost a local economy and bring some commercial life back to neighbouring towns that have few or no businesses in them. For example, this farmer gave an evocative description of the economic desolation of their neighboring town:

I think about that every time I drive through the tiny towns that my farms are next to. I mean the towns are just totally desolate and devastated compared to what they once used to be. [...] And now, the only place to buy food is the gas station - there are no businesses there anymore. There's nothing. Because over time all the money in Ag has gone out of the community and there's nothing left there. So everyone there just drives over to [nearby city] and works somewhere in the city, and then goes back, and there's literally no economy left there. And so, yeah, if I can produce or I can work with a farm that is selling to the local community or employing the local community - none of these farms around here are employing the local community - that would be amazing. If we can put in a little processing plant there. Process all the berry crops. That would just, even the little, tiny positive things for a couple farms would be the biggest business in the whole town. [1]

Thus, their concern for, and connection to, a larger story of the economic decline of the rural midwest was a theme that arose alongside their own livelihood goals (for more quotes, see Appendix C Table S1).

4.3.2 Motivations for perennial polyculture

We found that the participants typically had multifaceted motivations that were anchored in one or more relational values and often interwoven with each other. The most common recurring themes in motivations for establishing perennial polyculture enterprises were the following: 1) to experiment, innovate, and educate; 2) to restore or be in harmony with nature; 3) to create a healthy environment and grow healthy food 4) to have a successful, profitable business; 5) to grow food for their own households; 6) to establish markets and industries; 7) to provide land access for the next generation of farmers; and 8) to share new and interesting foods and tastes. Other motivations that were less frequent were to breed plants and to sequester carbon. Refer to Appendix C Table S2 for additional supporting quotes throughout the section.

Complex suites of motivations were presented as being interdependent: for example, the motivation to restore or be in harmony with nature was coupled with all the other motivations in various combinations. By mentioning them together so often, it seems that our participants' relationships to nature and the land anchored both explicitly nature-oriented motivations, and more anthropocentrically oriented motivations of growing food, and building profitable businesses. These motivations, though nominally separated, were not so much separate but consistently paired. For example, this farmer introduced their motivations as stemming from an understanding of the environmental problems caused by industrial agriculture, and then followed up with stating multifaceted goals as a group that included beauty, safety, and livelihood together with environment:

Our original purpose in getting into agriculture was to give out a system of agriculture that didn't cause all the environmental problems that modern industrial agriculture causes. And I realized, before I even graduated from college, that most of the problems that natural resource professionals deal with are a result of modern industrial agriculture. At least in Iowa and probably around the world also. We wanted a farm that was beautiful, it was safe to live on, it would be profitable, environmentally sound. [2]

Another common pairing of motivations involved the desire to set an example for others (i.e. experimentation, innovation, education). This motivation was frequently paired with livelihood motivations (i.e. building sustainable, profitable businesses); farmers wanted to be able to show that perennial polyculture enterprises are not only possible but financially viable and attractive. The same pairing applied to motivations and practices anchored in the farmer-land relationship, such as building soil or having a healthy environment on the farm. Thus, a variety of motivations like profitability or soil restoration became interwoven with relationships to community and larger structures through the motivation to experiment, innovate, educate, and be visible. This motivation was cited by all participants and was the most ubiquitous, manifesting in different emphases, for example on experimentation for biophysical systems like variety trials or in outreach and education. The common thread was that all participants were motivated to serve as a resource and example in some way to others. When asked about their goals for the perennial polyculture enterprise, one farmer demonstrated these pairings concisely in their answer:

Well, one is make money. Two is sequester carbon. And then three would be inspire others to do the same because numbers one and two work. [1]

An even larger scale of community and structural involvement was the motivation to create markets and industries. Several of the farmers we spoke to had lofty goals that transcended their own farm properties, involving the development of local processing capacity for perennial crops, the creation of marketing cooperatives or companies, and the overall development of agricultural industries in the US Midwest that gear towards perennial food products. This motivation came from the understanding of the scale of systems necessary to support perennial enterprises like their own. In emphasizing the motivations to experiment/innovate/educate and to create markets and industries, the farmers recognized their positions as early adopters, and often embraced the goals of creating knowledge and collectively organized structures for others to follow in their footsteps more easily. (More on this is below in the section on knowledge generation and sharing). For example, this farmer had formed a company owned with three other partners (two of whom were also farming) to market their products, and those of other farmers using similar practices, under a brand:

We want to create a brand, the [name of the company] brand. And we want to grow not just our farm, but other farmers that are using these types of practices and that can sell their products under our label. So at the same time that we're establishing a farm, we're also establishing a food company that can market these products. [...] we're working to build a farm production model. And building the food business. And in building that business foundation to have processing and marketing and distribution and all of those pieces in place to be able to train other people and grow that supply chain with the same system. [9]

Healthy food and health of people sometimes intersected with direct statements of motivation, but they often came up as motivations and values in a negative valence - i.e., by pointing out how unhealthy and hazardous the prevailing conventional practices of chemical and resource intensive farming are. In this way, participants frequently constructed a distinction between their way of farming and prevailing agricultural practices on the subjects of health even if it wasn't brought up as an explicit motivation or goal for their perennial polyculture enterprise.

I almost cried this year when they pulled in across the road and tore up the hay and put corn in. Right across the street from my house, conventional corn was going to get [sprayed]…. oh, I've already seen it get sprayed multiple times. [...] I saw the sprayer before they even planted ...multiple sprays. It's emotional. When you've had cancer twice and they tell you it's environmental, you tend to want to change your environment to where you live. [3]

Interestingly, the notion of feeding people did not appear many times in a straightforward form as a motivation (though it did a few times). Farmers were more apt to state motivations of introducing people to interesting tastes, of growing food that has high quality and is healthy, and of supplying their own household's food needs than of providing people's staple foods. The notion of production efficiency appeared more often in a financial context than in the context of the amount or yield of food produced. Thus while agri-food businesses, academics, and some farmers often speak about "feeding the world" (Yoshida et al. 2017) this group of farmers did not. Their motivations often involved production, but this goal was seen through the lens of livelihoods, and providing healthy, good quality, nutrient-dense food for people rather than amount of food.

... my personal main objective is to create a better lifestyle for the public in general. My motto is, you know, get your wealth or health from the farm, not the pharmacy. So that's why we're really concentrating on perennial crops because you have the nutritional value there. Field crops produce a lot of caloric input, but we're concerned about health and well-being [6]

4.3.3 Local knowledge about perennial polyculture management

The farmers in this study used a variety of different management practices for weed control, pest control, fertilization, and harvest. The particulars of these practices related more to the species of crop and to the type and intensity of inputs farmers were interested in using (for example if they were organic or not). Despite this diversity of approaches, there were some aspects of management and design that many participants discussed as important. These common features of perennial polyculture management are placed in the context of adaptive management within complex adaptive systems in Figure 4.4. Refer to Appendix C Table S3 throughout for additional supporting quotes on each section.

4.3.3.1 Designing for diversity: perennial interplanting and livestock integration.

Fundamentally, all the farms established the diversity of their system through some form of interplanted woody perennials with continuous groundcover between plants and rows (that is, no bare soil). The interplanting strategies themselves varied: some farmers interplanted different perennial species within the same row, while some kept the same species within a row and added diversity by alternating rows of different crops. Two farms planted in clumps or guilds. Some harvested hay from alleys, while others mowed or grazed livestock in them, usually using rotational-grazing or mob-mowing techniques (i.e., frequently moving livestock in enclosed areas, or mowing small areas at a time to allow herbaceous ground cover to fully regenerate before being mowed or grazed again). Overall, the diversity of plants and animals in the system was seen as a fundamental and important aspect of farming to many of the participants, and they achieved this diversity in a variety of ways. In the following quote, a farmer describes the interplanting design on their farm:

The way that we've outlined the farm is elderberry, hazelnut, hardwood, hazelnut, elderberry. And there's 15 foot spacing between the elderberries and that first set of hazelnuts and then there's 10 feet between where we put hardwoods. So right there, that's our polyculture. That's the footprint that we've modeled our farm after. And it's really based on what grew here indigenously or natively. And we believe that it'll create this forested canopy. It'll mimic a forested canopy even though it's in rows. Really mimic that umbrella having the hardwoods above the lower shrub-like species. [9]

A unique aspect of interplanting mentioned in this quote, and by many of the other farmers, was designing the system by thinking about multiple layers/strata of vegetation, whereby canopy trees, shade-tolerant shrubs, and understory vegetation all occupy niches in the three dimensional structure of the farm. This contrasts to simplified “orchard-style” perennial plantings where there is one type of tree and bare ground. Another unique aspect of the design of these systems that was mentioned by several participants was the intentional mimicry of native ecology and native species with perennial crop species which reproduce some aspects of natural ecology while producing food. While this mimicry doesn't necessarily involve native plants (though it can), the intention of the design is that ecological niches are filled and that interactions can be activated. Multi-strata planting and mimicry of native ecology are two aspects of design that are characteristic of design principles from the permaculture movement, and they informed the choice of species and interplanting strategies for several farmers.

In addition to the interplanting of different perennial crops, the integration of these crops with livestock was seen as fundamental to many of the farmers. Six of the farms had livestock integrated into the perennials at least for a part of the year, and integration of livestock was mentioned as the most common practice that the farmers wanted to adopt, or adopt more of (five farms). The integration of livestock was described as a benefit for cash flow through the sale of meat, and also for providing pest control and nutrient cycling for improved fertility of the perennials, as in this example:

I think it [having animals in the orchard] is part of how we envision our orchard management proceeding. We want to use the animals to biological benefit in our orchard. So, for weed control, or for pest control, and for fertility. Like I think there's a lot of benefit that they bring. We're not necessarily managing them to optimal effect this year, but I think even what we're doing right now, which is not, which is far from optimal, is still beneficial. [11]

This farmer is referring to the fact that animals can be crucial for weed-control (replacing mowing of grass), for soil-building (due to deposits of urine and feces), as well as for pest control (by eating insects and eating fallen/diseased fruit), enabling farming systems that are less reliant on greenhouse gas-intensive external inputs and harmful chemicals. Livestock was sometimes allowed to range throughout a field, but they were more commonly managed in a rotational-grazing approach that kept them within portable fencing and moved them to different locations frequently. Since livestock must be removed from an area six weeks before it is harvested (and can be returned after), two of the farmers we spoke to had planned the timing of maturation for their numerous apple varieties in a sequential wave across their field so that animals could be rotated through each section sequentially, moving out and onto the next section six weeks before harvest. After harvest, the same rotation could repeat with the animals cleaning up fallen and diseased fruit. This integration of plant and animal considerations from the design stage to simplify the work needed for rotational grazing among tree crops was a notable innovation.

4.3.3.2 Timing over short and long term

Management involving timing in perennial polycultures came up often in two distinct contexts: sequencing within seasons, and succession over years. Sequencing within seasons involved timing of management and harvest of different crops within a given year. Unlike conventional producers, who have one harvest per season, our respondents reported harvest season taking place in waves throughout the summer and fall. For example, this farmer described the sequence of their harvests:

Observing the farmers around here who haven't begun harvesting yet, their corn or soybeans, although they've gotten wheat and they're taking in oats, we're sort of harvesting all summer, as different plants that we have are ripe. And we expected that. We planned for that. So, that's like *monitoring what's ready and getting it picked. [...] So far, we're, it's pretty much when one thing is done, the next is coming. I think we finished the black currants today and the next thing will be blackberries and boy they're coming. They're growing on the vines. [6]*

The second context was over the longer term involving the timing of a successionally appropriate range of management practices as perennial systems mature. For one farmer, that meant growing annual produce in the alleys of their trees in the early years which was replaced with hay or grazing as the trees matured. For another farmer, more intensive ground cover management through cover cropping and mulching in the earlier years gave way to less need for weed management and more of a focus on pruning and grafting in later years:

...the first three years in orchard establishment, if you're growing perennials, it's almost more like seeding nitrogen-fixing annuals, or things like that, that are things that are really going to help support your soil [...] that actually helps support plant establishment. And then you can kind of, after your two or three year design really starts to take shape, it's a lot more around shifting managements from intensive ground-cover and like planting, to more like grafting, or in winter, dormancy months we're pruning, we're collecting scion wood, we're taking cuttings, and we're kind of like at a place where we're able to grow out a nursery or do our own plant replacement and mix things up. [...] I do want to put a plug in for sequencing. I think it's a really important thing. [...] because what I've been learning is that now, like I'm intervening and interacting with the orchard in a different way because it's at a different level or stage of maturity. [8]

The understanding of perennial management as a succession of practices that change over the years was expressed by several participants.

4.3.3.3 Intentional lack of management

Another distinctive aspect of management that surfaced was intentional lack of management, or the idea that things can be left alone on purpose. This idea of purposeful neglect was not prompted, and did not come up with all the participants, but it is unique in that it contrasts strongly with literature on farmers who have a strong ethic of active stewardship and a neat and tidy aesthetic which ties into their identities (Chapman et al. 2019). In this way, many of the farmers in this study embodied an alternative to prevalent social norms of what it means to be a "good" farmer, and disregarded the stigma associated with a lack of conformity to them (Burton 2004; Lähdesmäki et al 2019). The concept of leaving things alone appeared in several contexts: 1) to do research into resilience of plants to minimal management either to test if plants could be locally adapted or for breeding purposes 2) to minimize labour or actively assess the costs and benefits of labour for a practice. Both of these contexts reflect the belief of the farmers that to some extent (and at least at some point in maturity), perennial systems should be resilient enough to take care of themselves while maintaining an acceptable level of function. For example, this farmer did not see the necessity of weeding their trees at the current stage in their maturity:

And quite honestly, weeding the trees is one of the most useless expenditures of time I can imagine. Because they're all old enough to hold their own against the weeds that are there right now, I think. Because they had been heavily mulched. As long as we can keep the hay down and *the trees can get sunshine, as long as we get enough rain, they'll get the two out of three things they need. [4]*

In this way, the value of stewardship and care for farmland that farmers in our study expressed was nuanced; rather than implying maximal management at all times, it embodied judicious withholding of active management as well.

4.3.3.4 Trade-offs arising from management complexity

Trying to grow multiple crops and attend to multiple ecosystem services yields trade-offs, because not all things can be optimized simultaneously. The complexity of interplanting and livestock integration within polyculture systems was linked by some farmers with challenges or trade-offs with other management (including pest control, fertilization, and harvest). For example, one farmer discussed needing to compromise on the timing of fertilizations because the chestnuts and currants in the row would ideally be fertilized at different times. Some of the farmers started with more interplanted species within rows and have subsequently simplified rows to one species so that they could make tractor/management passes that are easier, while maintaining overall complexity from row to row or area to area in the farm. For example, this farmer described the problem with combining within-row interplanting and mechanized harvest:

The other thing we did in the past is that we put, and we still have those, oaks and sugar maples on the same row interplanted with the hazelnuts. And we don't want to be doing that because we want to be able to mechanize all of the hazelnut harvesting. [...] So, in other farms that we planted after we planted this one we have a row of hazelnuts, a row of elderberries. And then in *between both of those rows we have a row of interplanted trees. So, the tree row is definitely diverse but not the row of hazelnuts or the row of elderberries. Because otherwise, you've locked yourself into manually having to do too much stuff. And that's not good. [10]*

As this farmer notes, labour was a key driver behind trade-offs in interplanting complexity, particularly around harvesting. Hand-harvest labour was time-consuming for the farmer, but they could not necessarily afford to hire labour either; thus, several farmers discussed making harvest more efficient by simplifying rows either for machine harvest or more streamlined hand harvest. The other prominent tradeoff in complexity involved livestock integration: because of US food safety policy that regulates temporal separation between the presence of animals and fruit harvest, the interplanting of perennials that are harvested at different times can make rotational grazing in the understory complicated. In addition, since certain types of livestock can damage maturing fruit and young trees, additional planning is required both in choice of species and in timing of rotational grazing. One farmer expressed this difficulty in relation to rotating their pigs around interplanted berries and pears, pointing out that if s/he was only doing woody polyculture without animals, it would be simpler, but animals were important for pest and disease control:

And here, it was very hard to move them [the pigs] around because we have berries and pears because we have early and late season stuff. [...] It's hard to do, I feel like we could do a mix of just woody perennial things and then just not have animals. There are some things that I'd like to try to do... maybe if I wasn't thinking about getting animals in there. I feel like eventually, once the trees are fully grown, it's going to be easier to integrate animals in there. I kind of, don't want to do it when they're young because they can do a lot of damage. But I feel like it's *potentially eliminating some tractor use and doing more to help with pest and disease pressure, rather than just spraying, you know? [11]*

The alternative to simplification and streamlining was to prioritize adequate labour and limit the scale of operation. Some farmers intended to maintain interplanting within rows or within clumps, but this was mostly the case for farms whose perennial polyculture enterprises were a) designed for hand harvest or smaller in scale or b) not integrating animal grazing.

4.3.3.5 Holistic and adaptive approaches to management

Throughout their discussions of management, the breadth of the knowledge needed and systems thinking involved in perennial polycultures were themes that emerged from the conversations. Many of the farmers described aspects of management as inherently bound up together. Others emphasized that they need to think in systems and have a large breadth of knowledge to master the different aspects of management in their enterprises. The interacting aspects of management, in many cases over the long term, are consistent with what one might expect when managing complex adaptive systems that contain many components interacting on various spatial and temporal scales (Blesh and Wolf 2014; Chapman et al. 2017; Kremen et al. 2012). Indeed, many of the management solutions the farmers described can be understood as examples of adaptive management (Figure 4.4).

For example one farmer offered an explanation of how the interdependent management of their farm keeps the system going and created a level of complexity that s/he contrasted with the simplicity of a corn field:

Certainly, I mean if the farm ecosystem is working properly and the pollinators are doing their job, there are not weed issues because the niches are occupied with the plants that I want them to be occupied with. And either they're being managed appropriately if there's chickens in there reducing the disease pressure. If that's working then the whole system works better and more money will be made. And I'll be less stressed. [...] You're just fundamentally, you have to acknowledge and work with the system and make sure the system is healthy otherwise it will fall apart because it is more complex. Whereas if you're working over in a corn monoculture, it's so just devoid of complexity, so devoid of life that not many things go wrong. Until the catastrophic thing goes wrong and like everything dies from a new bug that nothing is resistant to it. But on a day-to-day level it's so much simpler. [1]

In another interesting exchange, when I was attempting to discern trade-offs in management intensity and finances, one participant admonished me for "monocrop thinking", emphasizing that they had a breadth of management priorities and goals where no one thing takes precedence over another:

Let's just take our language that we've been using here. For one, I've stopped every once in a while saying well that's monocrop language and that's not how I'm thinking. So it's a different way of thinking here. What would it take for you to all of a sudden start to examine how you approach all these situations? Say whoa, this is total conditioning based on monocrop thinking. That this is not the right question. [7]

Despite the undeniable existence of certain trade-offs between labour/management intensity and yield on their farm (this farmer did not always fully harvest their crops), this admonishment emphasized the farmer's reluctance to rhetorically choose one thing over another - as s/he reiterated, "that's not how I'm thinking". However, this farmer also had an established consulting practice and a more experimental mindset; in this way their business model allowed them to be less concerned about optimizing their land for production, even as they worked towards larger systems (through education and collective organizing) that would ultimately facilitate increased perennial production.

An aspect of adaptive management that came up many times was the role of observation of the land. Many of the farmers explained that they liked to spend time observing, and that decisions they had made resulted from careful observation, for example, the slope and soil of land dictating the design of contours and selection of appropriate species and machinery. The act of observation thus seemed to constitute an important aspect of their relationship to the land they manage. For example, this farmer explained how they had formed their enterprises after adapting to the conditions they has observed on the land, not by coming in with a definitive plan ahead of time:

I have enterprises that I've created after observing what's best on the land here. [...] I'm not coming in with a vision that I'm wedded to that has to happen on this land, no matter what, I guess is what I'm saying. So, I really want to learn from what the landscape is teaching me, which is, you can't really have tractors here. You know, you can have them for mowing or you *know, doing some yard work or something, but it's not going to work for agriculture, for tillage or weed management. [13]*

Further to observation, the active experimentation and learning that the farmers engaged in are also hallmarks of adaptive management strategies. When farmers were asked about practices they had discontinued, they happily shared stories about various failures involving types of trees, ineffective tree-shelters, bad fencing, unhelpful landscaping fabric, destructive goats, interplanted herbs and vegetables that got in the way, and other ‘wasted’ efforts. These trials and errors (some of which were intentional and some not) informed their current practices. For example, this farmer explicitly set out to experiment with fruit varieties in their region:

But mainly, I think the first three years in the orchards in establishment, we did it more as an experiment, because we did get some grant funding to test, like does this combination of food forest work, or like plants in a food forest model work? And you know, we're building on the continuum, right? And there's been other growers we have chatted with who have been planting a lot of things like quince, aronia, red, white, and black currents, elderberry, serviceberry, seaberry, gooseberries and they were, kind of like, the top eight. So, we were like, "Well, let's test them here." [8]

Here, the farmer acknowledges that they are building on a continuum of knowledge that was received from other growers in the region. In this way, the motivation to experiment, innovate and educate served to expand the scale and impact of farmers’ adaptive management beyond their farm gate.

Features of complex adaptive systems	Features of Perennial polycultures	Management challenges arising from complexity	Adaptive management solutions
• Multi-causality – multiple components and interacting parts	• Designing for diversity of multi-strata plants and livestock that interact with each other in the same space	• Complexity limits specialization, mechanization and streamlining • Timing of management is complicated	• Diversity achieved through interplanting in largely linear designs; simplification within rows with diversity across rows; acceptable compromises and/or planning compatibility of timing and inputs; supporting complexity with adequate labour
• Regime shifts - systems change in fits and spurts	• Establishing trees creates non-linear ecological changes	• Return of biodiversity to the land can cause plant damage as well as benefit	• Cycles of observation, learning and intervention • Diverse products and incomes
• Teleconnections – "transporting" impacts and benefits across time and space through larger scale processes	• Historical policies, land uses, and ecologies create conditions for perennial regeneration	• Legacy effects of previous land degradation affect soil condition and productivity	• Choice of locally adapted species for legacy conditions • Mimicry of native ecologies • Permanent ground and tree cover for soil building, water retention and erosion mitigation
• Multi-scalarity – drivers and impacts at multiple levels of organization interact	• Long-lived crops transport energy through space and time accumulating biomass, cycling nutrients from deep roots to surface.	• Wide breadth of knowledge is needed • Long maturation period of perennials poses challenges for cashflow	• Cycles of learning from one's own land and other farmers • Long-term and systems thinking • Collective organizing with other farmers
• Cumulative benefits and impacts – the combined total effect exceeds individual components	• Benefits of multiple vegetation layers and livestock together is greater than the sum of the parts (overyielding)	• Cumulative benefits can be difficult to understand, fund or monetize, and take a long time to appear	• Planning to integrate shorter and longer term enterprises at a high level of organization • Purposeful neglect at some points in maturity

Figure 4.4. Perennial polycultures through a complex adaptive systems lens. Five features of complex adaptive systems adapted from Chapman et al. 2017.

4.1.4 Community relationships

When prompted to speak about communities they felt part of, the farmers in the study usually talked first about communities of like-minded people and farmers (see Appendix C Table S4 for quotes for this section). Organizations of farmers, including the Savanna Institute, Practical Farmers of Iowa, Women Food and Ag Network, Northern Nut Growers, Organic Valley, Main Street Project, and the Sustainable Iowa Land Trust were mentioned as important dimensions of

their community, where people could meet and share information. Networks of women farmers were mentioned a number of times as an important community for female respondents.
Five people in particular (who were part of the study) were mentioned by other participants in the study as mentors, teachers, or inspiration for their enterprises, and many of the farmers that participated in the study knew each other either personally or by reputation. Many of the farmers, including those who were mentioned by others in the study, saw themselves as teachers and spoke about ways that they have mentored and consulted with others. At the same time, many participants (sometimes including the same people) also talked about being learners, and having elders and mentors. From these findings, the community of perennial farmers in the upper Midwest seems to be well connected to each other. This understanding may be in part an artifact of our methods, which relied on the farmer networks of the Savanna Institute to find study participants.

In response to prompts inviting participants to reflect on whether they thought the wellbeing of their communities were connected to the land in any way, respondents cited many pathways operating (such as flooding, availability of clean water, rural livelihoods, healthy food, and toxic chemicals). Some participants also said that they did not think local communities or neighbours saw or understood these connections. This perception of distinctness from the surrounding or general community evoked a sense of ambivalence. Sometimes a sense of isolation or alienation was coupled with a desire for greater connection with community. For example, one farmer expressed the sentiment that others look at them like they’re crazy for being organic in Iowa, and that they sometimes felt that it was just them and their spouse against the world. This farmer, who was an active member of at least two farmer organizations, was moved to emotion in our interview when they related a story about their conventional neighbour sharing appreciation for what the farmer was doing on their land.

He said to me, I just want you to know that I really admire what you guys are doing. That was nice to hear…. I'm sorry I'm getting emotional, but I feel like people think that we're just like freaky weirdos. So having that validation from my neighbor was nice. [3]

In addition to being meaningful, the neighbor's recognition and acknowledgement of their practices were evidently unusual. Another farmer shared that when they say that they are farmers to people in their area, people often assume that they have a dairy farm. This farmer and their spouse felt that their type of farming wasn't visible to most of the local community. Another participant, who does quite a lot of teaching and speaking in the perennial agriculture community (and was one of the people mentioned by other study participants as a mentor), mentioned that people in the closeby village don't even know about their farm. These farmers' experiences of being connected to like-minded farmers, but feeling invisible, misunderstood, or yearning for more connection in their own neighborhoods seemed to indicate that communities of practice rather than immediate locality were the primary spheres of communication and influence these farmers were creating and accessing.

Nonetheless, many participants seemed to be seeking local connections and actively building community on their farms by welcoming people to their land through educational activities with children, u-pick customers, and field days. For example, two of the farms regularly hosted school groups, and at least three had hosted field days in the previous year. One participant (whose perennials were young and not yet yielding, and whose other farm enterprises were entirely wholesale), said that s/he heard that if people would come to their farm to buy berries, that they might start asking about buying half a pig, or some produce. S/he said that s/he would be excited to do direct marketing and build relationships with people in the area that care about food. Thus, these activities, or the hope for future on-farm activities seemed to partially fulfill or hold a promise of greater connection with a local or wider community.

4.1.5 Challenges, barriers, and policy priorities

Of the 14 perennial polyculture enterprises in the study, 5 were planning for expansion, with an additional 3 planning for intensification by infilling and adding livestock within the perennials (without expanding their physical footprint). Thus, a majority of the farmers in the study had plans to expand or intensify their perennial enterprises (Table 4.3).

Table 4.3. Intentions for expansion.

Planning to expand perennial enterprise	# farms (total 14)
yes	5
no	4
maybe	2
infill/ intensify	3

When asked about barriers they faced to expansion (or success), the participants frequently made a key distinction between management challenges and systemic or economic challenges. For biophysical management challenges (for example, finding the right interplanting scheme, timing of grazing, weed control issues), the farmers were able to take on the issues by consulting with others, and using trial and error over the seasons, rarely expressing serious regret over mistakes they had made or discontinued management. They were usually curious about understanding and fine tuning the ecological dynamics and management rhythms of their farms, and in many cases, were actively coming from an experimental mindset. Thus, management challenges involving the biophysical aspects of running their perennial enterprises, while sometimes leading to minor regrets (such as about varieties, animals, timing, or fencing), were largely addressed through adaptive management solutions (Figure 4.4), and not perceived as barriers.

These issues were distinct from economic and systemic challenges that were more often cited by participants as barriers for success or expansion (see quotes for this section in Appendix C Table S5). These included lack of access to financing, lack of insurance for perennial crops, and the absence of regional marketing and processing capacity for perennial crops, as this participant explained:

We can establish 100 acres of some perennial crop, but it's not going to mature and produce a full yield for, you know, 5 to 7 to 10 years. And there's really not financing systems that are even set up to think about that. And there are some starting to develop out there in the world. […] But you can't go to a conventional bank and tell them you're going to plant hazelnuts and say we'll have a yield in six years. And we can't pay that loan back for six years. You just can't do that in a conventional financing system [9].

Access to labour was also frequently mentioned as a barrier, in one of two ways: 1) too little time to get the work done within the farm family, implying lack of money to hire labour, or 2) too few workers with the right skills to manage perennial systems. The following is an example of the latter, from one farmer who was actively trying to scale up their enterprises:

But I also think that the community is small, and it desperately needs to get bigger. I mean I think that's really the biggest problem. Investors and landowners are not the biggest bottleneck. It's finding farmers or people and skilled employees to do the work, to do the farming. It's difficult. And SI [Savanna Institute] is going to try to start an apprenticeship program next year and start trying to turn that tide. But it's hard. We just desperately need more farmers. [1]

Farmers often observed that various systems (government, finance, marketing) were in place to support conventional crops, but that these didn't fit perennial crops well. Thus, the dominance of the conventional crops, and the resulting conventional economic structures, were seen as a barrier for many farmers, especially those who were not actively involved in up-scaling schemes for production, regional marketing, or processing. The availability or crop insurance for conventional crops in particular was seen by many of the farmers as a key subsidy that created an unfair playing field, and rewarded bad actors in the system because their practices carried no risk to themselves. For example, two farmers told stories of neighbours or tenant farmers who planted annual crops in poor conditions seemingly on purpose to collect insurance when the harvests were subsequently lost. In contrast, the prevailing perception seemed to be that they had to mitigate the risks of taking on a long-term investment in perennial crops on their own.

Four of the farmers in the study were enrolled or had been enrolled in a government program that assisted in some aspect of their perennial polyculture: these were all through the US Department of Agriculture (USDA) or its subsidiaries: a Natural Resource Conservation Service (NRCS) contract was used for a buffer around the perennial field that was itself planted with edible species; and NRCS Environmental Quality Incentives Program (EQIP) grant was used for fencing; and two Sustainable Agriculture Research and Innovation (SARE) grants were used for establishment costs. Seven farms (including the same four) used additional programs that did not directly relate to the perennial enterprises, chiefly Conservation Reserve Program (CRP) contracts or permanent easements for prairie or wetland habitat; one farm also received an NRCS payment for rotational grazing and cost-share on organic certification from the USDA.

A synthesis of the ways these and other programs worked or did not work with perennial enterprises is presented in Table 4.4. This synthesis shows how the payments for ecosystem services programs available to participants were designed for taking land out of production, prohibiting harvest. For example, one farmer had entered into an NRCS contract to receive a payment for a buffer that included three edible species, but would not be able to harvest them until the end of the 10 year contract - a work-around that was feasible for maturing trees. However, a main field consisting of a woody polyculture that would need to be harvested within the first decade (if it includes faster maturing berries and shrubs for example) would be ineligible for an NRCS contract, even if it is providing similar services that the same woody mixture would if planted as a hedgerow and not harvested. In many cases the composition of woody species that farmers were growing could have met government requirements for set-aside payments based on habitat quality, but they were intended for harvest.

Thus, the dichotomy of set-aside and productive land did not work well with the diverse food-producing perennial systems of our participants. Several participants suggested that instead of contracts that preclude harvest (Table 4.4), contracts could accommodate harvest, provided that the same ecological services were being provided. This would require tailoring contracts to the services being provided at a particular site (Chan et al. 2017; Chapman et al. 2019), an approach commonly used in European countries. Such an approach might appeal to the farmers in this study, who like many farmers, often complained about working to "someone else's system" (Chan et al. 2017; Chapman et al. 2019), and also serve as a practical way of assessing the conservation value of a spectrum of management practices instead of attempting to rigidly categorize them.

Table 4.4. Existing USDA programs with application to perennial enterprises. Programs include those mentioned by participants, including some that were not used, and are cross-referenced with information from program guidelines.

Program	**Program goals/function**	**How it can be used with tree crops/ perennial polycultures**	**Challenges/ mismatch**
Sustainable Agriculture Research and Innovation (SARE)	Farmer-led experimentation, innovation	Various innovative intercropping and animal integration design can be supported	Supports small-scale innovation, but not up-scaling
Natural Resource Conservation Service (NRCS) - Conservation Reserve Program (CRP)	Ten-fifteen year contracts to remove land from agricultural production and implement conservation practices (riparian, pollinator, wind buffers; hardwood plantings, etc)	Contracts for 10 or 15 years provide farmers an annual payment while plants are young, before full bearing	No commercial harvest allowed during contract
Natural Resource Conservation Service (NRCS) easement programs	Permanent easements on wetland, prairie etc	Incompatible with producing perennial crops	Land is taken out of production permanently, no commercial harvest allowed
Natural Resource Conservation Service (NRCS) - Environmental Quality Incentives Program (EQIP)	Cost-share for infrastructure and plants deemed environmentally beneficial	Deer fencing around orchard; elderberry canes for new planting	Cost-share for fencing must follow proven losses due to pest damage
US Department of Agriculture (USDA) - Organic certification	Cost-share for organic certification	For organic tree crops/ perennial polycultures	Kickback for organic producers, but does nothing for non-organic farmers with many of the same perennial & diversified practices

Noninsured Crop Disaster Assistance Program (NAP)	Provides financial assistance to producers of non-insurable crops when low yields, loss of inventory, or prevented planting occur due to natural disasters	Can be applied to food producing perennial crops	Calculation of premiums may be complicated by having multiple crops on each acre in a polyculture.
Tree Assistance Program (TAP)	Provides financial assistance to replant or rehabilitate eligible trees, bushes and vines damaged by natural disasters.	Can be applied to the loss of food producing perennial crops from disasters	Only assists in replacing losses, not in establishing new plantings

Several farmers mentioned that they would like to see proactive policies that provide cost-share or investment upfront, instead of programs that mitigate damage, for example, needing to prove after the fact that you're sustaining deer damage to get cost-share for a fence. At the same time, a number of producers identified the lack of crop insurance for perennial crops as a need as well (they did not seem to be aware of the NAP program).

The study's respondents encompassed a range of political views: some of whom were enthusiastic about government policies, and some of whom were not. Nonetheless, most of them discussed ways that programs could be improved to better suit perennials, indicating that even farmers who were generally resistant to public interventions and expressed annoyance and impatience with program administration, recognized the positive role that government could play. However, most of the farmers prioritized the concept of a "level playing field" involving the removal of existing government programs above ideas for reforming programs that might benefit them. Indeed compared to the 60% of income of corn/soy farmers which came from the government on average between 1985 and 2006 (Duffy 2006), the farmers in this study were not heavily subsidized, and several that could have qualified for programs chose not to. Thus, while this group of farmers did not depend heavily on existing programs and had mostly funded their work entrepreneurially, they highlighted the role of the public sector in the larger scale barriers facing perennial enterprises compared to conventional agriculture.

4.1.6 Cross-cutting themes: values of perennial polyculture farmers

Drawing out statements of value from across the topics of motivations, livelihoods, management practices, community relationships, and challenges, a number of cross-cutting themes emerged. We use an explicitly relational approach to classify these eight themes (hereafter "relational values") based on two relationships (Figure 4.5). We chose this framing because for our participants, material & non-material concerns, personal and community-oriented aspirations, and natural & cultivated landscapes, were often bound together. These "messy" distinctions make existing classifications of instrumental vs. intrinsic values, intrinsic vs extrinsic, and self vs other-oriented values awkward to use (Bennet et al. 2018, Meijer et al. 2015). We therefore draw on Chapman et al. (2019) to anchor the value statements that were expressed to component-relationships-component "triads" (Knippenberg et al. 2018) rather than individual system components (yellow arrows in Figure 4.5), moving to a more process-oriented language than a thing-oriented language (Knippenberg et al. 2018). In this way, we attempt to embrace the shared and overlapping aspects of various values, making no attempt to create rigid definitions and instead highlighting overlap and connections. The constructs of value are useful in that they synthesize distinct ways that people expressed what was important to them, but, in part because our conversations centred chiefly around the farmers' own land, the physical scope they applied to and their objects understandably overlapped substantially. As an example, we further connected these values with one of the topic areas covered in this study, linking the farmers' concrete motivations for perennial polyculture farming (see section above) to one or more values (dark orange in Figure 4.5), allowing for as much overlap as necessary. Refer to Appendix C Table S6 for supporting quotes throughout the section.

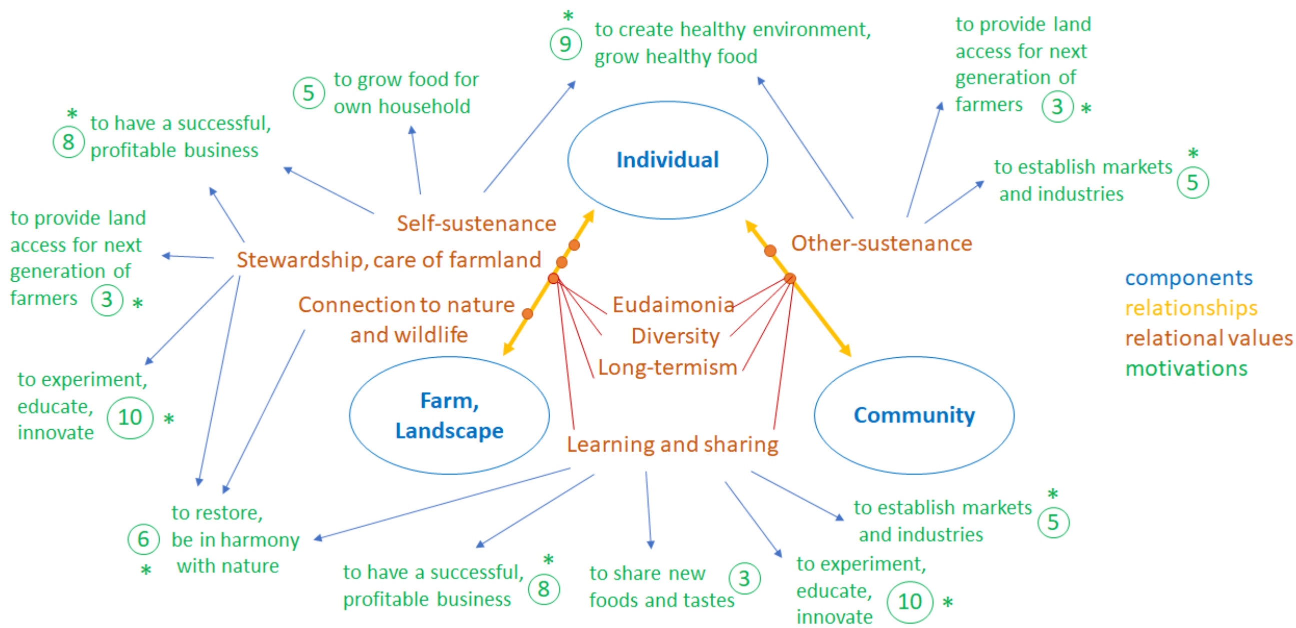


Figure 4.5. Illustration of a relational approach to values and motivations. Numbers indicate the relative proportion of participants that mentioned the motivation (on a 10 point scale where 10 is all participants). Asterisks (*) indicate motivations linked to more than one relational value. System components drawn from Chapman et al. (2019).

The relationship between the farmers and their land was a multifaceted one, that involved several aspects of value: the value of self-sustenance, the stewardship and care of farmland, and the connection to nature and wildlife. *Self-sustenance* refers to farmers' desire to reap economic, nutritional, medicinal, and spiritual sustenance from their land, and was often embodied in the appreciation and love of the abundant and wonderful food that they had access to. The ability to eat from their own land went far beyond just satisfying nutritional needs; in several cases the farmers said that they could "eat like a king" on a small income and wouldn't be able to afford to buy food of the same quality, or that eating from their land constituted a sense of physical oneness with the land, gave them energy, or made them feel proud, as in this example where I was served paw-paw ice cream for dessert:

When we have food on our plates that came from our farm, I feel more energized and more provided for than when it's a matter of growing things and getting paid for it, and then I go buy the food. And we always take a lot of pride with all the things that we put on the table, like this evening, that come from our farm. [2]

Stewardship and care of farmland refers to the farmers' commitment to active care and improvement of domestic, food-producing land, and was often embodied in the ways they spoke about tending to animals, plants, and soil, as well as the hope of improving and sustaining the farm for the future. *Connection to nature and wildlife* refers to the farmers' connection to spontaneous/un-tended nature both on their land and beyond it, for example the enjoyment of the biodiversity of insects, or the spiritual connection to a clean stream; it does not require active care.

These values, all anchored in a relationship to land, intersected in many ways. For example, many of the farmers brought up how important soil health was to them (or how much of a threat soil erosion was) in sustaining agricultural production both on their own farms and in general, embodying the value of stewardship and care of farmland, and of self-sustenance. This farmer directly identifies the health of their soil the with the ability to grow food and the economic potential of their land:

I think our ability to use our land to grow food, to sell, you know, to grow our business is really based on the health of the land. And I think about, erosion is a really good example. Erosion is something that, with the landscape around here, that we see on a lot of farms. And we basically don't see on our farm. A little bit, on the side of our driveway. But I think that erosion washes away topsoil. It washes away, you know, organic matter and everything that you've spent time building. And it washes away like the economic potential of your land too, if you're thinking about it that way. [11]

Several farmers brought up the abundance of birds and insects they see on their land, and connected their enjoyment and beauty with the health of their farms, embodying both the value of stewardship and care for farmland and of connection to nature and wildlife. For example, this farmer spoke about providing habitat for pollinating species and migratory bird species:

Migratory patterns of birds and insects, and butterflies, and a lot of that stuff that we are seeing kind of fluctuate in population - I think that when you have a healthy system you're creating habitat for them to rest and recoup before they get back on the road. And from what I've learned from our partners with the [Department of Natural Resources] and the fly over initiative. I'm really, really excited to contribute to pollinator species and migratory birds as they move. Like that's I think a really big one for me, is like allowing niches to be filled by the appropriate actor in the environmental world. You know, like having no real chemical solutions for mosquitos here is okay because of all of the birds that we've attracted and provided safe space for. That's my favorite I think. [12]

While this farmer clearly appreciated the pollination and mosquito-control services being provided on their farm by the insects and migratory birds, s/he was also clearly excited about being able to provide habitat for them on their journeys as well. Thus, the study participants often blurred the line between their commitment to care and stewardship of farmland for the purposes of ongoing production, and their connection with nature and wildlife for their own sake; their relationship with land comprised both of these values.

The relationship between farmers and other people anchored the value of *Other-sustenance.* This refers to the farmers' desire to provide others with food, medicine, land, or other infrastructure. The farmers often saw themselves and their farms as sources of abundance and sustenance beyond their own families. While several had a homestead mentality of self-sustenance, all the farms were also oriented towards feeding and sustaining people on a larger, though mostly local, scale. For example, this farmer spoke about how important it was for them to share what they grow:

I get a lot of satisfaction from sharing what we grow. Without always asking for the money. My philosophy is if we have it, we should share it. Because ... it's been so good to us. The land, you get this deep appreciation and yes, you put in a lot of hard work. There's a lot of labor and all that blah, blah, blah. However, the benefits that you reap from that far exceed the effort that goes into it. And you know, it's just, I don't know. It's very rewarding. [6]

The values of *learning and sharing*, *eudaimonia*, *diversity*, and *long-termism* related to both types of relationships, (farmers to land, and farmer to community); each is explained in more detail below. These four values were often found overlapping in the same passages with other values, and permeated many of the motivations, management practices, livelihood considerations, community relations, and challenges described. For example, several of the quotes that were used as examples for the values discussed above also contain within them the values of *diversity*, *eudaimonia*, and *learning and sharing*. For the sake of simplicity, we did not draw direct connections between all of these values and specific motivations for perennial enterprises in Figure 4.5 (though we did for *learning and sharing* as an example).

Learning and sharing refers to the farmers' active embrace of knowledge production and sharing, and it relates directly to the motivation (see above) of experimentation/innovation/education. A strong ethic of investigation and innovation ran through the interviews, along with the farmers' propensity to think in systems about the ecology and management of their land. The farmers often expressed that they enjoyed how their way of farming was intellectually interesting, and involved constant learning from what they observed and experimented with on their land, like in this example, where the farmer contrasts the type of curiosity they exercise with the questions that might face a cattle producer:

I think one of things that I'm grateful for in this way of farming is we get to ask more creative questions than like what antibiotic I should give this cow that's standing in three feet of shit. Like, why does it keep getting sick? You know? [12]

Some emphasized the pioneering nature of this learning, and saw themselves as researchers in their own rite, which was expressed through their adaptive management practices and experimentation over the years. Many of the farmers saw themselves as teachers and leaders among different communities of farmers they were part of, where they were able to share their knowledge. Thus, learning and sharing was very important to this group of farmers, and related both to their relationship with land (where learning took place though trial and error and experimentation) and to community (where learning from and sharing with others took place). This value permeated many of their motivations for establishing perennial enterprises and appeared in their discussions of livelihoods, management, as well as community relations.

Eudaimonia and connection to identity refers to the ways that farmers expressed meaningfulness, fulfillment, flourishing, and notions of a good life, beyond the satisfaction of goals and material needs (Born et al. 2018). Many participants embraced their identity as a farmer or even as a perennial or regenerative type of farmer. The farmers often made normative claims about why they wanted to get into farming the first place, or what kind of farmer they wanted to be. They sometimes contrasted themselves to conventional prevailing practices, and identified with a community of like-minded farmers. In these ways, they seemed to desire and value the ability to identify as a particular type of farmer. In their reflections of their experiences farming, several farmers expressed notions of ‘a good life’ (eudaimonic values). For example, some expressed a deep sense of kinship, or even one-ness with their land, indicating a non-substitutable sense of identity with place. Others spoke of the hard work involved but that they felt a sense of rightness, calling, or belonging in doing it. Sometimes they expressed the idea that they couldn’t imagine not living this way or going back to a normal job, or that farming is how they felt most themselves. Some expressed a sense of spirituality and sacredness in their land or work, like in this example.

But all in all, farming teaches you how to be, it really does. You have to have a real strong self-awareness and a sort of keen observation of the land and what it's telling you and how to best intervene, so that's my view, or my view right now. [...] You know, it's taxing, the isolating part, it can be isolating. There's, yeah like, you're never really alone, but at the same time you're alone. It's sort of a weird thing, but anyway. I guess like, to me it's sacred. [8]

This farmer talks about how farming teaches him/her "how to be", and how to interact with the land through self-awareness, observation, and intervention (harkening to the adaptive management practices discussed above). Despite the taxation and isolation the farmer recalls, they end by saying that these experiences are sacred. These expressions show how the participants' satisfaction with the lives they have chosen was related to principles, virtues, or identities that are fulfilled and embodied in their way of life, rather than the simple satisfaction of goals or preferences (or an absence of hardship) (Gould et al. 2019; Kaltenborn et al 2017). *Diversity* appeared in a number of contexts. Farmers mentioned how they enjoyed the diversity of wild plants and animals that were on their land or that had recently started to appear there. In the context of farm design and management, the diversity of their interplantings, and even the breeds of animals they had chosen were the most fundamental aspect of the polyculture approach to farming (see section above, "designing for diversity"). In addition to wildlife and farm management, the diversity concept also applied to finances: farmers expressed that having a diversity of farm enterprises and a diversity of crops within their polyculture enterprises mitigated financial risk, and spread enterprises over time, as in this cases:

Like, resilient income streams that wouldn't all hinge on the success or failure of one or two things a season. I think it's…stuff can be pretty unpredictable. Especially, when you're not super experienced. And so, scaling up at the right time is important. Well for the success of each individual project, and for my quality of life, and for the quality of life of the animals that we bring onto the scene. You know we want it to happen when I know that there's enough time to make it all go correctly. [...] And that's one of things that I think is the most enjoyable about a diverse system. If you can pace it out like that. But, it's also one of the things that makes it the hardest. [12]

The embrace of a diversity of income streams resonates with the diverse income sources of permaculture farmers in the US (Ferguson and Lovell 2017). Beyond the diversity of income from farm enterprises, some of the farmers also enjoyed the balance of on- and off-farm work as an added aspect of diversity in income that they had come to embrace (though some did not embrace the necessity for off-farm work). Thus, the value for diversity permeated the farmers' biophysical management, their experiences with spontaneous nature on their land, and their approach to livelihood. The inherent system complexity of perennial polyculture farming necessarily involves a strategy of diversity rather than ultra-specialization, an approach that these farmers seemed to embrace and value across several topics.

Long-termism - An aspect of the interviews that was often value-laden was related to the life stages of farmers and how these are linked to the life stages and succession of their perennials. Because there is no starting over each season, the maturing of perennials happens alongside stages in the farmer's life. This parallel progression seemed to frame thinking about succession of business, land, and life stages of the farmer themselves. The long-termism implicit in perennial enterprises and in the stages of one's own life was an interesting value that emerged - farmers were thinking in decades, and their relationship with time was a deliberate one. For example, this farmer was in a transitional phase of their life where they were looking for a long-term tenant for their farm that would take the management load off of themselves, but would necessarily inherit the trees on the property and need to make decisions about them.

Well, I mean, that's the thing about perennials. You, kind of, end up inheriting what the last guy did. It's not like you just get to tear it all under and start over. Like with corn or beans, or squash, or watermelons. But, that said, I don't think we're going to leave it [decisions about thinning of trees] to us. [...] I think we get somebody who's got a long-term investment in it, like a really long-term lease, and let them figure it out. They can study up. They're going to be the ones doing the work. [4]

4.4 Discussion

4.4.1 Relational values and the good life for perennial farmers

The most common synthetic themes that emerged through the farmers' relationships to both land and community were the values of *learning and sharing, eudaimonia, diversity,* and *long-termism*. These values, alongside *self-sustenance, stewardship and care of farmland, connection* *to nature and wildlife, and other-sustenance* together paint a picture of a worldview where values and relationships exist in a pluralistic balance rather than being dominated by specific or "mastery" oriented relationships (de Groot et al 2011). The integrated nature of these relationships and values agrees with Yoshida et al. (2017)'s study of Midwestern farmers' relationships to nature where they found a strong overlap between 'master', 'participant', 'partner', 'steward' and 'user' relationship types, rather than a distinct separation. They also comport with a study of farmers who transitioned to sustainable farming practices in Canada which found that after the transition the values of the farmers shifted towards an emphasis on guardianship of human and environmental health, and the integrated 'organismal' nature of the farm (MacRae et al. 1990).

These pluralist notions of relationship (de Groot et al. 2011; Teel and Manfredo 2010) agree with our observation that values often have an instrumental component alongside a relational component where the relationship itself matters (i.e. isn't substitutable; Himes and Muraca 2018). For example, relational values like *self-sustenance* or *stewardship and care of farmland* influenced what farmers chose to bring to market in the first place, or determined the appropriateness of monetary transactions with their customers and partners. This observed coexistence of instrumental and relational values within agricultural context is consistent with Jones and Tobin (2018): in their review of the values of *reciprocity* and *redistribution* in sustainable agriculture, they found that these values coexisted with instrumental values rather than replaced them. In agricultural systems, the economic structures of markets and commerce where instrumental values are enacted are very important. The relational values discussed by Jones and Tobin (2018), as well as those discussed here, needn't be understood as dualistic with this reality. Rather, they create the context in which the instrumental components of value (like economic transactions) operate.

While the relational values expressed by farmers imply a generally positive valence, it's important to remember that not all values are necessarily fulfilled in practice, and moreover, that even good relationships and good lives still include hardship, challenging decisions, and endurance of harsh conditions, (for example see Kaltenborn et al. 2017 for a study of what a 'good life' looks like in a remote Norweigan fishing community). Indeed, some of the challenges encountered by this group of farmers, especially around plant varieties, tradeoffs in diversity of plants and animals, and management complexity, contributed rather than detracted from their sense of purpose and satisfaction, since meeting these challenges through adaptive management aligned with their motivation to experiment and innovate (as farmers have done since time immemorial; Saad 2002) and with their underlying value of learning and sharing knowledge. Though the same is true for some of the more entrepreneurially-minded farmers regarding economic challenges, most of the farmers saw these issues as barriers, not positive challenges that they were equipped to meet.

The idea that people's quality of life transcends economic considerations is gaining policy traction with instruments such as the sustainable development index, which incorporates both human development markers and planetary boundaries (Bravo 2014) and the "happiness index", a collection of wellbeing indicators which has been adopted by the governments of Bhutan and New Zealand to prioritize budgets in place of GDP (Samuel 2020). In a similar vein, the latest IPBES Global Assessment has named 'visions of a good life' as a leverage point, highlighting the ways in which good quality of life can be achieved through the quality of socially and environmentally mediated relationships rather than through the improvement of material conditions alone (Chan et al. 2019). These concepts all recognize that more relational conceptions of a good quality of life are a tool in achieving long-term sustainable outcomes as they provide an alternative to production and consumption as sole markers of wellbeing. The farmers in this study are an example of this possibility, as they constructed a personalized conception of a good life combining typically modest means with practices that richly rewarded them through the fulfillment of relational values.

4.4.2 Perennial polyculture, mainstream agricultural science, and farm-scale permaculture

The design and management knowledge implemented by the farmers in this study in many cases goes beyond practices established in mainstream agricultural science both in academia and in extension oriented resources. Academically, a large body of agroecological and agroforestry research has investigated the integration of perennials into food producing landscapes in various capacities (including perennial grasslands, woody linear design elements like buffers, and silvopasture or alley cropping involving timber trees) but little of it has studied diverse tree crop systems in the temperate North (with a few notable exceptions; see Brown 2012 and Martins et al. 2011). Independent research organizations including the Savanna Institute and Land Institute have begun to publish practical resources for growers. The dearth of ecological and agronomic information on non-tropical food-producing perennial polyculture systems has occasioned opinion pieces and reviews (Jose 2009; Wolz et al. 2017), experimental sites (Lovell et al. 2018) and on-farm research (Kreitzman et al. in prep), yet these are still few.

The development of practical guides for perennial polyculture growers is currently taking place chiefly in the non-academic and non-government sector with permaculture resources and pedagogy (see below). Permaculture guides have a wealth of information about woody polycultures, but tend to be evangelical and understate challenges and risks in establishing them (Ferguson and Lovell 2013). A search of Canadian and American extension guides found useful information about specific woody species, silvopasture, rotational grazing, alley cropping with timber trees, installation of buffers, and edible woody landscaping on a small scale. Much of this practical information is relevant to perennial polycultures, but the integration of food-producing woody perennial crops together, and/or together with animals involves additional design and management considerations around compatibility, timing, spacing, and so on. Thus, the horizon of diverse systems supported by mainstream extension remains confined to more simplified or smaller agroforestry systems, and has not yet extended to food-producing perennial polycultures (including animals) at scale.

In contrast to their general absence from scientific and institutional resources, the practices and experiences of this group of farmers relate strongly to the permaculture (a portmanteau of “permanent” and “agriculture”) movement through an embodiment of many of its 12 design principles. Permaculture, though it was founded by two Australian academics (Bill Mollison and David Holmgren) largely developed in isolation from science in the last four decades (Ferguson and Lovell 2013). Many of its tenets align with the findings of agroecology and are based on ecological principles, but permaculture’s distinctive approaches to perennial food systems, water management, and the spatial design of agroecosystems go beyond the scope of scientific literature (Ferguson and Lovell 2013). However, permaculture is beginning to receive more academic attention, and in an interesting review, its design principles were recently compared and integrated with available science (Krebs and Bach 2018). Permaculture has also been critiqued for appropriating indigenous knowledge and land use practices, thereby divorcing traditional ecological knowledge from its cultural context (Morel et al 2019). Indigenous management of oak savanna and tallgrass prairie ecosystems represents a point of connection between traditional ecological knowledge and contemporary perennial polyculture farms in the US Midwest, and these farming systems could be framed in a decolonization discourse, but except for two participants, the farmers in this study did not identify this as a source of knowledge or motivation.

While only 3 participants in our study mentioned permaculture explicitly, they all to some degree enacted some of the 12 permaculture design principles (Holmgren 2002) including the principles "observe and interact", "catch and store energy," "obtain a yield," "design from patterns to details," "integrate rather than segregate," "use and value diversity", and "creatively use and respond to change". For example the principle "catch and store energy" was embodied in the accumulation of energy in perennial biomass, and contoured planting and ditching designs that caught and soaked in water. The principle of "integrate rather than segregate" was embodied in perennial interplanting and animal integration within the same field. The principle of "obtain a yield" was embodied through the result-oriented practicality of needing to produce food and income. The principle of "designing from patterns to details" was embodied in the design process of farms that started from the pattern of native multi-strata vegetation, and then mimicked this with locally adapted and marketable species. The principle of "observe and interact" and "creatively use and respond to change" was embodied through the observation, experimentation and adaptive management processes that the farmers constantly engaged in. This is not a comprehensive list of the connections to permaculture principles, but serves to demonstrate the natural and close alignment between these practitioners and permaculture, even if they didn't identify as permaculturists. In general, both our farmers and the permaculture movement placed a heavy premium on perenniality and the long-term as well as process-oriented, integrative, and adaptive thinking.

In contrast to these aspects of design and practice that were strikingly similar, the scale and commercial aspirations of these farmers are perhaps distinct from the majority of permaculture farms and the general orientation of the permaculture movement. Although the principles of permaculture were not necessarily designed for homesteading and small-scale gardening, the permaculture movement has developed to emphasize these contexts and the purposes of self-sustenance and education rather than production. The participants in this study shared the motivations of growing healthy, local, and high-quality foods (see motivations, above), but they were all implementing their perennial polyculture enterprises on a commercial scale. Some also had an explicit intention of scaling up to much larger industries that include mechanization, while others were certainly satisfied to keep their farms on a small, non-mechanized scale. The combination of ecological and permaculture-oriented design that is explicitly conservationist (or even regenerative) combined with the intended scale of execution for commercial harvest makes some of the examples in this study unusual in the agroforestry and permaculture literature. The ambition to large-scale landscape transition to woody perennials (and also industrial transition to perennial-based products) expressed by some of the participants echoes the large-scale systemic ambitions of J Russel Smith (1929) more so than they do the homestead oriented utopia of most permaculture writers and practitioners.

4.4.3 Barriers to adoption and barriers to continuing

Much of the literature that engages farmers about pro-environmental practices, and specifically around agroforestry, sets about assessing why adoption is failing (Pattanayak et al. 2003; Meijer et al. 2014; Chapman et al. 2019). In this study, we spoke with farmers that were already adopters, enabling us to compare their perceived needs with those of landowners who had not yet become involved in perennial polyculture in the Midwest.

Several recent papers have surveyed, interviewed and/or conducted workshops with Midwestern landowners and farmers about the adoption of perennial grass strips and buffers (Atwell 2009), the transition to perennial-based rotational grazing (Blesh and Wolf 2014), and about the adoption of woody perennial polycultures on marginal lands (Trozzo et al. 2014, Mattia et al. 2018, and Stanek et al. 2019). In talking to conventional corn and soybean farmers about adoption of perennial grass strips or buffer zones, Atwell et al. found that several barriers on different scales were at play: compatibility with existing systems on the farm scale, reinforcement through social norms and networks on the community scale, and consistency and ease of programs on the institutional scale. In particular, they found that community-scale interactions were important for brokering information across scales to promote social learning about perennial conservation practices. Trozzo et al. (2014) investigated the interest in adoption of harvestable native fruit and nut trees within riparian buffers among Virginian owners of non-forested creekside land, thus getting closer to the multifunctional paradigm that includes harvest, but still evaluating the use of “edge” spaces for doing so. They found that newer landowners that were younger, less involved in hands-on farming, and had higher income were more interested in this practice, and that social influence significantly contributed to interest. Mattia et al. (2018) surveyed Illinois landowners about their interest in food-producing perennial cropping systems, also targeted towards marginal lands (but not necessarily riparian zones). Similarly to Trozzo et al (2014), they found that interest was greater in younger and more affluent landowner demographics, but also found that education, the possession of known marginal land, and higher involvement in on-farm management were correlated with interest in perennial adoption; they also found that lack of information about these practices was the largest barrier. Stanek et al. (2019) built on Mattia et al. (2018)’s study, and worked with the landowners from that dataset that were most interested in perennial adoption in a collaborative scoping and design process where the researchers developed three custom alternative perennial polyculture designs for each farm over several iterations of consultation. For this group of high-potential adopters, the most attractive aspects of the perennial designs were edible fruit and nuts, improving pollinator and wildlife habitat, and increasing productivity of marginal land. Interestingly, despite these herculean efforts (and free design services) only a handful of the farmers in the study indicated intention of following through on their preferred “ideal” design anytime soon, citing a lack of processing infrastructure, labour requirements, unknown markets, and lack of familiarity with management of woody crops.

Blesh and Wolf (2014) stand out as an example of work that integrates socioeconomic and ecological angles of transition to perennialized sustainable agriculture after transition/adoption takes place (in this case, rotational grazing). The authors selected participants from a subset of farms visited in a companion study that measured the nutrient pollution from agricultural lands in Iowa (Blesh and Drinkwater 2013). They found that, much like the farmers in the present study, their respondents were resourceful innovators who had overcome the isolation and technical barriers to perennial transition by harnessing ecological and enterprise diversity, engaging in personal learning and experimentation processes, and accessing information from peer communities and government programs.

These studies, which applied practical, instrumental tools (but, also included social dimensions) to assessing the motivations and barriers for prospective adopters of perennial practices in the Midwest agreed and contrasted with aspects of our findings. The significance (and insufficiency) of social norms and networks found in Atwell et al. (2009) and Mattia et al. (2018) contrast with our results and those of Blesh and Wolf (2014) for farmers is North-East Iowa, that indicated that these farmers felt well connected to like-minded farmers, though not necessarily in their immediate neighborhoods. Our findings that the availability of markets, financing/labour capacities, and processing infrastructure were barriers to the success and expansion of practicing perennial polyculture farmers largely agreed with the barriers found by Stanek et al. (2019) regarding marketing, processing and labour. However, the prospective adopters in that study also cited a lack of management information, which was not a barrier (though it was a challenge) for our participants, and expressed a strong reluctance to convert any but marginal lands to perennials, a sentiment that reflected some but not all of our farmers choice of land. This indicates that the reluctance of prospective farmers in adopting these practices was at least in part justified in that some of the same issues they bring up as barriers to adoption also appeared as major barriers to success and expansion of existing enterprises. The findings of Trozzo et al.

(2014) that landowners who were less involved in farming were more interested in perennial adoption contrasted to the findings of Mattia et al. (2018) that landowners who were more involved in on-farm management were more interested - but this difference might be accounted for because of the prevalence of absentee landowners in the latter study and not in the the former. In summary, the similarities and contrasts between this group of studies are in part a result of the very different groups of farmers that were involved, who ranged along a spectrum from randomly selected landowners from census data who had no familiarity with perennial practices, to (in our case and that of Blesh and Wolf 2014) individually selected farmers contacted because of their existing enterprises. Further integration of the information from these Midwestern studies to better understand both different groups of farmers, and different stages in the perennial adoption journey could be worthwhile.

An aspect of our work that is not as easily compared to this literature is in the realm of values. While they are interdisciplinary in important ways that layer cognitive and material dimensions of transitions to perennial agriculture, the papers discussed above did not attempt to elicit values that, if lived up to, can contribute to notions of a good life. In contrast, this study counters a potential underestimation of the importance of people's ability to fulfill relational values that they hold, particularly those at odds with the agricultural systems prevalent in North America, which currently prioritize profits and short-term production over long-term prosperity and food security. Studies of transition to and maintenance of sustainable perennial practices that include an element of values, even if they focus on economics, management, or community relations (for example, MacRae et al. 1990) can lend important context to practical findings.

4.4.4 Enabling a transformation toward perennial agriculture

In this paper, we have integrated information about several dimensions of perennial polyculture farming including livelihoods, practices, motivations, community relations, barriers, and values, and linked these with the ecological dimension covered in the companion study (Chapter 3). Throughout these topics, we have seen how perennial farmers expressed values rooted in relationship with land and community, and met challenges with resources recruited from themselves (their own curiosity, money, agency, and land) and available collective structures (investors, farmer organizations, and government). The adoption and continuation of complex farming systems like perennial polycultures are unlike other technological agricultural innovations, in that they involve multiple levels of competencies and resources, both individually and as part of collectives on different scales (Blesh and Wolf 2014). Integrated approaches that attend to these complexities and include an emphasis on *how* (rather than just *why*) such transitions continue (as discussed in Blesh and Wolf 2014) can inform ongoing efforts to accelerate these needed transformations from niche phenomena to more broadly applicable policies and standards.

Several of the themes found in this study relate to policy-oriented pathways for larger scale change. Restructuring of subsidies and incentives, integration of scales and sectors, precautionary and long-term action, and adaptive decision-making are four of the actionable “levers” laid out in Chapter 5 of the IPBES Global Assessment on Biodiversity and Ecosystem Services for a transformative change towards a globally sustainable economy (Chan et al. 2019). The fact that one small group of farmers (like many others around the world) have broken out of a rigid social-ecological configuration in the US Midwest (Atwell 2009) and are enacting changes through these same mechanisms on the scale of their land and community is a source of hope and guidance, if not optimism, that larger scale changes can follow.

To forward the goal of upscaling diverse perennialization of the Midwestern landscape, larger scale structures, both in the nonprofit, private, and public sectors seem to be necessary to ease those barriers which farmers struggle to deal with on their own or in their existing networks. Such structures, and the programs they design, should learn from the ways that existing programs work and do not work for perennial polyculture farmers, as well as the insights collected from farmers that have not adopted these practices. They should honor the knowledge and values of perennials farmers in a few specific ways: 1) by enabling and embracing farmer experimentation and knowledge sharing; 2) by acknowledging the combination of livelihood and other sources of fulfillment and satisfaction that contribute to a good life for farmers; 3) by designing incentives and resources that make sense for diverse multi-strata tree crop systems that often include livestock, including allowing for harvest and tailoring to site; 4) by adopting an explicitly perennial, long-term approach that plans over decades, and considers the years until production starts. In summary, policy and program development that has an aim of enhancing the multifunctionality of agrarian landscapes through diversified tree crop systems should use the extensive knowledge amassed by this unique group of farmers to drive appropriate and successful transitions to sustainable environments and livelihoods.

Chapter 5: Conclusion

5.1 Summary of key findings and contributions

This thesis has studied perennial agriculture on several scales, and found that this agricultural paradigm can embody ecological principles to manifest nutritional, environmental, and relational benefits, particularly in the presence of diverse complimentary agroecosystem components. I have found that some perennial crops can produce as much food as annual staples, but even those that do not can find viable pathways to adoption and thriving, thereby potentially transforming agricultural landscapes. Chapter 2 studied perennial agriculture on the scale of the global food system where synthetic analysis from multiple studies and data types were used to understand the current yield, distribution, nutrition, and carbon sequestration of a wide range of perennial crops. Chapters 3 and 4 were carried out on a regional scale in a specific place, the US Midwest, where resourceful farmers are implementing and innovating diversified management practices with perennial polyculture systems.

Chapter 2 demonstrated a substantial potential for perennial staple crops to contribute to the global food supply. Its framework of perennial staple crops enables researchers and practitioners to identify or classify crops according to nutritional categories and cultivation status. The study assembled literature to report on the yield potential of 51 perennial staple crops, only 15 of which are well characterized in existing global datasets. It also synthesized the extent and distribution of perennial staple crop production in relation to annual crop types, calculated the carbon stocks they hold, and analysed their nutritional content for three macronutrients and nine micronutrients. The results showed that despite structural barriers to perennial adoption in a system that emphasizes short term returns and continuous increases in cereal yields, perennial staple crops constitute a small but significant (4.5 %), and growing portion of global cropland. At least one perennial staple crop in each of the five nutritional categories had yields over 2.5 t/ha, in some cases considerably higher, competitive with and in many cases exceeding those of nutritionally comparable annual staples, suggesting that transition of agricultural land to perennial crops may not entail yield losses in some areas. Most perennial staple crops, including many of those with high potential yields, are regional crops (not globally traded) that grow in the subtropics to tropics, suggesting that there is space for market expansion and increased investment in some crops.

Many perennial crops also had macronutrient densities and yields (per unit area) that were competitive with annual staples; moreover, specific perennial staples are abundant in specific micronutrients, indicating that they can be a nutrient-dense part of diets, unlike the most ubiquitous annual staple crops (corn, wheat, rice), which do not appear in the top 85th percentile for any of the nine micronutrients analysed. Perennial staple crops currently hold 11,386 MtC above and below ground. If linear growth in land under perennial staple production continues to 2040, and replaces annual cropland, 965 MtC could be sequestered. The yield, nutrition, and carbon sequestration data assembled in this chapter indicated that transition of land and diets to perennial staple crops, if judiciously managed, can provide win-win solutions for both food production and ecosystems. However, examples of unsustainable expansion of perennial staple crops mean that such ideal scenarios are by no means to be taken for granted.

Chapter 3 demonstrated that the structural heterogeneity and functional diversity of perennial polycultures are key for supporting biodiversity and ecosystem services, via a natural snapshot experiment in the US Midwest. Perennial agriculture, and particularly perennial polycultures that combine a variety of long-lived woody perennial crops with continuous ground cover, seem to embody ecological concepts of diversity and complex adaptive systems. This study therefore assessed the benefits and trade-offs of perennial polyculture practices compared to conventional agriculture in a temperate, industrialized geography. Though there were sometimes distinct differences between the three conventional cover types (hay, corn and soy) and the perennial polyculture fields, the results generally showed that compared to conventional fields perennial fields had (a) more diverse soil fungal, invertebrate, and plant communities but found no difference in soil bacterial communities; (b) less compacted soil; (c) denser ground cover; (d) more active carbon, organic carbon, and nitrogen, and the same available phosphorus in the top layer of soil; (e) and more pest-control, pollination (compared to corn only) and nutrient cycling as well as more herbivorous arthropods. Plant diversity increased with the age of the perennial polyculture, as did calorie production, though the latter was low compared to corn and soybeans.

Together, this study shows that planting perennials on formerly conventional annual cropland or marginally used fallow land in the American Midwest has several diversity and ecosystem service benefits. Though perennial polycultures in this study do not compete with annual corn and soy on the basis of yield, they do produce a wide variety of nutritious foods for direct human consumption while sustaining biodiversity and indicators of ecosystem service supply. From an ecological perspective, perennial polycultures indeed seem to increase landscape functional diversity, and can play a role in the transition of agricultural landscapes towards sustaining both people and nature over the long term.

Chapter 4—the parallel social science study to Chapter 3—synthesized the local knowledge of the perennial polyculture farmers on whose land we carried out biophysical sampling. Learning from farmers pioneering a transition to perennial polycultures in the Midwest via 13 interviews with 18 midwestern perennial polyculture farmers, we found that farmers largely used a small portion of their farm's land for their perennial enterprises. Furthermore, interviewed farmers did not earn a large portion of their income from them, though this was generally projected by the farmers to increase as trees matured. Through experimentation, innovation, and farmer networks, the farmers had amassed unique adaptive management expertise for balancing diverse crops and livestock within multifunctional tree crop systems over time and space, an area of management largely absent from mainstream agricultural science and policy.

Though farmers faced a range of management and production challenges, these were generally met with curiosity and adaptation and were rarely expressed as major barriers to expansion or success. The serious barriers these farmers reported facing were largely economic rather than biophysical, involving access to capital, insurance, labour, mid-sized markets, and regional processing infrastructure, as well government programs that were mis-matched with the long-term timescale of perenniality. The values that were important to the farmers were anchored in their relationships to land and community: self-sustenance, stewardship and care of farmland, connection to nature and wildlife, other-sustenance, diversity, long-termism, learning and sharing, and eudaimonia/connection to identity.

The analysis led to the following general recommendations about agrarian policy and program development for multifunctional tree crop systems in both the public and private sector: 1) enabling and embracing farmer experimentation and knowledge sharing; 2) acknowledging the combination of livelihood and other sources of fulfillment and satisfaction that contribute to a good life for farmers; 3) designing incentives and resources that make sense for diverse multi-strata tree crop systems that often include livestock, including allowing for harvest and tailoring to site; 4) adopting an explicitly perennial, long-term approach that plans over decades, and considers the years until production starts. Thus, I concluded that honouring the specific knowledge and values of perennial farmers might help to drive appropriate and successful transitions to sustainable environments and livelihoods in the US Midwest.

The work summarized here constitutes several contributions. First, by focusing on both food production and environmental aspects of tree crops, this work as a whole advances the integration of agroforestry and agronomic literatures, which especially in temperate regions, have been largely separated. Second, the classification of a significant number of perennial staple crops, and the assembly of literature-based data on their yields, distribution, nutrition, and carbon sequestration advances the ability of future studies to further explore little-known crops individually but also in categories and groups together with more familiar perennial crops using clear logic. This assembly provides an empirical basis for more accurate modeling of land transitions to perennial crops than the guidelines and data currently available in the IPCC and UN FAO. Third, the original data collection on biodiversity of several taxa and indicators of ecosystem services (as well as yields) in the US Midwest constitute one of the very few available studies of multi-species tree crop management in temperate climates, and the only one I am aware of that sampled multiple sites for multiple indicators using a natural snapshot experiment. Fourth, the companion study based on interviews with perennial polyculture farmers enables more robust program development for perennial transitions in the US Midwest, by highlighting the capacities, values and management expertise of farmers that have already undergone this transition. The findings complement previous studies of landowners and farmers who are at an earlier stage in their adoption process or have not chosen to adopt diversified perennials. Perennial multi-strata systems that produce food in developed economies are a niche phenomenon largely found within permaculture gardens at present, and the sparse scientific information about them stands in the way of up-scaling these practices. The biophysical and sociological findings presented here from these nascent commercial enterprises are both practical and validating documents for the communities practicing this agriculture, and novel contributions to literature on agroforestry and sustainable transitions.

5.2 Limitations and research needs

As much as the design and implementation of the research enabled contributions to sustainable agriculture and its study, they also confer gaps and raise additional questions for future work to pursue. In chapter 2, the choice to concentrate on perennial staple crops excluded the more familiar and generally more ubiquitous fruit crops from most of the analysis. Yet undoubtedly, fruit crops and perennial vegetables are also important parts of diets and will be necessary components of adequate regional or global models of land transitions. The 51 perennial staple crops that were included in yield and nutrition analysis were chosen based on the ability to find reliable yield information on them. The quality of data on many of these was limited by lack of credible sources; indeed, a documentation of the types and amount of evidence available for each crop was part of the contribution of this work. This selection and documentation process meant that over 100 perennial staple crops that were collected in the previous non-peer reviewed work of Eric Toensmeier (2016) were not included. This limitation is not a small one: even though this work brings some little-known crops into the Western academic literature, it perpetuates the marginalization of many crops that are already functioning as domesticated perennial staples in the global South, but do not already have a foothold in citable documentation on yields and nutrition. The track record of development agencies and governments in embracing research on lesser-known crops in the developing world is not strong, and academic literature like my work can perpetuate biases towards species that are better known and documented already. I hope that my contribution is understood as a starting point for collecting and improving the documentation of perennial staple crops in all their specificity and diversity, not as an endpoint that seals the marginalization of many wonderful species from further investigation.

The limitations of chapter 3 are several. First, apart from food production, I was not able to measure actual ecosystem services, but rather various indicators or proxies of ecosystem service supply. Measurement of actual services (such as pest control or pollination) involves more labour intensive methods of assessing actual damage on plants or fruit set on trees which wasn't practically possible for the present study as it involved so many different species of crops at many different sites. Likewise, the soil fertility measures I used (e.g. soil bulk density, soil organic carbon, and soil active carbon) do not necessarily translate directly to increased plant growth and vigour, which would be the actual ecosystem service resulting from soil properties (perhaps over many years). The connection between the proxy of plant cover on the ground for erosion control and mitigation of nutrient pollution is well established, but nonetheless, this study did not directly measure soil moisture, or erosion and nutrient leaching in adjacent waterways. Thus, like many studies that attempt to assess biodiversity and multiple ecosystem services, this study does not directly establish evidence for well-quantified units of benefit but rather for more basal indicators of supply (Chan and Satterfield, in press).

The fact that many of the farms in this study were young limited the effort to compare not only yields but also the benefits of mature perennial polycultures over annual row crops. This limitation was unavoidable, since enterprises of this kind are only recently becoming numerous enough to study, but the small number of sites at different ages (and the lack of longitudinal data about particular sites) limited my ability to address the fascinating temporal dimension of perennial transition (though this was found to be significant for plant diversity and food production even with the limited data). Longitudinal work that follows perennial polycultures as they mature over years and decades is necessary for the real advantages of long-lived systems such as these to be evaluated. Third, the design of one-to-one paired comparisons of perennial and adjacent annual cropland obscures the reality that several of the farmers were not necessarily managing their perennial plantings for maximal productivity in the same way as for the annual fields (as I explored in chapter 4). Thus, this study shouldn't be taken as a blueprint for what perennial agriculture could look like from a food production perspective if it was scaled up massively (the more production oriented farms that were designed for up-scaling might be a good blueprint once they mature), but rather as an initial study of this moment in largely very recent transitions. The limited number of perennial polyculture farms to choose from in 2018 was itself an indicator of the early stage in the development of these systems—which is one of the critical contexts that the parallel social science chapter explored.

The challenges that accompanied chapter 4 likely have more to do with my own shortcomings than anything inherent in the scale or study design. My inexperience as an interviewer in a social science context became clear to me during the analysis, when I found that I sometimes cut people off just as they were saying interesting things. This was a symptom of my overzealous attempts to move along the interviews in an orderly way or not take up too much of my participants' time (a resource they were constantly short of, though they seemed to enjoy talking to me at length). Like the previous chapter, this work would also benefit from longitudinal follow ups. As discussed in the chapter, long-term, successional thinking applied to the people just as much as the plants. The sustainability of these enterprises depends on the ability of the farmers to find labour, markets, and fair prices year after year, as well as the sense of satisfaction and thriving that enables the farmers themselves to continue. Thus, future work on the subsequent experiences of the farmers that were managing newer enterprises in my study would be valuable. Another limitation of this study is that I was aware, in choosing how to frame the study, that there were many literatures and theories that could have been valid to choose, some of which I may not even be aware of. My hope is that the framing of this work is not too rigidly bound up with one discipline or set of terms that it can relate to other work even if not explicitly cited. Finally, this chapter is not a comprehensive study of the barriers to perennial farming - it is instead an in depth investigation about the perspectives of pioneering farmers that *are already* sustaining perennial enterprises. Thus, this work complements other literature that addresses barriers facing those who are earlier in the adoption process. Further integration of studies in the US Midwest that evaluate barriers and bridges to perennial adoption among different cohorts of landowners and farmers that are in different stages along the adoption process would be valuable.

5.3 Synthetic insights, cautions, and opportunities

Though differing in scale, the outcomes of the three chapters of this thesis are interconnected, particularly in how they might inform the study of perennial agriculture. It is interesting to re-think the findings of chapter 2, which centres on yields and nutrition from underutilized crops, through the context of the findings from chapters 3 and 4 where a (small, but potentially catalytic) transition is taking place towards systems that are generally low-yielding compared to what they are replacing. The case study of the US Midwest shows that even within a developed economy where commodity oriented production-maximization is nearly hegemonic, transitions to lower yielding but more multifunctional systems can take place. The general satisfaction with, and fulfillment of values from, these enterprises that farmers expressed had little to do with yield maximization or a sense of responsibility to "feed the world" but rather with more locally grounded principles and virtues about ongoing stewardship of farmland, connection with wildlife, healthy and high-quality food production, long-termism, and diversified livelihoods and ecologies.

This case study indicates that the yield and biomass data collected in chapter 2, which was intended in part to be useful in parameterizing better models of land transition to perennial crops, should be used with caution. The temptation of modellers to optimize scenarios based on the best yielding crops, under efficient management, in the least damaging places, may bear little resemblance to what motivates the mostly private actors that actually enact land transitions—

either because of an absence of enabling political and economic factors, or an absence of nuance about people's values, or both. This can happen in either direction (i.e. over-predicting or under-predicting uptake of transition). These limitations are not a reason to shy away from future models that present an idealized and geographically explicit vision of perennial food production (nor are they necessarily a reason to develop increasingly complex models), but rather an argument to pair such exercises with socio-political context or analysis. The strong environmental, nutritional, and psychological advantages of transitions to perennial agriculture, documented in this thesis, are unlikely to live up to their potential at scale without powerful, centrally planned incentive and regulatory policies that embody a similar vision of what is optimal as those held by the wider public (or at least by the sustainability scientists that make models).

As many authors point out, agricultural transitions and agriculture itself are abundantly multidimensional: they involve ecology, technology, sustenance, livelihood, identity, and even resistance, and operate on several scales that all include cycles of adaptation and learning (Michon 2011; Blesh and Wolf 2014; Cabel and Oelofse 2012; Chapman et al 2017). Permeating all these dimensions, people's connections to food and agriculture illuminate their values and conceptions of a good life, both fulfilled and unfulfilled. Given this complexity, no single set of methods or theories can adequately describe agricultural transitions, and, as discussed above, interdisciplinary work is necessary.

This thesis is an example of such interdisciplinary work that connects biophysical realities and tradeoffs with rich social context situated in place. Such approaches serve as a remedy to overly bounded paradigms that produce seemingly rigorous results, but have little relevance in the applied realm because of a lack of attention to the social and political contexts where agricultural practices and transitions are situated (for example, the land sparing vs. land sharing debate of the early 2010s; Ramankutty and Rhemtulla 2012). The reflexively stated intention of this thesis places my work squarely in the realm of post-normal science (Dankel et al. 2017): I sought both to make original empirical contributions that describe perennial agriculture as it exists, and to use this knowledge to catalyze normative claims about necessary changes.

The role of perennial crops, (and in particular woody ones or those that are tree-like in form) for food production and as part of a sustainable agricultural matrix deserves additional attention in integrated scientific literature. Whether perennial crops are managed in simplified forms or as part of diversified perennial systems, their specific capacities for ES and food production should be recognized and understood. Yet a lack of synthetic data about management, impacts, and benefits of perennial crops, which this thesis only begins to remedy, should not itself be a reason to impede policy development in both the private and public sectors. The information currently available is enough in many contexts to justify a dedicated strategy for pursuing further practice and research through a pro-active, adaptive management lens. In 1929, J Russel Smith envisioned a set of “Institutes of Mountain Agriculture” that would breed, study, and promote the use of perennial crops. This vision has never come to full fruition. But, two remarkable organizations in the US, the Land Institute and the Savanna Institute serve as examples to emulate: they marry breeding, training, education, networking, and lobbying and are far ahead of larger and better funded organizations in their outputs and capacities to support perennial transitions.

Policy frameworks in both the US and EU have made progress in recognizing the importance of agroforestry, and both have integrated language into policy that specifically acknowledges food-producing perennial crops (though the extent to which this has been done is still minor compared to non-food producing agroforestry practices). For example, the USDA's Agroforestry Strategic Framework recognizes alley cropping as one of its five agroforestry practices, which is defined as "integrat[ing] annual crops with high-value trees and shrubs" (USDA 2019b). This definition hints that "high-value" might mean fruit and nut producing crops, but the Strategic Framework does not explicitly make mention of the edible products from tree crops, nor does it include either 1) tree crops that are grown without integrating annual crops or 2) tree crops with edible harvest that are managed together with animals (as distinct from timber-based silvopasture). Thus, there is much room for US policy to better address the potential of woody perennial polycultures.

The European union's Common Agricultural Policy (CAP) is more accommodating of integrated tree crop systems, including those that combine fruit and nut harvest with animals. This more inclusive position may reflect Europe's longer history with these systems, including long-standing but threatened agroforest cultural landscapes systems such as *Dehesa*, *Montada,* and *Streuobstwiesen* (Smith et al 2012). The European Commission Regulation 1305/2017 Measure 8.2 includes "grazed or intercropped orchards" under its definition of agroforestry (Mosquera-Loseda et al. 2018). CAP has funding provisions for woody perennial agricultural systems under a variety of different designations under both Pillar I (provisions that apply to all states) and Pillar II (provisions defined and implemented by each country). These are not identified as agroforestry practices per se, but rather under the general term "permanent crops" and under a variety of country-dependent sub-measure definitions; according to a recent analysis, the uptake of agroforestry related measures among member states is very low (see Mosquera-Loseda et al. 2018, Figure 1). Moreover, these provisions are currently very limited compared to provisions for annual agriculture. Furthermore, a lack of clarity about definitions and practices has sometimes been counterproductive: for example limits on the tree density allowed for CAP payments through the "arable land" provisions have led to the destruction rather than preservation of trees in some cases (Mosquera-Loseda et al. 2018). In their analysis of CAP policy, Mosquera-Loseda et al. conclude that while there is a recognition of woody components in the policy, the lack of recognition of agroforestry practices as such undermines the flexibility of farmers to pursue the best combinations of woody practices including harvestable tree crops on their lands.

Thus, recent policy developments in the US and EU are encouraging, but still insufficient. However, there is clearly a need to enact perennial-based solutions for both food production and to address the global ecological crisis, as indicated by the several perennial agriculture-based solutions in Project Drawdown (Hawken 2017), and the priority given to agroforestry as a climate solution in a recent IPCC special report on climate change and land (IPCC 2019). Policies to advance perennial agriculture should prioritize 1) compensating and rewarding farmers using well-designed values-aware PES programs (Chan et al. 2017) for high levels of ES provision from perennials without restricting harvest; 2) assisting with the financial burden of upfront investment in long-term perennial enterprises with cost-share programs and loans; 3) easing restrictive food-safety regulations that make the integration of animals with harvested tree crops difficult; 4) investing in applied research for the development of ready-to-implement crop combinations and systems tailored for specific geographies, including learning from farmers; 5) developing regional infrastructure and capacity in the private or cooperative sector for the processing and marketing of locally appropriate perennial crops; 6) fostering and funding bridging organizations like the Practical Farmers of Iowa, the Sustainable Iowa Land Trust, the Savanna Institute and the Land Institute; and last but not least 7) removing or shrinking the financial and policy support currently offered to environmentally damaging competing farming practices (Chan et al. in press).

Academic research alongside bridging organizations and advances in policy will be necessary to understand and enact the large questions of where and how perennial agriculture might be deployed to restore soil on degraded land (while providing side benefits), and where and how it can replace annual agriculture by producing staple foods through a more production-oriented paradigm. Undoubtedly, these are not either/or questions: perennial crops can and do already play a role in both increasing the function of degraded lands in some contexts, and in substantial food production on prime lands in others. But, the multifunctional nature of perennial crops, while creating significant synergies in many contexts, does not absolve researchers and policy makers from grappling with trade-offs and conflicting values (for example between specialization and diversification, local and global markets, commodification and self-sustenance, private and public capitalization, and many others) that must arise in any agricultural paradigm.

In summary, there is transformative potential in perennial polycultures to provide food for people while nourishing wild biota. The transformative potential does not rest in perenniality per se, however: the ills of the existing agricultural system can be easily reproduced in perennial systems. Rather, the transformation lies in the embodiment of agroecological principles in diverse self-organizing ecosystems that are structured by perennial plants, alongside associated fungi, other microbiota, and animals. Perennial crops (in particular ones with tall, woody physiognomy) can make unique contributions to existing paradigms of sustainable agriculture such as diversified farming systems (DSF) and agroecology, by producing nutritionally dense foods while providing long-term structural complexity and accumulating stored energy. Instead of such crops being grown either in simplified plantations or as minor edge elements on farms, an agroecological approach to perennial crops would see them take a predominant role in a farming landscape while integrating layers diversity from other annual and perennial crops. The expansion of land under perennial staple crop production since the 1970s to the present indicates that the demand for perennial products globally is increasing, but a substantial expansion of sustainable perennial polycultures will require regulatory reforms and rebalancing incentive structures that require or encourage rather than discourage regenerative practices. Thus, the opportunity to manage these transitions sustainably or even accelerate them to catalyze transformative changes in agriculture is still very much in play. The question of whether these transitions will benefit nature and local people or serve to further degrade forests, consume fossil fuels, and exploit labour is what is at stake for this and future research on perennial crops.

Bibliography

Abrams MD, Nowacki GJ (2008) Native Americans as active and passive promoters of mast and fruit trees in the eastern USA. The Holocene; London 18:1123–1137. http://dx.doi.org.ezproxy.library.ubc.ca/10.1177/0959683608095581

Adewale BD, Dumet DJ, Vroh-Bi I, et al (2012) Morphological diversity analysis of African yam bean (Sphenostylis stenocarpa Hochst. ex A. Rich.) Harms and prospects for utilization in germplasm conservation and breeding. Genet Resour Crop Evol 59:927–936. https://doi.org/10.1007/s10722-011-9734-1

Adewale BD, Vroh-Bi I, Dumet DJ, et al (2015) Genetic diversity in African yam bean accessions based on AFLP markers: towards a platform for germplasm improvement and utilization. Plant Genetic Resources 13:111–118. https://doi.org/10.1017/S1479262114000707

AgriOrbit (2018) More and more macadamia produced globally. AgriOrbit

Altieri MA, Toledo VM (2011) The agroecological revolution in Latin America: rescuing nature, ensuring food sovereignty and empowering peasants. The Journal of Peasant Studies 38:587–612. https://doi.org/10.1080/03066150.2011.582947

Arnaez J, Lasanta T, Errea MP, Ortigosa L (2011) Land abandonment, landscape evolution, and soil erosion in a Spanish Mediterranean mountain region: The case of Camero Viejo. Land Degradation & Development 22:537–550. https://doi.org/10.1002/ldr.1032

Asbjornsen H, Brudvig LA, Mabry CM, et al (2005) Defining Reference Information for Restoring Ecologically Rare Tallgrass Oak Savannas in the Midwestern United States. j for 103:345–350. https://doi.org/10.1093/jof/103.7.345

Asbjornsen H, Hernandez-Santana V, Liebman M, et al (2014a) Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. Renewable Agriculture and Food Systems 29:101–125. https://doi.org/10.1017/S1742170512000385

Atwell R, Schulte L, Westphal L (2009) Linking Resilience Theory and Diffusion of Innovations Theory to Understand the Potential for Perennials in the U.S. Corn Belt. Ecology and Society 14:. https://doi.org/10.5751/ES-02787-140130

Atwell RC, Schulte LA, Westphal LM (2010) How to build multifunctional agricultural landscapes in the U.S. Corn Belt: Add perennials and partnerships. Land Use Policy 27:1082–1090. https://doi.org/10.1016/j.landusepol.2010.02.004

Bailey D, Schmidt-Entling MH, Eberhart P, et al (2010) Effects of habitat amount and isolation on biodiversity in fragmented traditional orchards. Journal of Applied Ecology 47:1003–1013. https://doi.org/10.1111/j.1365-2664.2010.01858.x

Bainbridge DA (1985) The Rise of Agriculture: A New Perspective. Ambio 14:148–151

Balvanera P, Pfaff A, Viña A, et al (2019) Status and trends - drivers of change. Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

Barrett C B, Place F, Aboud A, Brown D (2002) The challenge of stimulating adoption of improved natural resource management practices in African agriculture. In: Barrett, CB, Place, F, and Aboud, A (eds) Natural resource management in African agriculture: understanding and improving current practices Wallingford, UK: CABI Publishing

Baselga A (2010) Multiplicative partition of true diversity yields independent alpha and beta components; additive partition does not. Ecology 91:1974–1981. https://doi.org/10.1890/09-0320.1

Baselga A (2013) Separating the two components of abundance-based dissimilarity: balanced changes in abundance vs. abundance gradients. Methods in Ecology and Evolution 4:552–557. https://doi.org/10.1111/2041-210X.12029

Baselga A (2017) Partitioning abundance-based multiple-site dissimilarity into components: balanced variation in abundance and abundance gradients. Methods in Ecology and Evolution 8:799–808. https://doi.org/10.1111/2041-210X.12693

Baselga A, Orme CDL (2012) betapart: an R package for the study of beta diversity. Methods in Ecology and Evolution 3:808–812. https://doi.org/10.1111/j.2041-210X.2012.00224.x

Battles JJ, Jackson RD, Shlisky A, Bartolome JW Net Primary Production and Biomass Distribution in the Blue Oak Savanna. 14

Beals EW (1984) Bray-Curtis Ordination: An Effective Strategy for Analysis of Multivariate Ecological Data. In: MacFadyen A, Ford ED (eds) Advances in Ecological Research. Academic Press, pp 1–55

Beer R, Kaiser F, Schmidt K, et al (2008) Vegetation history of the walnut forests in Kyrgyzstan (Central Asia): natural or anthropogenic origin? Quaternary Science Reviews 27:621–632. https://doi.org/10.1016/j.quascirev.2007.11.012

Begon M, Harper J, Townsend C (1990) Chapter 23: Community stability and Community Structure. In: Ecology: Individuals Populaitons and Communities, 2nd edn. Blackwell, Boston MA

Bennett AB, Isaacs R (2014) Landscape composition influences pollinators and pollination services in perennial biofuel plantings. Agriculture, Ecosystems & Environment 193:1–8. https://doi.org/10.1016/j.agee.2014.04.016

Bennett E, Carpenter SR, Gordon L, et al (2014) Toward a more resilient agriculture. Solutions: For a Sustainable and Desirable Future 5:65–75

Bennett NJ, Whitty TS, Finkbeiner E, et al (2018) Environmental Stewardship: A Conceptual Review and Analytical Framework. Environmental Management 61:597–614. https://doi.org/10.1007/s00267-017-0993-2

Bentley JW (1994) Facts, fantasies, and failures of farmer participatory research. Agric Hum Values 11:140–150. https://doi.org/10.1007/BF01530454

Bhagwat SA, Willis KJ, Birks HJB, Whittaker RJ (2008) Agroforestry: a refuge for tropical biodiversity? Trends Ecol Evol (Amst) 23:261–267. https://doi.org/10.1016/j.tree.2008.01.005

Bintoro MH, Nurulhaq MI, Pratama AJ, et al (2018) Chapter 2: Growing Area of Sago Palm and its Environment. In: Sago Palm: Multiple Contributions to Food Security and Sustainable Livelihoods. Springer, pp 20–29

Bishop TR, Robertson MP, van Rensburg BJ, Parr CL (2015) Contrasting species and functional beta diversity in montane ant assemblages. J Biogeogr 42:1776–1786. https://doi.org/10.1111/jbi.12537

Black AW (2000) Extension theory and practice: a review. Aust J Exp Agric 40:493–502. https://doi.org/10.1071/ea99083

Blesh J, Drinkwater LE (2013) The impact of nitrogen source and crop rotation on nitrogen mass balances in the Mississippi River Basin. Ecological Applications 23:1017–1035. https://doi.org/10.1890/12-0132.1

Blesh J, Wolf SA (2014) Transitions to agroecological farming systems in the Mississippi River Basin: toward an integrated socioecological analysis. Agric Hum Values 31:621–635. https://doi.org/10.1007/s10460-014-9517-3

Borges JAR, Foletto L, Xavier VT (2015) An interdisciplinary framework to study farmers decisions on adoption of innovation: Insights from Expected Utility Theory and Theory of Planned Behavior. AJAR 10:2814–2825. https://doi.org/10.5897/AJAR2015.9650

Born RJG van den, Arts B, Admiraal J, et al (2018) The missing pillar: Eudemonic values in the justification of nature conservation. Journal of Environmental Planning and Management 61:841–856. https://doi.org/10.1080/09640568.2017.1342612

Borremans L, Marchand F, Visser M, Wauters E (2018) Nurturing agroforestry systems in Flanders: Analysis from an agricultural innovation systems perspective. Agricultural Systems 162:205–219

Borremans L, Reubens B, Gils BV, et al (2016) A sociopsychological analysis of agroforestry adoption in Flanders: understanding the discrepancy between conceptual opportunities and actual implementation. Agroecology and Sustainable Food Systems 40:1008–1036. https://doi.org/10.1080/21683565.2016.1204643

Bradford MA, Carey CJ, Atwood L, et al (2019) Soil carbon science for policy and practice. Nature Sustainability 2:1070–1072. https://doi.org/10.1038/s41893-019-0431-y

Brady MJ, McAlpine CA, Possingham HP, et al (2011) Matrix is important for mammals in landscapes with small amounts of native forest habitat. Landscape Ecol 26:617–628. https://doi.org/10.1007/s10980-011-9602-6

Brady NC, Weil RR (1986a) Chapter 1: The soils around us. In: The nature and properties of soils, 11th edn. Prentice-Hall, Upper Saddle River

Brady NC, Weil RR (1986b) Chapter 12: Soil organic matter. In: The nature and properties of soils, 11th edn. Prentice-Hall, Upper Saddle River

Brady NC, Weil RR (1986c) Chapter 17: Soil erosion and its control. In: The nature and properties of soils, 11th edn. Prentice-Hall, Upper Saddle River

Brandt SA, Spring A, Hiebsch C, et al Enset-Based Agricultural Systems in Ethiopia. 5

Brandt S, Spring A, Diro M, et al (1997) Tree Against Hunger: Enset-based Agricultural Systems in Ethiopia. American Association for the Advancement of Science

Brauman KA, Garibaldi LA, Polasky S, et al (2019) Status and trends - nature's contributions to people (NCP). Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

Bravo G (2014) The Human Sustainable Development Index: New calculations and a first critical analysis. Ecological Indicators 37:145–150. https://doi.org/10.1016/j.ecolind.2013.10.020

Briggs HM, Perfecto I, Brosi BJ (2013) The Role of the Agricultural Matrix: Coffee Management and Euglossine Bee (Hymenoptera: Apidae: Euglossini) Communities in Southern Mexico. Environ Entomol 42:1210–1217. https://doi.org/10.1603/EN13087

Brown MW (2012) Role of biodiversity in integrated fruit production in eastern North American orchards. Agricultural and Forest Entomology 14:89–99. https://doi.org/10.1111/j.1461-9563.2011.00540.x

Burton RJF (2004) Seeing Through the 'Good Farmer's' Eyes: Towards Developing an Understanding of the Social Symbolic Value of 'Productivist' Behaviour. Sociologia Ruralis 44:195–215. https://doi.org/10.1111/j.1467-9523.2004.00270.x

Cabell JF, Oelofse M (2012) An Indicator Framework for Assessing Agroecosystem Resilience. Ecology and Society 17:. https://doi.org/10.5751/ES-04666-170118

Callahan BJ, McMurdie PJ, Rosen MJ, et al (2016) DADA2: High resolution sample inference from Illumina amplicon data. Nat Methods 13:581–583. https://doi.org/10.1038/nmeth.3869

Campbell B, Beare D, Bennett E, et al (2017) Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecology and Society 22:. https://doi.org/10.5751/ES-09595-220408

Cardoso IM, Guijt I, Franco FS, et al (2001) Continual learning for agroforestry system design: university, NGO and farmer partnership in Minas Gerais, Brazil. Agricultural Systems 69:235–257. https://doi.org/10.1016/S0308-521X(01)00028-2

Cassidy ES, West PC, Gerber JS, Foley JA (2013) Redefining agricultural yields: from tonnes to people nourished per hectare. Environ Res Lett 8:034015. https://doi.org/10.1088/1748-9326/8/3/034015

Cates AM, Ruark MD, Hedtcke JL, Posner JL (2016) Long-term tillage, rotation and perennialization effects on particulate and aggregate soil organic matter. Soil and Tillage Research 155:371–380. https://doi.org/10.1016/j.still.2015.09.008

Cavalcante MC, Oliveira FF, Maués MM, Freitas BM (2012) Pollination Requirements and the Foraging Behavior of Potential Pollinators of Cultivated Brazil Nut (Bertholletia excelsa Bonpl.) Trees in Central Amazon Rainforest. In: Psyche. https://www.hindawi.com/journals/psyche/2012/978019/. Accessed 10 Apr 2020

Chan KMA, Agard J, Liu J, et al (2019) Pathways towards a Sustainable Future. Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

Chan KMA, Anderson E, Chapman M, et al (2017) Payments for Ecosystem Services: Rife With Problems and Potential—For Transformation Towards Sustainability. Ecological Economics 140:110–122. https://doi.org/10.1016/j.ecolecon.2017.04.029

Chan KMA, Balvanera P, Benessaiah K, et al (2016) Opinion: Why protect nature? Rethinking values and the environment. PNAS 113:1462–1465. https://doi.org/10.1073/pnas.1525002113

Chan KMA, Boyd DR, Gould RK, et al (in press) Levers and Leverage Points for Pathways to Sustainability. People and Nature

Chan KMA, Satterfield T (in press) The maturation of ecosystem services: Social and policy research expands, but whither biophysically-informed valuation? People and Nature

Chapman M, Klassen S, Kreitzman M, et al (2017) 5 Key Challenges and Solutions for Governing Complex Adaptive (Food) Systems. Sustainability 9:1594. https://doi.org/10.3390/su9091594

Chapman M, Satterfield T, Chan KMA (2019) When value conflicts are barriers: Can relational values help explain farmer participation in conservation incentive programs? Land Use Policy 82:464–475. https://doi.org/10.1016/j.landusepol.2018.11.017

Chapman M, Satterfield T, Wittman H, Chan KMA (2020) A payment by any other name: Is Costa Rica's PES a payment for services or a support for stewards? World Development 129:104900. https://doi.org/10.1016/j.worlddev.2020.104900

Charlesworth S, Sañudo-Fontaneda LA, Mays LW (2018) The history of Sustainable Drainage. 20:1484

Chase JM, Kraft NJB, Smith KG, et al (2016) Using null models to disentangle variation in community dissimilarity from variation in α-diversity. Ecosphere art24. https://doi.org/10.1890/ES10-00117.1@10.1002/(ISSN)2150-8925(CAT)VirtualIssue(VI)ECS2

Chifamba E (2011) Cultivation and commercialization of Indigenous fruit trees to improve household food security in dry regions of Buhera Zambabwe. Journal of Sustainable Development in Africa 13:95–108

Clement CR, Weber JC, van Leeuwen J, et al (2010) Why extensive research and development did not promote use of peach palm fruit in Latin America. 12

Clot S, Grolleau G, Méral P (2017) Payment Vs. Compensation For Ecosystem Services: Do Words Have A Voice In The Design of Environmental Conservation Programs? Ecological Economics 135:299–303. https://doi.org/10.1016/j.ecolecon.2016.12.028

Cretney R (2014) Resilience for Whom? Emerging Critical Geographies of Socio-ecological Resilience. Geography Compass 8:627–640. https://doi.org/10.1111/gec3.12154

Crews TE, Carton W, Olsson L (2018) Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. Global Sustainability 1:. https://doi.org/10.1017/sus.2018.11

Daniel JN, Ong CK (1990) Perennial pigeonpea: a multi-purpose species for agroforestry systems. Agroforest Syst 10:113–129. https://doi.org/10.1007/BF00115360

Dankel DJ, Vaage NS, van der Sluijs JP (2017) Post-normal science in practice. Futures 91:1–4. https://doi.org/10.1016/j.futures.2017.05.009

Datta R (2015) A relational theoretical framework and meanings of land, nature, and sustainability for research with Indigenous communities. Local Environment 20:102–113. https://doi.org/10.1080/13549839.2013.818957

de Baaij JHF, Hoenderop JGJ, Bindels RJM (2015) Magnesium in Man: Implications for Health and Disease. Physiological Reviews 95:1–46. https://doi.org/10.1152/physrev.00012.2014

de Groot M, Drenthen M, de Groot WT (2011) Public Visions of the Human/Nature Relationship and their Implications for Environmental Ethics. Environmental Ethics 33:25–44. https://doi.org/10.5840/enviroethics20113314

Desert Harvesters (2008) About Mesquite Millings. In: Desert Harvesters: Appreciating the Native Foods of the Southwest. https://www.desertharvesters.org/how-we-run-mesquite-millings/. Accessed 9 Apr 2020

Diamond JM (1983) Ecology: Laboratory, field and natural experiments. Nature 304:586–587. https://doi.org/10.1038/304586a0

Díaz S, Settele J, Brondízio ES, et al (2019) Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366:. https://doi.org/10.1126/science.aax3100

Dixon P (2003) VEGAN, a package of R functions for community ecology. Journal of Vegetation Science 14:927–930. https://doi.org/10.1111/j.1654-1103.2003.tb02228.x

Dorazio RM, Royle JA, Söderström B, Glimskär A (2006) Estimating Species Richness and Accumulation by Modeling Species Occurrence and Detectability. Ecology 87:842–854. https://doi.org/10.1890/0012-9658(2006)87[842:ESRAAB]2.0.CO;2

Estrada A, Coates-Estrada R, Meritt DA (1997) Anthropogenic landscape changes and avian diversity at Los Tuxtlas, Mexico. Biodiversity and Conservation 6:19–43. https://doi.org/10.1023/A:1018328930981

FAO (2019) The state of food security and nutrition in the world: safeguarding against economic slowdowns and downturns.

FAO (2020) FAOSTAT - Statistics Division Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat/en/#data/QC. Accessed 9 Jun 2020

Feil JP (1997) Pollination biology and seed production of dioeciousCaryodendron orinocense (Euphorbiaceae) in a plantation in coastal Ecuador. Econ Bot 51:392–402. https://doi.org/10.1007/BF02861051

Felker P (2005) Mesquite Flour: New Life for an Ancient Staple

Felker P, Clark PR, Laag AE, Pratt PF (1981) Salinity tolerance of the tree legumes: Mesquite (Prosopis glandulosa var.torreyana, P. velutina andP. articulata) Algarrobo (P. chilensis), Kiawe (P. pallida) and Tamarugo (P. tamarugo) grown in sand culture on nitrogen-free media. Plant Soil 61:311–317. https://doi.org/10.1007/BF02182012

Ferguson RS, Lovell ST (2013) Permaculture for agroecology: design, movement, practice, and worldview. A review. Agron Sustain Dev 34:251–274. https://doi.org/10.1007/s13593-013-0181-6

Ferguson RS, Lovell ST (2017) Livelihoods and production diversity on U.S. permaculture farms. Agroecology and Sustainable Food Systems 41:588–613. https://doi.org/10.1080/21683565.2017.1320349

Fernandes ECM, Nair PKR (1986) An evaluation of the structure and function of tropical homegardens. Agricultural Systems 21:279–310. https://doi.org/10.1016/0308-521X(86)90104-6

Flannery NP (2017) Mexico's avocado army: how one city stood up to the drug cartels. The Guardian

Fleskens L, Duarte F, Eicher I (2009) A conceptual framework for the assessment of multiple functions of agro-ecosystems: A case study of Trás-os-Montes olive groves. Journal of Rural Studies 25:141–155. https://doi.org/10.1016/j.jrurstud.2008.08.003

Foley JA, DeFries R, Asner GP, et al (2005) Global Consequences of Land Use. Science 309:570–574. https://doi.org/10.1126/science.1111772

Foley JA, Ramankutty N, Brauman KA, et al (2011) Solutions for a cultivated planet. Nature 478:337–342. https://doi.org/10.1038/nature10452

Food and Agriculture Organization of the United Nations (2019) The state of food security and nutrition in the world: safeguarding against economic slowdowns and downturns.

Frey GE, Mercer DE, Cubbage FW, Abt RC (2013) A real options model to assess the role of flexibility in forestry and agroforestry adoption and disadoption in the Lower Mississippi Alluvial Valley. Agricultural Economics 44:73–91. https://doi.org/10.1111/j.1574-0862.2012.00633.x

Frishkoff LO, Karp DS, M'Gonigle LK, et al (2014) Loss of avian phylogenetic diversity in neotropical agricultural systems. Science 345:1343–1346. https://doi.org/10.1126/science.1254610

Gao C, Zhu JG, Zhu JY, et al (2004) Nitrogen Export from an Agriculture Watershed in the Taihu Lake Area, China. Environmental Geochemistry and Health 26:199–207. https://doi.org/10.1023/B:EGAH.0000039582.68882.7f

Gerten D, Heck V, Jägermeyr J, et al (2020) Feeding ten billion people is possible within four terrestrial planetary boundaries. Nature Sustainability 3:200–208. https://doi.org/10.1038/s41893-019-0465-1

Glover JD, Reganold JP, Bell LW, et al (2010) Increased Food and Ecosystem Security via Perennial Grains. Science 328:1638–1639. https://doi.org/10.1126/science.1188761

Gordon C, Manson R, Sundberg J, Cruz-Angón A (2007) Biodiversity, profitability, and vegetation structure in a Mexican coffee agroecosystem. Agriculture, Ecosystems & Environment 118:256–266. https://doi.org/10.1016/j.agee.2006.05.023

Gotelli NJ (2000) Null Model Analysis of Species Co-Occurrence Patterns. Ecology 81:2606–2621. https://doi.org/10.1890/0012-9658(2000)081[2606:NMAOSC]2.0.CO;2

Gould RK, Pai M, Muraca B, Chan KMA (2019) He ʻike ʻana ia i ka pono (it is a recognizing of the right thing): how one indigenous worldview informs relational values and social values. Sustain Sci 14:1213–1232. https://doi.org/10.1007/s11625-019-00721-9

Guillaume T, Kotowska MM, Hertel D, et al (2018) Carbon costs and benefits of Indonesian rainforest conversion to plantations. Nature Communications 9:1–11. https://doi.org/10.1038/s41467-018-04755-y

Harden CP (1996) Interrelationships between Land Abandonment and Land Degradation: A Case from the Ecuadorian Andes. Mountain Research and Development 16:274–280. https://doi.org/10.2307/3673950

Harvey CA, González Villalobos JA (2007) Agroforestry systems conserve species-rich but modified assemblages of tropical birds and bats. Biodivers Conserv 16:2257–2292. https://doi.org/10.1007/s10531-007-9194-2

Hawken P (2017) Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming. Penguin

Health Canada HP and FB (2012) Canadian Nutrient File Search Engine Online. https://food-nutrition.canada.ca/cnf-fce/index-eng.jsp. Accessed 12 Jun 2020

Heilmayr R, Echeverría C, Lambin EF (2020) Impacts of Chilean forest subsidies on forest cover, carbon and biodiversity. Nature Sustainability 1–9. https://doi.org/10.1038/s41893-020-0547-0

Himes A, Muraca B (2018) Relational values: the key to pluralistic valuation of ecosystem services. Current Opinion in Environmental Sustainability 35:1–7. https://doi.org/10.1016/j.cosust.2018.09.005

Hubbell SP (1997) A unified theory of biogeography and relative species abundance and its application to tropical rain forests and coral reefs. Coral Reefs 16:S9–S21. https://doi.org/10.1007/s003380050237

Hughes JB, Daily GC, Ehrlich PR (2002) Conservation of tropical forest birds in countryside habitats. Ecology Letters 5:121–129. https://doi.org/10.1046/j.1461-0248.2002.00294.x

Hutto RL, Pletschet SM, Hendricks P (1986) A Fixed-Radius Point Count Method for Nonbreeding and Breeding Season Use. The Auk 103:593–602

IPBES (2019a) Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat

IPBES (2019b) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Task Force on National Greenhouse Gas Inventories

IPCC (2019a) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Task Force on National Greenhouse Gas Inventories

IPCC (2019b) Summary for Policy Makers: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Internation Panel on Climate Change

IPCC (ed) (2015) Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the IPCC Fifth Assessment Report. Cambridge University Press, Cambridge, pp 811–922

Jach-Smith LC, Jackson RD (2018) N addition undermines N supplied by arbuscular mycorrhizal fungi to native perennial grasses. Soil Biology and Biochemistry 116:148–157. https://doi.org/10.1016/j.soilbio.2017.10.009

Jax K, Barton DN, Chan KMA, et al (2013) Ecosystem services and ethics. Ecological Economics 93:260–268. https://doi.org/10.1016/j.ecolecon.2013.06.008

Jax K, Calestani M, Chan KM, et al (2018) Caring for nature matters: a relational approach for understanding nature's contributions to human well-being. Current Opinion in Environmental Sustainability 35:22–29. https://doi.org/10.1016/j.cosust.2018.10.009

Jones CD, Oates LG, Robertson GP, Izaurralde RC (2018) Perennialization and Cover Cropping Mitigate Soil Carbon Loss from Residue Harvesting. J Environ Qual 47:710–717. https://doi.org/10.2134/jeq2017.04.0177

Jones K, Tobin D (2018) Reciprocity, redistribution and relational values: organizing and motivating sustainable agriculture. Current Opinion in Environmental Sustainability 35:69–74. https://doi.org/10.1016/j.cosust.2018.11.001

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agroforest Syst 76:1–10. https://doi.org/10.1007/s10457-009-9229-7

Jose S, Gold MA, Garrett HE (2012) The Future of Temperate Agroforestry in the United States. In: Nair PKR, Garrity D (eds) Agroforestry - The Future of Global Land Use. Springer Netherlands, Dordrecht, pp 217–245

Kaltenborn BP, Linnell JDC, Baggethun EG, et al (2017) Ecosystem Services and Cultural Values as Building Blocks for 'The Good life'. A Case Study in the Community of Røst, Lofoten Islands, Norway. Ecological Economics 140:166–176. https://doi.org/10.1016/j.ecolecon.2017.05.003

Karnitz H, Asbjornsen H (2006) Composition and Age Structure of a Degraded Tallgrass Oak Savanna in Central Iowa. naar 26:179–186. https://doi.org/10.3375/0885-8608(2006)26[179:CAASOA]2.0.CO;2

Karp DS, Chaplin-Kramer R, Meehan TD, et al (2018) Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. Proc Natl Acad Sci USA 115:E7863–E7870. https://doi.org/10.1073/pnas.1800042115

King AE, Blesh J (2018) Crop rotations for increased soil carbon: perenniality as a guiding principle. Ecological Applications 28:249–261. https://doi.org/10.1002/eap.1648

Kloppenburg J (1991) Social Theory and the De/Reconstruction of Agricultural Science: Local Knowledge for an Alternative Agriculture1. Rural Sociology 56:519–548. https://doi.org/10.1111/j.1549-0831.1991.tb00445.x

Knippenberg L, de Groot WT, van den Born RJ, et al (2018) Relational value, partnership, eudaimonia: a review. Current Opinion in Environmental Sustainability 35:39–45. https://doi.org/10.1016/j.cosust.2018.10.022

Krebs J, Bach S (2018) Permaculture—Scientific Evidence of Principles for the Agroecological Design of Farming Systems. Sustainability 10:3218. https://doi.org/10.3390/su10093218

Kreitzman M, Eyster H, Czajewska A, et al Perennial polycultures in the US Midwest have multiple ecosystem benefits but produce little food yet. in prep

Kremen C (2015) Reframing the land-sparing/land-sharing debate for biodiversity conservation. Annals of the New York Academy of Sciences 1355:52–76. https://doi.org/10.1111/nyas.12845

Kremen C, Iles A, Bacon C (2012) Diversified Farming Systems: An Agroecological, Systems-based Alternative to Modern Industrial Agriculture. Ecology and Society 17:. https://doi.org/10.5751/ES-05103-170444

Kremen C, Merenlender AM (2018) Landscapes that work for biodiversity and people. Science 362:eaau6020. https://doi.org/10.1126/science.aau6020

Lähdesmäki M, Siltaoja M, Luomala H, et al (2019) Empowered by stigma? Pioneer organic farmers' stigma management strategies. Journal of Rural Studies 65:152–160. https://doi.org/10.1016/j.jrurstud.2018.10.008

Lal R (2003) Soil erosion and the global carbon budget. Environment International 29:437–450. https://doi.org/10.1016/S0160-4120(02)00192-7

Landis DA, Wratten SD, Gurr GM (2000) Habitat Management to Conserve Natural Enemies of Arthropod Pests in Agriculture. Annual Review of Entomology 45:175–201. https://doi.org/10.1146/annurev.ento.45.1.175

Langellotto GA, Denno RF (2004) Responses of invertebrate natural enemies to complex-structured habitats: a meta-analytical synthesis. Oecologia 139:1–10. https://doi.org/10.1007/s00442-004-1497-3

Le Gal P-Y, Dugué P, Faure G, Novak S (2011) How does research address the design of innovative agricultural production systems at the farm level? A review. Agricultural Systems 104:714–728. https://doi.org/10.1016/j.agsy.2011.07.007

Le Quéré C, Andrew RM, Friedlingstein P, et al (2018) Global carbon budget 2018. Earth System Science Data 10:2141–2194

Leopold A (1986) A Sand County Almanac: With Essays on Conservation from Round River, Reprint edition. Ballantine Books, New York

Leprieur F, Albouy C, Bortoli JD, et al (2012) Quantifying Phylogenetic Beta Diversity: Distinguishing between 'True' Turnover of Lineages and Phylogenetic Diversity Gradients. PLOS ONE 7:e42760. https://doi.org/10.1371/journal.pone.0042760

Lovell ST, Dupraz C, Gold M, et al (2018) Temperate agroforestry research: considering multifunctional woody polycultures and the design of long-term field trials. Agroforest Syst 92:1397–1415. https://doi.org/10.1007/s10457-017-0087-4

Lozupone C, Lladser ME, Knights D, et al (2011) UniFrac: an effective distance metric for microbial community comparison. ISME J 5:169–172. https://doi.org/10.1038/ismej.2010.133

MacRae RJ, Hill SB, Mehuys GR, Henning J (1990) Farm-Scale Agronomic and Economic Conversion from Conventional to Sustainable Agriculture11Ecological Agriculture Projects Research Paper No. 9. In: Brady NC (ed) Advances in Agronomy. Academic Press, pp 155–198

Magrach A, Sanz MJ (2020) Environmental and social consequences of the increase in the demand for 'superfoods' world-wide. People and Nature 2:267–278. https://doi.org/10.1002/pan3.10085

Makowski D, Ben-Shachar M, Lüdecke D (2019) bayestestR: Describing Effects and their Uncertainty, Existence and Significance within the Bayesian Framework. JOSS 4:1541. https://doi.org/10.21105/joss.01541

Martins A, Marques G, Borges O, et al (2011) Management of chestnut plantations for a multifunctional land use under Mediterranean conditions: effects on productivity and sustainability. Agroforestry Systems 81:175–189. https://doi.org/10.1007/s10457-010-9355-2

Maybery D, Crase L, Gullifer C (2005) Categorising farming values as economic, conservation and lifestyle. Journal Of Economic Psychology 26:59–72. https://doi.org/10.1016/j.joep.2003.10.001

Mays LW, Gorokhovich Y (2010) Water Technology in the Ancient American Societies. In: Mays L (ed) Ancient Water Technologies. Springer Netherlands, Dordrecht, pp 171–200

McElreath R (2016) Rethinking: an R package for fitting and manipulating Bayesian models. Version 1.56

Mehlenbacher SA (2003) PROGRESS AND PROSPECTS IN NUT BREEDING. Acta Hortic 57–79. https://doi.org/10.17660/ActaHortic.2003.622.4

Meijer SS, Catacutan D, Ajayi OC, et al (2015) The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. International Journal of Agricultural Sustainability 13:40–54. https://doi.org/10.1080/14735903.2014.912493

Méndez VE, Lok R, Somarriba E (2001) Interdisciplinary analysis of homegardens in Nicaragua: micro- zonation, plant use and socioeconomic importance. Agroforestry Systems 51:85–96. https://doi.org/10.1023/A:1010622430223

Mercer DE (2004) Adoption of agroforestry innovations in the tropics: A review. Agroforestry Systems 61:311–328. https://doi.org/10.1023/B:AGFO.0000029007.85754.70

Meyer D, Becker R, Gumbmann MR, et al (1986) Processing, composition, nutritional evaluation, and utilization of mesquite (Prosopis spp.) pods as a raw material for the food industry. J Agric Food Chem 34:914–919. https://doi.org/10.1021/jf00071a037

Michon G (2011) Revisiting the Resilience of Chestnut Forests in Corsica: from Social-Ecological Systems Theory to Political Ecology. Ecology and Society 16:. https://doi.org/10.5751/ES-04087-160205

Miller RP, Nair PKR (2006) Indigenous Agroforestry Systems in Amazonia: From Prehistory to Today. Agroforest Syst 66:151–164. https://doi.org/10.1007/s10457-005-6074-1

Mollison B, Slay RM (1995) Introduction to Permaculture. Tagari Publications

Molnar TJ, Kahn PC, Ford TM, et al (2013) Tree Crops, a Permanent Agriculture: Concepts from the Past for a Sustainable Future. Resources 2:457–488. https://doi.org/10.3390/resources2040457

Monfreda C, Ramankutty N, Foley JA (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem Cycles 22:GB1022. https://doi.org/10.1029/2007GB002947

Morandin LA, Kremen C (2013) Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. Ecological Applications 23:829–839. https://doi.org/10.1890/12-1051.1

Mora-Urpí J, Weber JC, Clement CR (1997) Peach palm, Bactris gasipaes Kunth

Morel K, Léger F, Ferguson RS (2019) Permaculture. In: Fath B (ed) Encyclopedia of Ecology (Second Edition). Elsevier, Oxford, pp 559–567

Mosquera-Losada MR, Santiago-Freijanes JJ, Pisanelli A, et al (2018) Agroforestry in the European common agricultural policy. Agroforest Syst 92:1117–1127. https://doi.org/10.1007/s10457-018-0251-5

Muthayya S, ah JH, Sugimoto JD, et al (2013) The global hidden hunger indices and maps: an advocacy tool for action. PLoS ONE 8:e67860. https://doi.org/10.1371/journal.pone.0067860

Oksanen J, Blanchet FG, Kindt R, et al (2018) Package 'vegan'community ecology package

Orians GH, Pfeiffer EW (1970) Ecological Effects of the War in Vietnam. Science 168:544–554

Pattanayak SK, Evan Mercer D, Sills E, Yang J-C (2003) Taking stock of agroforestry adoption studies. Agroforestry Systems 57:173–186. https://doi.org/10.1023/A:1024809108210

Perfecto I, Mas A, Dietsch T, Vandermeer J (2003) Conservation of biodiversity in coffee agroecosystems: a tri-taxa comparison in southern Mexico. Biodiversity and Conservation 12:1239–1252. https://doi.org/10.1023/A:1023039921916

PFAF Plant Database Caryodendron orinocense Taccy Nut, Nuez de Barinas. https://pfaf.org/user/Plant.aspx?LatinName=Caryodendron+orinocense. Accessed 10 Apr 2020

Philpott SM, Arendt WJ, Armbrecht I, et al (2008) Biodiversity Loss in Latin American Coffee Landscapes: Review of the Evidence on Ants, Birds, and Trees. Conservation Biology 22:1093–1105. https://doi.org/10.1111/j.1523-1739.2008.01029.x

Pumariño L, Sileshi GW, Gripenberg S, et al (2015) Effects of agroforestry on pest, disease and weed control: A meta-analysis. Basic and Applied Ecology 16:573–582. https://doi.org/10.1016/j.baae.2015.08.006

Purvis A, Molnar Z, Obura D, et al (2019) Status and trends - nature. Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

Quinlan RJ, Quinlan MB, Dira S, et al (2015) Vulnerability and Resilience of Sidama Enset and Maize Farms in Southwestern Ethiopia. etbi 35:314–336. https://doi.org/10.2993/etbi-35-02-314-336.1

Ragone D (2006) Artocarpus camansi (breadnut)

Ramankutty N, Rhemtulla J (2012) Can intensive farming save nature? Frontiers in Ecology and the Environment 10:455–455. https://doi.org/10.1890/1540-9295-10.9.455

Ray DK, Ramankutty N, Mueller ND, et al (2012) Recent patterns of crop yield growth and stagnation. Nature Communications 3:1293. https://doi.org/10.1038/ncomms2296

Reich PB, Peterson DW, Wedin DA, Wrage K (2001) Fire and Vegetation Effects on Productivity and Nitrogen Cycling Across a Forest–Grassland Continuum. Ecology 82:1703–1719. https://doi.org/10.1890/0012-9658(2001)082[1703:FAVEOP]2.0.CO;2

Ricketts TH (2001) The Matrix Matters: Effective Isolation in Fragmented Landscapes. The American Naturalist 158:87–99. https://doi.org/10.1086/320863

Ries L, Fletcher RJ, Battin J, Sisk TD (2004) Ecological Responses to Habitat Edges: Mechanisms, Models, and Variability Explained. Annual Review of Ecology, Evolution, and Systematics 35:491–522

Ritchie H, Reay DS, Higgins P (2018) Beyond Calories: A Holistic Assessment of the Global Food System. Front Sustain Food Syst 2:. https://doi.org/10.3389/fsufs.2018.00057

Robertson GP, Swinton SM (2005) Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Frontiers in Ecology and the Environment 3:38–46. https://doi.org/10.1890/1540-9295(2005)003[0038:RAPAEI]2.0.CO;2

Rockström J, Steffen W, Noone K, et al (2009) Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecology and Society 14:

Rode J, Gómez-Baggethun E, Krause T (2015a) Motivation crowding by economic incentives in conservation policy: A review of the empirical evidence. Ecological Economics 117:270–282. https://doi.org/10.1016/j.ecolecon.2014.11.019

Rode J, Gómez-Baggethun E, Krause T (2015b) Motivation crowding by economic incentives in conservation policy: A review of the empirical evidence. Ecological Economics 117:270–282. https://doi.org/10.1016/j.ecolecon.2014.11.019

Rosa H, Kandel S, Dimas L (2004) Compensation for environmental services and rural communities: lessons from the Americas. International Forestry Review 6:187–194. https://doi.org/10.1505/ifor.6.2.187.38401

Rudel TK, Schneider L, Uriarte M, et al (2009) Agricultural intensification and changes in cultivated areas, 1970-2005. PROC NAT ACAD OF SCI (USA) 106:20675–20680. https://doi.org/10.1073/pnas.0812540106

Saad N (2002) Farmer Processes of Experimentation and Innovation: A Review of the Literature. CGIAR, Cali, Colombia

Saldana J (2015) The Coding Manual for Qualitative Researchers. SAGE

Samuel S (2019) Forget GDP — New Zealand is prioritizing gross national well-being. In: Vox. https://www.vox.com/future-perfect/2019/6/8/18656710/new-zealand-wellbeing-budget-bhutan-happiness. Accessed 5 Jun 2020

Savanna Institute Land Access. http://www.savannainstitute.org/land-access.html. Accessed 12 Apr 2020

Scales BR, Marsden SJ (2008) Biodiversity in small-scale tropical agroforests: a review of species richness and abundance shifts and the factors influencing them. Environmental Conservation 35:160–172. https://doi.org/10.1017/S0376892908004840

Schalkwyk J van, Pryke JS, Samways MJ, Gaigher R Congruence between arthropod and plant diversity in a biodiversity hotspot largely driven by underlying abiotic factors. Ecological Applications 0:e01883. https://doi.org/10.1002/eap.1883

Schenker N, Gentleman JF (2001) On Judging the Significance of Differences by Examining the Overlap Between Confidence Intervals. The American Statistician 55:182–186. https://doi.org/10.1198/000313001317097960

Schulte LA, Asbjornsen H, Liebman M, Crow TR (2006) Agroecosystem restoration through strategic integration of perennials. Journal of Soil and Water Conservation 61:164A-169A

Scoones I (1998) Sustainable Rural Livelihoods: A Framework for Analysis

Sereke F, Dobricki M, Wilkes J, et al (2016) Swiss farmers don't adopt agroforestry because they fear for their reputation. Agroforest Syst 90:385–394. https://doi.org/10.1007/s10457-015-9861-3

Shahabuddin S (2013) Contribution of Alpha and Beta Diversity Across Land-Use Type to the Regional Diversity of Dung Beetles in Central Sulawesi. HAYATI Journal of Biosciences 20:72–79. https://doi.org/10.4308/hjb.20.2.72

Shay CT (1978) Late Prehistoric Bison and Deer Use in the Eastern Prairie-Forest Border. Plains Anthropologist 23:194–212. https://doi.org/10.1080/2052546.1978.11908916

SIAP Agri-Food and Fisheries Information Service. https://www.gob.mx/siap/. Accessed 11 Apr 2020

Simon S, Bouvier J-C, Debras J-F, Sauphanor B (2010) Biodiversity and pest management in orchard systems. A review. Agronomy for Sustainable Development 30:139–152. https://doi.org/10.1051/agro/2009013

Siti HN, Kamisah Y, Kamsiah J (2015) The role of oxidative stress, antioxidants and vascular inflammation in cardiovascular disease (a review). Vascular Pharmacology 71:40–56. https://doi.org/10.1016/j.vph.2015.03.005

Smith DJ (2010) The History of Temperate Agroforestry. The Organic Research Centre, Elm Farm

Smith J, Pearce BD, Wolfe MS (2012) A European perspective for developing modern multifunctional agroforestry systems for sustainable intensification. Renewable Agriculture and Food Systems 27:323–332. https://doi.org/10.1017/S1742170511000597

Smith J, Pearce BD, Wolfe MS (2013) Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? Renewable Agriculture and Food Systems 28:80–92

Smith R (1929) Tree Crops, a Permanent Agriculture. Harcourt, Brace, New York

Sorace A, Gustin M, Calvario E, et al (2000) Assessing Bird Communities by Point Counts: Repeated Sessions and their Duration. aorn 35:197–202. https://doi.org/10.3161/068.035.0213

Stanek EC, Lovell ST, Reisner A (2019) Designing multifunctional woody polycultures according to landowner preferences in Central Illinois. Agroforest Syst 93:2293–2311. https://doi.org/10.1007/s10457-019-00350-2

Suter PM (2005) Carbohydrates and Dietary Fiber. In: von Eckardstein A (ed) Atherosclerosis: Diet and Drugs. Springer, Berlin, Heidelberg, pp 231–261

Taylor JR (1997) An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. University Science Books

Teshager AD, Gassman PW, Secchi S, Schoof JT (2017) Simulation of targeted pollutant-mitigation-strategies to reduce nitrate and sediment hotspots in agricultural watershed. Science of The Total Environment 607–608:1188–1200. https://doi.org/10.1016/j.scitotenv.2017.07.048

Thrupp LA (1989) Legitimizing local knowledge: From displacement to empowerment for third world people. Agric Hum Values 6:13–24. https://doi.org/10.1007/BF02217665

Toensmeier E (2017) Perennial Staple Crops and Agroforestry for Climate Change Mitigation. In: Montagnini F (ed) Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty. Springer International Publishing, Cham, pp 439–451

Torralba M, Fagerholm N, Burgess PJ, et al (2016) Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agriculture, Ecosystems & Environment 230:150–161. https://doi.org/10.1016/j.agee.2016.06.002

Trozzo KE, Munsell JF, Chamberlain JL (2014) Landowner interest in multifunctional agroforestry Riparian buffers. Agroforest Syst 88:619–629. https://doi.org/10.1007/s10457-014-9678-5

Tsegaye A, Struik PC (2002) ANALYSIS OF ENSET (ENSETE VENTRICOSUM) INDIGENOUS PRODUCTION METHODS AND FARM-BASED BIODIVERSITY IN MAJOR ENSET-GROWING REGIONS OF SOUTHERN ETHIOPIA. Experimental Agriculture 38:291–315. https://doi.org/10.1017/S0014479702003046

Turcotte MM, Araki H, Karp DS, et al (2017) The eco-evolutionary impacts of domestication and agricultural practices on wild species. Philosophical Transactions of the Royal Society B: Biological Sciences 372:20160033. https://doi.org/10.1098/rstb.2016.0033

USDA (2019) Census of Agriculture Highlights 2017: Farm Producers. United States Department of Agriculture National Agricultural Statistics Service

USDA (2019) Agroforestry Strategic Framework: Fiscal Years 2019-2024

USDA (2020) Pecan Production. National Agricultural Statistics Service USDA

USDA, USHHS (2011) U.S. Department of Agriculture and U.S. Department of Health and Human Services, Dietary Guidelines for Americans, 2010, 7th Edition. USDA, US Government Printing Office

Uylaşer V, Yildiz G (2014) The Historical Development and Nutritional Importance of Olive and Olive Oil Constituted an Important Part of the Mediterranean Diet. Critical Reviews in Food Science and Nutrition 54:1092–1101. https://doi.org/10.1080/10408398.2011.626874

Valle FRD, Marco E, Becker R, Saunders RM (1989) DEVELOPMENT of PRODUCTS CONTAINING MESQUITE (PROSOPIS spp.) POD FLOUR and THEIR NUTRITIONAL and ORGANOLEPTIC EVALUATION. Journal of Food Processing and Preservation 13:447–456. https://doi.org/10.1111/j.1745-4549.1989.tb00118.x

Van Herk WG, Vernon RS, Borden JH (2018) A pheromone-baited pitfall trap for monitoring Agriotes spp. click beetles (Coleoptera: Elateridae) and other soil- surface insects. 3

van Noordwijk M, Coe R, Sinclair F (2016) Central hypotheses for the third agroforestry paradigm within a common definition. World Agroforestry Centre (ICRAF)

Vandermeer J, Perfecto I, Philpott S (2010) Ecological Complexity and Pest Control in Organic Coffee Production: Uncovering an Autonomous Ecosystem Service. BioScience 60:527–537. https://doi.org/10.1525/bio.2010.60.7.8

Verbruggen E, Kiers ET (2010) Evolutionary ecology of mycorrhizal functional diversity in agricultural systems. Evolutionary Applications 3:547–560. https://doi.org/10.1111/j.1752-4571.2010.00145.x

Vongvisouk T, Broegaard RB, Mertz O, Thongmanivong S (2016) Rush for cash crops and forest protection: Neither land sparing nor land sharing. Land Use Policy 55:182–192. https://doi.org/10.1016/j.landusepol.2016.04.001

Waldman KB, Ortega DL, Richardson RB, Snapp SS (2017) Estimating demand for perennial pigeon pea in Malawi using choice experiments. Ecological Economics 131:222–230. https://doi.org/10.1016/j.ecolecon.2016.09.006

Walker B, Holling CS, Carpenter S, Kinzig A (2004) Resilience, Adaptability and Transformability in Social–ecological Systems. Ecology and Society 9:. https://doi.org/10.5751/ES-00650-090205

Walljasper C (2018) Large animal feeding operations on the rise. In: Investigate Midwest. https://investigatemidwest.org/2018/06/07/large-animal-feeding-operations-on-the-rise/. Accessed 2 Jun 2020

Weißhuhn P, Reckling M, Stachow U, Wiggering H (2017) Supporting Agricultural Ecosystem Services through the Integration of Perennial Polycultures into Crop Rotations. Sustainability 9:2267. https://doi.org/10.3390/su9122267

Wilcove DS, Koh LP (2010) Addressing the threats to biodiversity from oil-palm agriculture. Biodivers Conserv 19:999–1007. https://doi.org/10.1007/s10531-009-9760-x

Wilcove DS, Lee J (2004) Using Economic and Regulatory Incentives to Restore Endangered Species: Lessons Learned from Three New Programs. Conservation Biology 18:639–645. https://doi.org/10.1111/j.1523-1739.2004.00250.x

Wilson TS, Sleeter BM, Cameron DR (2016) Future land-use related water demand in California. Environ Res Lett 11:054018. https://doi.org/10.1088/1748-9326/11/5/054018

Withers PJA, Neal C, Jarvie HP, Doody DG (2014) Agriculture and Eutrophication: Where Do We Go from Here? Sustainability 6:5853–5875. https://doi.org/10.3390/su6095853

Wittman H (2011) Food Sovereignty: A New Rights Framework for Food and Nature? Environment and Society 2:87–105. https://doi.org/10.3167/ares.2011.020106

Wolz KJ, Lovell ST, Branham BE, et al (2017) Frontiers in alley cropping: Transformative solutions for temperate agriculture. Glob Chang Biol 24:883–894. https://doi.org/10.1111/gcb.13986

Yoshida Y, Flint CG, Dolan MK (2018) Farming between love and money: US Midwestern farmers' human–nature relationships and impacts on watershed conservation. Journal of

Environmental Planning and Management 61:1033–1050. https://doi.org/10.1080/09640568.2017.1327423

Young RR, Wilson B, Harden S, Bernardi A (2009) Accumulation of soil carbon under zero tillage cropping and perennial vegetation on the Liverpool Plains, eastern Australia. Soil Res 47:273–285. https://doi.org/10.1071/SR08104

Yusuf M, Teklehaimanot Z, Gurmu D (2013) The decline of the Vulnerable yeheb Cordeauxia edulis, an economically important dryland shrub of Ethiopia. Oryx 47:54–58. https://doi.org/10.1017/S0030605311000664

Zohary D (2002) Domestication of the carob (Ceratonia siliqua L.). Israel Journal of Plant Sciences 50:141–145. https://doi.org/10.1560/BW6B-4M9P-U2UA-C6NN

Zohary D, Weiss E, Hopf* M Fruit trees and nuts. Oxford University Press

Zomer RJ, Trabucco A, Coe R, Place F (2009) Trees on farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper - World Agroforestry Centre

Zuazo VHD, Pleguezuelo CRR Soil-erosion and runoff prevention by plant covers. A review. Agron Sustain Dev 28:65–86. https://doi.org/10.1051/agro:2007062

Appendices

Appendix A - Chapter 2 supplement

Table S1. Perennial staple crops with available yield data

Latin Name	**common name**	**region/climate**	**humidity**	**cultivation status**	**nutritional category**	**UN data?**
BALANCED CARBOHYDRATES						
Brosimum alicastrum	Mayan Breadnut	tropical	semi-arid to humid	regional crop	balanced carbohydrate	no
Castanea spp.	Chestnut	cold to warm temperate and mediterranean	semi-arid to humid	global commodity	balanced carbohydrate	yes
Cordeauxia edulis	Yeheb nut	tropical	arid to semi-arid	regional crop	balanced carbohydrate	no
Inocarpus fagifer	Tahitian chestnut	tropical	humid	regional crop	balanced carbohydrate	no
Prosopis (hardy)	Mesquite	temperate	arid	regional crop	balanced carbohydrate	no
Prosopis (tropical)	Mesquite	sub-tropical to tropical	humid to arid	regional crop	balanced carbohydrate	no
Quercus ilex	Evergreen Oak/ Encina	mediterranean, warm-temperate, to subtropical	semi-arid	regional crop	balanced carbohydrate	no
BASIC STARCH						

Artocarpus altilis	Breadfruit	tropical	humid	minor global commodity	basic starch	no
Ceratonia siliqua	Carob	mediterranean, subtropical	arid to semi-arid	minor global commodity	basic starch	yes
Dioscorea bulbifera	Air potato	subtropical to humid tropical to tropical highlands	humid	minor global commodity	basic starch	no
Ensete ventricosum	Enset	tropical highlands	humid	regional crop	basic starch	no
Metroxylon sagu	Sago palm	tropical	humid	regional crop	basic starch	no
Musa (banana)	Banana	lowland to highland tropics	humid	global commodity	basic starch	yes
Musa (plantain)	Plantain	tropical	humid	global commodity	basic starch	yes
PROTEIN						
Acacia colei	Edible acacia	tropical	semi-arid	historical wild staple, new crop	protein	no
Cajanus cajan (perennial)	Pigeon pea (perennial)	subtropical to tropical, tropical highlands	semi-arid to humid	global crop as annual, new perennial crop	protein	no
Canavalia gladiata	Sword bean	tropical, tropical highlands	semi-arid to humid	regional crop	protein	no
Erythrina edulis	Chachafruto	tropical highlands	semi-arid to humid	regional crop	protein	no

Gleditsia triacanthos	Honey locust	boreal to subtropical, lowlands and hihglands	semi-arid to humid	minor global crop	protein	no
Medicago sativa (LPC)	Alfalfa	boreal to warm temperate, tropical highlands	semi-arid to humid	global crop	protein	no
Phaseolus coccineus	Runner bean (vine types)	warm temperate, tropical highlands	humid	minor global crop	protein	no
Phaseolus lunatus	Lima bean (vine types)	tropical, tropical highlands	semi-arid to humid	minor global crop	protein	no
Sphenostylis stenocarpa	African yambean	Tropical, tropical highlands	humid	regional crop	protein	no
Urtica dioica (LPC)	Stinging nettle	boreal to subtropical	humid	regional crop	protein	no
PROTEIN-OIL						
Anacardium occidentale	Cashew	tropical	semi-arid to humid	global crop	protein-oil	yes
Artocarpus camansii	Asian breadnut	tropical	humid	minor global crop	protein-oil	no
Bertholletia excelsa	Brazil nut	tropical	humid	minor global crop, mostly wild-collected	protein-oil	yes
Blighia sapida	Akee	tropical	humid	regional crop	protein-oil	no
Caryodendron orinococense	Inche/ Tacay nut	tropical	humid	experimental crop	protein-oil	no
Citrullis colocynthis	Colocynth/perennial egusi	subtropical to tropical	arid to semi-arid	regional crop	protein-oil	no

Corylus avellana	Hazelnut	warm temperate, Mediterranean	humid	global crop	protein-oil	yes
Cucurbita foetidissima	Buffalo gourd	cold temperate to subtropical	arid to semi-arid	regional crop	protein-oil	no
Juglans regia	Persian walnut	warm temperate, Mediterranean	semi-arid to humid	global crop	protein-oil	yes
Parkia biglobosa	African locust bean	tropical	semi-arid	regional crop	protein-oil	no
Pinus pinea	Italian stone pine	warm temperate to subtropical, Mediterranean	arid to semi-arid	minor global crop	protein-oil	no
Pinus siberica	Siberian pine	boreal to warm temperate	semi-arid to humid	minor global crop	protein-oil	no
Pistacia vera	Pistachio	warm temperate to subtropical, Mediterranean	arid to semi-arid	global crop	protein-oil	yes
Prunus dulcis	Almond	cold temperate to subtropical, Mediterranean	semi-arid to humid	global crop	protein-oil	yes
Psophocarpus tetragonobolus	Winged bean	tropical, tropical highlands	humid	minor global crop	protein-oil	no
Schinziophyton rautenenii	Mongongo nut	subtropical to tropical	semi-arid	wild staple	protein-oil	no
Telfairia pedata	Oyster nut	tropical, tropical highlands	humid	regional crop	protein-oil	no
Vitellaria paradoxa	Shea	tropical	semi-arid to humid	minor global crop	protein-oil	yes
Xanthoceras sorbifolium	Yellowhorn	cold to warm temperate	semi-arid to humid	regional crop	protein-oil	no

OIL						
Bactris gasipaes	Peach palm	tropical	humid	regional crop	Oil	no
Carya illinoiensis	Pecan	cold temperate subtropical, tropical highlands	humid	global crop	Oil	no
Cocos nucifera	Coconut	tropical	semi-arid to humid	global crop	Oil	yes
Elaeagnus rhamnoides	Seaberry	boreal to warm temperate	semi-arid	minor global crop	Oil	no
Elaeis guineensis	African oil palm	tropical	humid	global crop	Oil	yes
Macadamia spp.	Macadamia nut	subtropical, tropical, tropical highlands	semi-arid to humid	global crop	Oil	no
Olea europea	Olive	Mediterranean, tropical	semi-arid	global crop	Oil	yes
Persea americana	Avocado	tropical, tropical highlands	humid	global crop	Oil	yes
Pinus koraiensis	Korean pine	boreal to warm temperate	humid	minor global crop	Oil	no
Tetradium daniellii	Evodia	cold to warm temperate	humid	regional crop	Oil	no

Supplementary Table 2: Carbon stocks and changes of perennial staple crops

Latin Name	common name	total C current (Mega Tonnes C)	total C 2040 (Mega Tonnes C)	change in C - from annual cropland (Mega Tonnes C)	change in C - from grassland (Mega Tonnes C)	change in C - from forest (Mega Tonnes C)
BALANCED CARBOHYDRATES						
Castanea spp.	Chestnut	86.38	120.43	12.53	2.67	-18.01
BASIC STARCH						
Ceratonia siliqua	Carob	3.18	0.00	-0.45	0.48	3.59
Musa (banana)	Banana	818.69	1101.72	34.90	-26.18	-412.22
Musa (plantain)	Plantain	831.38	959.81	17.39	-11.88	-187.05
Metroxylon sagu	Sago palm	1108.25	1108.25	0.00	0.00	0.00
PROTEIN						
PROTEIN-OIL						
Prunus dulcis	Almond	142.68	196.87	12.24	-6.20	-57.41
Bertholletia excelsa	Brazil nut	2.92	4.41	0.96	0.52	-0.69
Anacardium occidentale	Cashew	942.94	1297.44	75.72	-10.75	-466.75
Corylus avellana	Hazelnut	81.86	131.90	7.03	-4.96	-43.74
Juglans regia	Persian walnut	156.63	224.91	25.06	7.07	-36.13

Pistacia vera	Pistachio	55.84	111.92	16.81	-1.81	-50.90
Vitellaria paradoxa	Shea	91.65	114.10	3.80	-1.15	-11.11
OIL						
Bactris gasipaes	Peach palm	1.43	1.43	0.00	0.00	0.00
Elaeis guineensis	African oil palm	3610.02	4518.78	354.08	73.75	-1282.54
Persea americana	Avocado	114.45	210.70	43.39	20.92	-73.13
Cocos nucifera	Coconut	2456.06	3098.49	285.65	122.79	-185.48
Macadamia spp.	Macadamia nut	13.65	13.65	0.00	0.00	0.00
Olea europea	Olive	823.65	1129.93	75.42	-32.64	-319.98
Carya illinoiensis	Pecan	44.67	44.67	0.00	0.00	0.00
Totals		**11386.34**	**14389.41**	**964.98**	**132.13**	**-3145.14**

Appendix B - Chapter 3 supplement

B.1 Supplementary methods

Table S1: Crops on perennial and comparison fields.

Farm #				
	Perennial field 1	**Perennial field 2**	**Comparison field 1**	**Comparison field 2**
1	Chestnut, plum, blackberry, black currants, sugar maple, witch hazel, winterberry		corn	
2	Chestnut, hazelnut, red currants, black currants, rhubarb		soybean	
3	Chestnut, pawpaw, gooseberries, black currants, comfrey	Chestnuts, persimmon, asian pear, heartnuts, blackberries	soybean	
4	Chestnut, hazelnut, persimmon, pawpaw		hay - young alfalfa, with nurse crop of oats	
5	Chestnut, persimmon, cherry, apple, seaberry, pawpaw, honeyberry, elderberry, hawthorne, apricot, hay in some alleys		corn	
6	Hazelnut, blackberry, red currant, black currant, chestnut, apple, saskatoon berry, raspberry, rhubarb, hay in some alleys		corn	
7	Plum, persimmon, cherry, quince, ash, pear, blackberry, rose, black currant, gooseberry, aronia		corn	
8	Chestnut, hazelnut	Chestnut, gooseberry, black currant, red currant, mulberry, elderberry, apple	soy	
9	Apple, quince, black currant, aronia, saskatoon berry, seaberry, elderberry, apricot, crabapple, asian pear, plum, chives		corn	

10	Hazelnut, elderberry, corn & sunflower & clover in alleys		soybean	
11	Hazelnut, elderberry, apple, sugar maple, corn & sunflower in alleys		corn	
12	Apple, pear, grape, saskatoon berries, red currant, black currant, gooseberries, plum, apricot, highbush cranberry, aronia, blueberry, honeyberry, garlic		Hay - mature alfalfa rotated with corn every 3-4 years.	
13	Apple, plum, black currant, apricot, cherry, clover in alleys, various flowers		corn	fallow hay field, not regularly mowed
14	Pear, apple, highbush cranberry, elderberry, linden		Hay, diverse grass-based, mowed once a year.	

Table S2: Statistical models

R package	Response variable	Model syntax
lme4	Bulk density	z <- lmer(density ~ treatment + (1|farm), data = mydata)
lme4	pH	z <- lmer(pH ~ treatment + (1|farm), data = mydata)
lme4	Active carbon	z <- lmer(Active.Carbon ~ treatment + Silt + (1|farm), data = mydata)
lme4	Total carbon	z <- lmer(Total.Carbon ~ treatment + Silt + (1|farm), data = mydata)
lme4	Inorganic carbon	z <- lmer(Inorganic.Carbon ~ treatment + Silt + (1|farm), data = mydata)
lme4	Total nitrogen	z <- lmer(Total.Nitrogen ~ treatment + (1|farm), data = mydata)
lme4	Available phosphorus	z <- lmer(Available.Phosphorus ~ treatment + (1|farm), data = mydata)
lme4	Insect diversity (Richness, Shannon, functional richness, Abundance)	z <- lmer(Diversity index ~ treatment*trap type + visit + (1|farm), data = indices) note** full study design structure not included in random effects (ie. quadrant) because of singular fits.
lme4	Insect ecosystem services/ disservices (number of species, number of individuals)	z <- lmer(ES supply index ~ cover.type*ES*trap_type + visit + (1|farm), data=ES_matrix)

lme4	Plant cover (Shannon, abundance, Pielou's evenness)	z <- lmer(Diversity index ~ cover.type + (1|farm), data=indices) **full study design not included (ie. quadrant) because of singular fits.
lme4	Plant general diversity (total richness)	z <- lmer(Richness ~ cover.type + (1|farm), data=indices_all)
lme4		z <- lmer(percent.cover ~ cover.type + (1|farm/quadrant), data=mydata_ground)
lme4	Plant diversity (vs time)	lm(Richness ~ field.age*cover.type, data = indices_all)

Study design and sampling methods

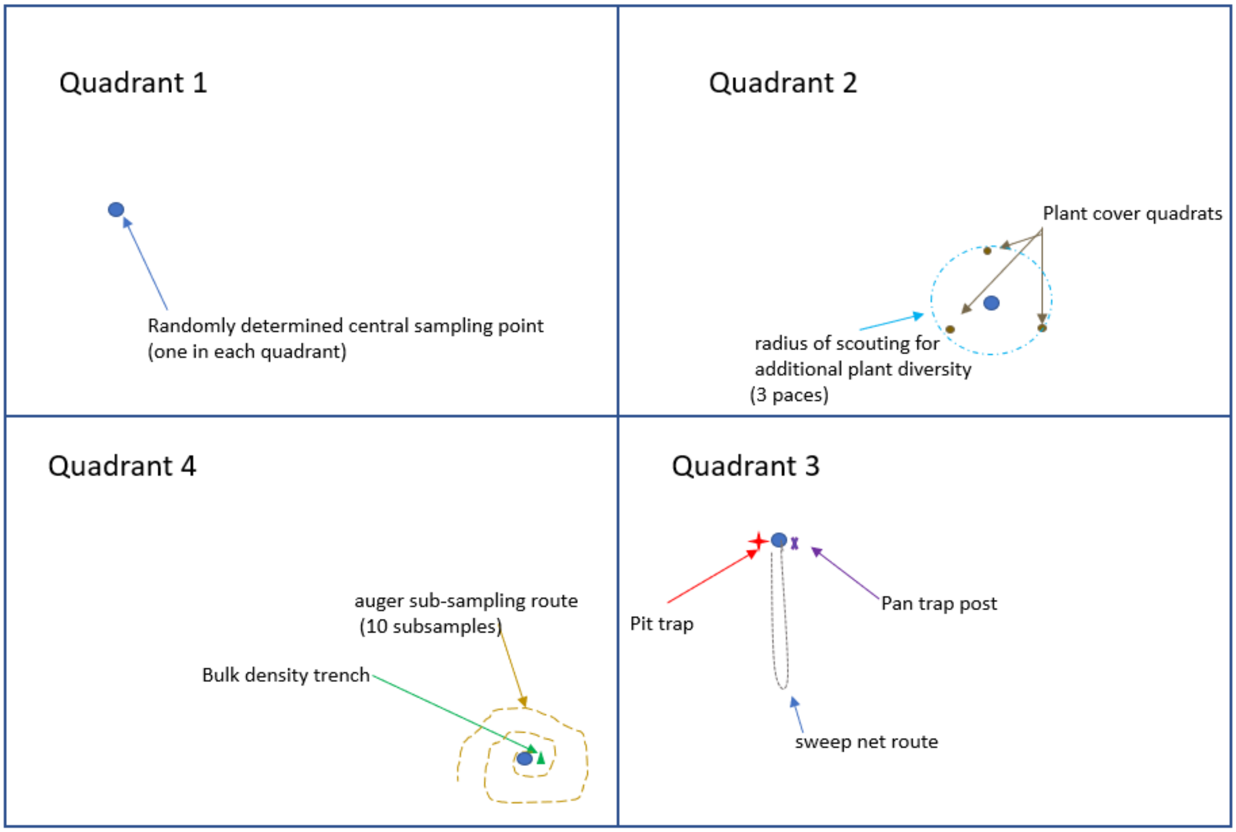


Figure S1: Study design. Each field was divided into quadrants. A randomly determined central sampling point was found in each quadrant. Plant, insect, and soil sampling was conducted centred around this central point. For clarity of illustration, plant methods are illustrated in quadrant 2, insect methods in quadrant 3, and soil methods in quadrant 4. All methods were carried out in every quadrant. Illustration is not to scale.

Figure S2: Sampling methods. a) Auger - ten auger samples were composited into buckets (on for 0-15 cm, one for 15-30 cm), and then subsampled. b) Bulk density - a trench was dug with two “shelves” at the appropriate depth. The ring was then pounded into the shelf and removed using a flat palette knife. c) Pit trap - Vernon pitfall traps were used (photo courtesy of Wim va Herk). d) Pan trap - a post pounded into the ground was fitted with a wooden platform with three holes designed to fit the colourful nested bowls. Bowls were kept in place using wire clips fixed to the wooden platform.

<u>Soil physical and chemical properties</u>

1. pH (H2O) – The <2mm soil was mixed at a soil : water ratio of 1:1 and the resulting supernatant was analyzed for pH (Carter, 2008; section 15.2).
2. Active Carbon - The soil is mixed with potassium permanganate to oxidize it and evaluated for absorbance on a colour scale (Weil, 2003).

3. Available Phosphorus - Extracted using Bray P1 extractant, then complexed with ammonium molybdate and antimony potassium tartrate to form a stable antimony-phospho-molybdenum blue complex that absorbs strongly at 882 nm. (Kalra, 1991).
4. Total nitrogen and carbon - Combustion: the <2mm sieve was finely ground and was combusted at high temperature. During the combustion process, virtually all compounds containing the elements of interest are decomposed and the elements are released as the oxide gases (CO_2, NO_x, and SO_2). The ensuing gas mixture is processed to convert the NO_x gas to more easily measurable nitrogen gas, and to remove interfering water vapour. The gases are separated by chromatography and measured by thermal conductivity by comparison against values obtained from certified calibration standards; these values are converted back to element concentrations in the original sample (Thermo Fisher application notes).
5. Total organic carbon - Subtraction of inorganic carbon from the total carbon.
6. Texture – The <2mm sieve was mixed with a dispersion agent and a Hydrometer was used to measure the density of the resulting suspension, which is proportional to the settling rates of soil particles in suspension (Carter, 2008; Section 55.3).

Microbial diversity: library construction and Sequencing

gDNA templates were used as starting material to generate PCR products of 16S and ITS using the following primers.

Bacteria 16S	16S_F	CGCTCTTCCGATCTCTGCCTACGGGNGGCWGCAG
	16S_R	TGCTCTTCCGATCTGACGACTACHVGGGTATCTAATCC

Fungal ITS ITS_F CGCTCTTCCGATCTCTGTCCGTAGGTGAACCTGCGG

ITS_R TGCTCTTCCGATCTGACTCCTCCGCTTATTGATATGC

The primers were tagged with Illumina adapters to enable a direct sequencing approach with the following tags: 5'- CGCTCTTCCGATCTCTG and 5'- TGCTCTTCCGATCTGAC. PCR was set up using Q5 Hot Start High-Fidelity DNA Polymerase (NEB, catalogue # M0493L) with the following conditions. There was an initial denaturation of 98°C for 30 seconds, followed by 30 cycles of 98°C for 10 seconds, 55°C for 30 seconds and 72°C for 30 seconds, and a final extension at 72°C for 5 minutes. PCR was assessed on a 1.2% agarose gel for a 16S and ITS amplicons of approximately 500bp and were subsequently cleaned up using PCRClean DX beads (Aline Biosciences, USA). Sample preparation involved a second round of amplification using Q5 Hot Start High-Fidelity DNA Polymerase with 6 cycles using PE primer 1.0-DS (5'-AATGATACGGCGACCACCGAGATCTACACNNNNNNNNTCTTTCCCTACACGACGCTCTTCCGATCTCTG-3') and a custom PCR Primer (5'-CAAGCAGAAGACGGCATACGAGATNNNNNNNGTGACTGGAGTTCAGACGTGTGCTCTTCCGATCTGAC-3') that contained a unique dual nucleotide 'index' shown here as N's. DNA quality was assessed using the Caliper LabChip GX High Sensitivity Assay (Caliper Life Sciences, USA) and DNA quantity was measured using a Qubit dsDNA HS assay kit on a Qubit fluorometer (Life Technologies, USA). The indexed samples were pooled together and sequenced on the Illumina MiSeq platform with paired-end 250bp reads using v2 reagents. An in-house generated PhiX control library was spiked into the samples as a sequencing control.

Microbial abundance: Library construction and QPCR gDNA templates were used as starting material for quantitative PCR to estimate bacterial (Liu et al. BMC Microbiology 2012, 12:56) and fungal (Liu et al. BMC Microbiology 2012, 12:255) loads using the following primers.

BacQuant Fw	CCTACGGGDGGCWGCA
BacQuant Rv	GGACTACHVGGGTMTCTAATC
FungiQuant Fw	GGRAAACTCACCAGGTCCAG
FungiQuant Rv	GSWCTATCCCCAKCACGA

gDNA for the samples was quantified using the Qubit dsDNA HS assay kit on a Qubit fluorometer (Life Technologies, USA) and a normalized template amount was used for qPCR. qPCR was performed in triplicate using the KAPA SYBR FAST Universal kit (Sigma-Aldrich, cat# KK4602) on a CFX384 Touch Real-Time System (Bio-Rad). qPCR reactions were in 10µL reaction volume with 5µL of 2x Mastermix, 0.25µL of forward primer (10µM), 0.25µL of reverse primer (10µM), and 2.1ng gDNA template. The cycling conditions for bacterial load consisted of one cycle of 95°C for 10 min, followed by 40 cycles of 95°C for 10 sec, 60°C for 30 sec and 72°C for 30 sec, and a final step of 72°C for 5 min. The conditions for the melting curve analysis were according to the instrument's default setting of 65°C to 95°C with 0.5°C increments. The cycling conditions for fungal load consisted of one cycle of 95°C for 10 min, followed by 50 cycles of 95°C for 10 sec, 65°C for 30 sec and 72°C for 30 sec, and a final step of 72°C for 5 min. The conditions for the melting curve analysis were according to the instrument's default setting of 65°C to 95°C with 0.5°C increments.

Insect identification framework

Trophic groups

1. herbivorous
2. herbivorous (aquatic)
3. Xylophagous (eats wood and/or burrows into wood)
4. mycophagous (fungus eater)
5. Exudativorous (eater of material that oozes out of a plant, like sap)
6. detritivorous
7. scavenger
8. omnivorous
9. predatory
10. parasitic
11. nectar/pollen
12. hematophagous
13. granivorous (seed eater)
14. unknown/diverse

Non-Insect arthropods

Order: Isopoda (woodbugs)
detritivorous

Class: Diplopoda (millipedes)
detritivorous

Class: Chilopoda (centipedes)
predatory

Class: Arachnida

- Order Araneae (spiders) (predatory)
- Order Opiliones (harvestman) (omnivorous/predatory)
- Subclass Acari (ticks and mites)
  - Order Trombidiformes (predatory)
  - Other mites (unknown)
  - Order Ixodida (ticks) (parasitic)

Class: Entognatha

- Order Collembola (springtails) (detritivorous)

Insect arthropods
Class Insecta
Order Hemiptera (true bugs)

- Homoptera (suborder) (all herbivorous)
  - Cicadellidae (leafhoppers)
  - Cercopidae (spittlebugs)

- Membracidae (treehoppers)
- Aphididae (aphids)
- Flatidae (planthoppers)
- Acanaloniidae (planthoppers)
- Derbidae (planthoppers)
- Issidae (planthoppers)
- Dictyopharidae (planthoppers)
- Fulgoridae (planthoppers)

- Heteroptera (suborder)

Predatory

- Reduviidae (assassin bugs)
- Phymatidae (ambush bugs)
- Geocoridae (big-eyed bugs)
- Enicocephalidae (unique-headed bugs)
- Anthocoridae (minute pirate bugs)
- Nabidae (damsel bugs)
- Saldidae (shore bugs)

Herbivorous

- Lygaeidae (seed bugs and milkweed bugs)
- Rhyparochromidae (seed bugs)
- Berytidae (stilt bugs)
- Coreidae (leaf-footed bugs)
- Alydidae (broad-headed bugs)
- Cydnidae (burrowing bugs)
- Pyrrhocoridae (red bugs)
- Tingidae (lace bugs)
- Scutelleridae (shield-backed bugs)
- Pentatomidae (stinkbugs)
  - Subfamily Asopinae (predatory)
  - Edessinae (herbivorous)
  - Pentatominae (herbivorous)
  - Podopinae (herbivorous)

Mycophagous

- Aradidae (flat bugs)

Unknown/Diverse Feeding

- Miridae

Order Thysanoptera (unknown)
except: Aelothripidae: mostly predatory ie: Genus *Franklinothrips, Aeolothrips (banded thrips)*
Order Orthoptera

- Caelifera (grasshoppers) (Suborder) (herbivorous)

- Ensifera (crickets) (unknown)
- Tettigoniidae (katydids)

http://entnemdept.ufl.edu/Walker/buzz/t000k1.htm
http://entnemdept.ufl.edu/Walker/buzz/katydids.htm

  - Pseudophyllinae (true katydids)(subfamily) (herbivorous)
  - Phaneropterinae (false katydids)
  - Conocephalini (meadow katydids)
  - Copiphorini (coneheaded katydids)
  - Listroscelidinae (raptorial katydids)
  - Meconematinae (quiet-calling katydids)
  - Prophalangopsidae (hump-winged grigs)
  - Saginae (stick katydids) (predatory)
  - Tettigoniinae (shield-backed katydids)

Order Coleoptera
(reference used is mostly *Insects: Their Natural History and Diversity : With A Photographic Guide to Insects of Eastern North America* by Marshall, S. A.)
Predatory Beetles:

- Carabidae (ground beetles)
- Histeridae (clown beetles)
- Staphylinidae (rove beetles)
- Cleridae (checkered beetles)
- Cantharidae (soldier beetles)
- Coccinellidae (ladybugs)

Subfamilies of Coccinellidae:

  - Sticholotidinae (predatory)
  - Scymninae (predatory)
  - Chilocorinae (predatory)
  - Coccinillinae (predatory)
  - Epilanchninae (herbivorous)

Herbivorous Beetles:

- Elateridae (click beetles)
- Chrysomelidae (leaf beetles)
- Lampyridae (firefly beetles)
- Meloidae (blister beetles)
- Bostrichidae (branch beetles)
- Buprestidae (jewel beetles)
- Byturidae (fruitworm beetle)
- Trogossitidae (bark-gnawing beetles)
- Synchroidae (synchoroa bark beetles)
- Cerambycidae (long-horned beetles)

Nectar/Pollen:

- Oedemeridae (false blister beetle)
- Kateretidae (short winged flower beetles)

Scavenger:

- Hydrophilidae (water scavenger beetles)

Mycophagous:

- Latridiidae (brown minute scavenger beetles)
- Phalacridae (shiny flower beetles)
- Sphindidae (cryptic slime mold beetles)
- Cerylonidae (minute bark beetles)
- Leiodidae (round fungus beetles)

Omnivorous:

- Tenebrionidae (darkling beetles)
- Anthicidae (ant-like beetles)
- Lucanidae (stag beetles)

Detritivorous:

- Cerophytidae (rare click beetles)
- Eucnemidae (false click beetles)
- Scirtidae (marsh beetles)
- Ptinidae (spider and deathwatch beetles)
- Hybosoridae (contractile scarabs)
- Leiodidae (small carrion and round fungus beetles)
- Silphidae (carrion beetles)

Unknown/Diverse feeding:

- Artematopodidae (artematopodid beetles)
- Mordellidae (tumbling flower beetles)
- Scarabaeidae (scarabs)
- Melandryidae (false darkling beetles)
- Nitidulidae(sap beetles)
- Pyrochroidae (fire-coloured beetles)
- Pythidae (dead log beetles)

Superfamily Curculionoidea (Weevils)

- Curculionidae (herbivore)
- Scolytidae (subfamily): bark beetles (xylophagous)
- Brachyceridae (primitive weevils) (herbivore)
- Anthribidae (fungus weevils) (detritivorous)
- Belidae (belid weevils) (pollinators)
- Nemonychidae (pine weevils) (herbivore)
- Brachyceridae (unknown)

Order Hymenoptera

- Symphyta -> mostly herbivore, a few parasitic (unknown)

Siricidae (horntails) (xylophagous)

Argidae (argid sawflies) (herbivore)

- Apocrita
    - Formicidae (ants) (omnivorous)
    - Apoidea
        - Anthophila (bees) (pollen/nectar)
        - Crabronidae, Sphecidae, Ampulicidae (digger wasps and other wasps) (predatory or parasitic/parasitoidal)
    - Parasitic wasps
        - Ichneumonidae (ichneumonid wasps)
        - Braconidae (braconid wasps)
        - Rhopalosomatidae (Rhopalosomatid wasps)
        - Chrysididae (cuckoo wasp)

    - Very small Wasps (parasitic)
        - Evaniidae (ensign wasps)
        - Diapriidae (diapriid wasps)
        - Platygastridae
        - Vanhorniidae
        - Unknown parasitic wasp (criteria: less than 5mm, fewer than 3 closed cells, or no stigma on front wing)

Superfamily Chalcidoidea - Chalcid Wasps (Most are parasitic)
https://bugguide.net/node/view/13405

- Pteromalidae (Pteromalids)
- Cynipidae (Gall wasps)
- Mymaridae (fairy wasps)
- Eupelmidae
- Eulophidae
- Unknown parasitic wasp (criteria: less than 5mm, fewer than 3 closed cells, or no stigma on front wing)

Mostly non-parasitic small wasps within Chalcidoidea:

- Agaonidae (Fig wasps) (pollinators/herbivorous)

Predatory wasps

- Vespidae (yellowjackets, etc)
- Sphecidae (Thread waisted wasps)
- Pompilidae (spider wasps)
- Crabronidae (digger wasps)

Order Diptera
(reference used is *Insects: Their Natural History and Diversity : With A Photographic Guide to Insects of Eastern North America* by Marshall, S. A.)
Predatory Flies:

- Asilidae (robber flies)
- Dolichopididae (long-legged flies)
- Rhagionidae (snipe flies)
- Empididae (dance flies)
- Sciomyzidae (larvae only, adults eat nectar)

Herbivorous Flies:
- Agromyzidae (leaf-miner flies)
- Bibionidae (marsh flies)
- Anthomyiidae (root maggot flies)
- Platystomatidae (flat footed flies)
- Opomyzidae
- Tipulidae (crane flies)
- Psilidae (rust flies)
- Clusiidae (druid flies)
- Tephritidae (true fruit flies)
- Drosophilidae (fruit flies)

Parasitic Flies:
- Pyrgotidae (Endoparasitic flies of beetles)
  (larvae are parasites of June beetles, as per Insects: Their Natural History and Diversity: With a Photographic Guide to Insects of Eastern North America by Marshall, S. A.)
- Pipunculidae (big-headed flies)
- Tachinidae (parasitic flies)

Nectar/Pollen (pollinators)
- Syrphidae (hover flies)
- Conopidae (thick headed flies)

Scavenger Flies (scavenger)
- Stratiomyidae (soldier flies)
- Calliphoridae (blow flies)
- Sarcophagidae (flesh flies)
- Phoridae (shuttle flies)

Hematophagous Flies (blood feeding)
- Tabanidae (horse flies)
- Ceratopogonidae (biting midges)
- Culicidae (mosquitoes)
- Simuliidae (black flies)

Mycophagous
- Asteiidae
- Mycetophilidae (fungus gnats)
- Platypezidae

Detritivorous

- Chironomidae (non-biting midges)
- Micropezidae (stilt legged flies)
- Sciaridae (dark-winged fungus gnats)
- Sphaeroceridae (lesser dung flies)
- Sepsidae (ant-like scavenger flies)

Xylophagous (associated with wood)

- Xylomyidae

Diverse feeding or unknown feeding= unknown

- Phoridae (shuttle flies)
- Cecidomyiidae (gall midges)
- Muscidae (house flies)
- Fannidae
- Richardiidae
- Ulidiidae (Picture-winged flies)

Table S3. Trophic functions in Ecosystem services and disservices

	Ecosystem services			Ecosystem disservices	Unknown
	pollination	nutrient cycling	pest control	plant damage	unknown
Trophic groups included	nectar/pollen	-detritivorous -scavenger -mycophagous	-predatory -hematophagous -parasitic	-herbivorous -herbivorous (aquatic) -xylophagous	-unknown -omnivorous -adults: nectar larvae: predatory

Classification of trophic groups into ecosystem service or disservice groups.

B.2 Supplementary results

<u>Biodiversity</u>

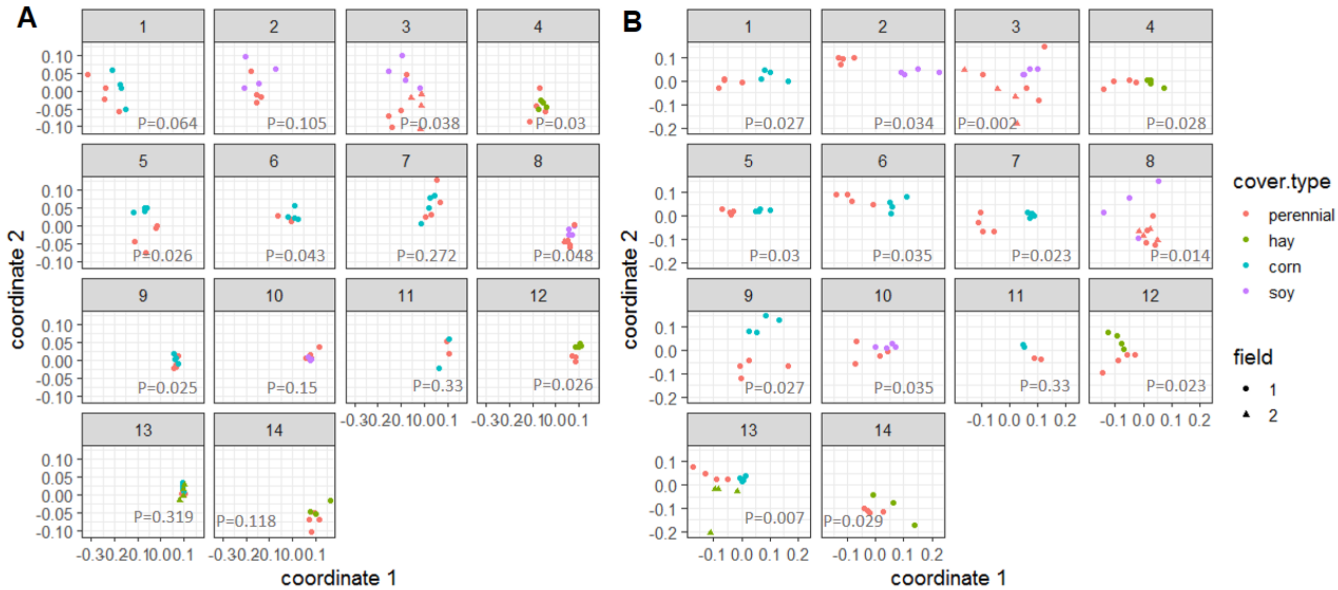


Figure S3: Prokaryotic and fungal species composition per farm. Non-metric multidimensional scaling (NMDS) of weighted unifrac distance (taking into account phylogenetic similarity) between 16S (A; prokaryotes) or ITS (B; fungi) sequences on 14 farms. Each point represents a soil sample (aggregated from 10 auger samples) from one quadrant of a perennial or control field. Most farms have one perennial field and one control field, but a few (farms 3, 8, & 13) have more than one perennial or comparison field. P values are the result of a PERMANOVA test carried out on each farm between the perennial and control sequences.

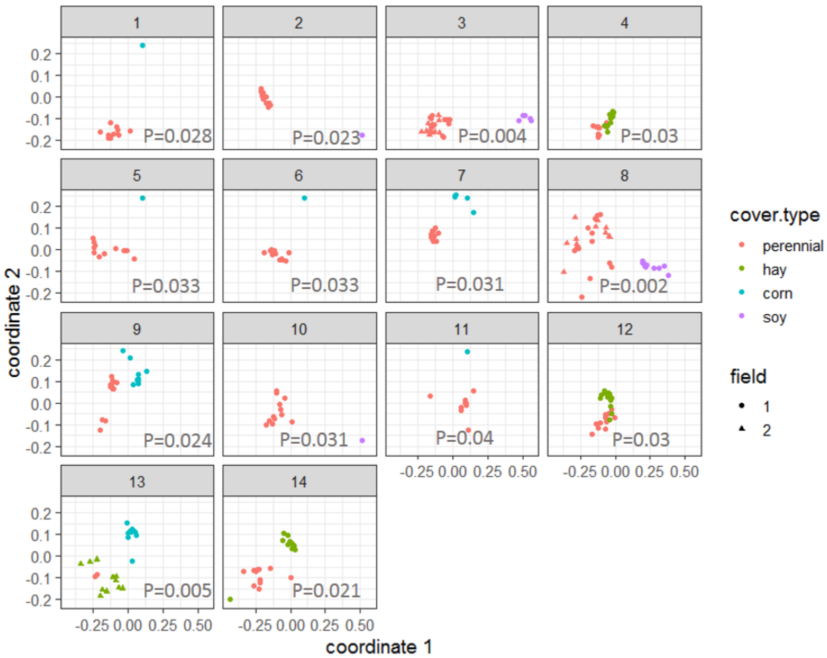


Figure S4: Plant species composition per farm. Non-metric multidimensional scaling (NMDS) of Bray-Curtis distance between plant cover communities on each far. Each point represents one sampling point (one .75m^2 quadrat). Most farms have one perennial field and one control field, but a few (farms 3, 8, & 13) have more than one perennial or comparison field. Each P values are the result of a PERMANOVA test carried out on each farm between the perennial and control sequences

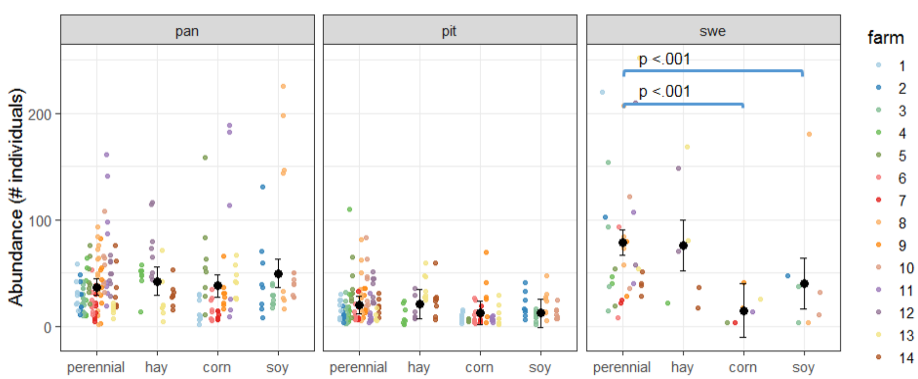


Figure S5. Invertebrate abundance. Total invertebrate abundance, calculated as the total number of individuals in any species.

Supplementary box 2: Insect Diversity

Beetles (Order Coleoptera): Beetles were second diverse to flies in family number with multiple trophic functions. Predatory beetles were not well represented with only a few notable families (Carabidae and Staphylinidae being the most common); however, there was a large diversity of species within these families. Chrysomelidae was the most representative herbivorous family but this was not surprising considering that most species are agricultural pests.

Flies (Diptera): Flies were the most diverse with well over 30 different families and 10 trophic functions. It was surprising to find 4 different predatory families, notably Dolichopodidae (the most common), Empididae, Asilidae and Rhagionidae. Syrphidae (hover flies) are important flower pollinators and were well represented in species diversity. The diversity of parasitic fly families was also surprising, notably families Pipunculidae, Pyrgotidae, Tachinidae (the most common), and Bombyliidae. The diversity of herbivorous flies was not well represented.

True Bugs (Hemiptera): Most hemipterans were herbivorous with only a few predatory families. Enicocephalidae was a rare family found that is poorly understood.

Wasps (Hymenoptera): Wasps were divided into herbivorous, predatory, or parasitic with parasitic wasps comprising the most families represented. Rhopalosomatidae was a rare and unexpected wasp family that are parasitic of crickets.

Ecosystem Services

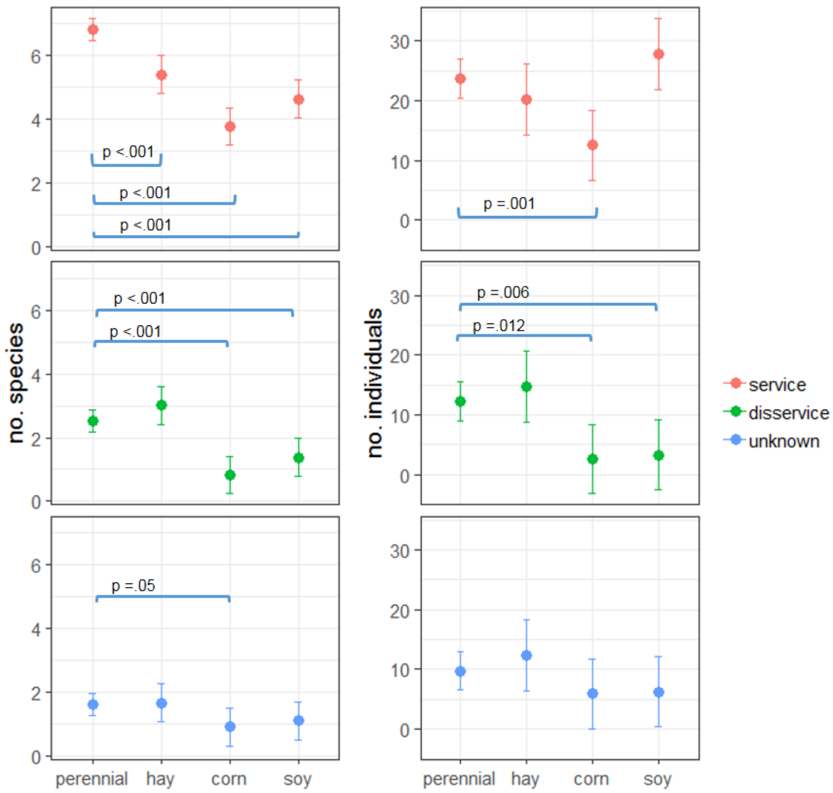


Figure S6. Ecosystem services and disservices (services aggregated). Estimates of invertebrate species richness and abundance per site. Ecosystem services and dis-services were classified by trophic group (see Appendix B1 table S3). Points and error bars represent model estimates and 95% CIs. Estimates are averaged over the levels of trap type and visit; P-values are adjusted using the Dunnett method.

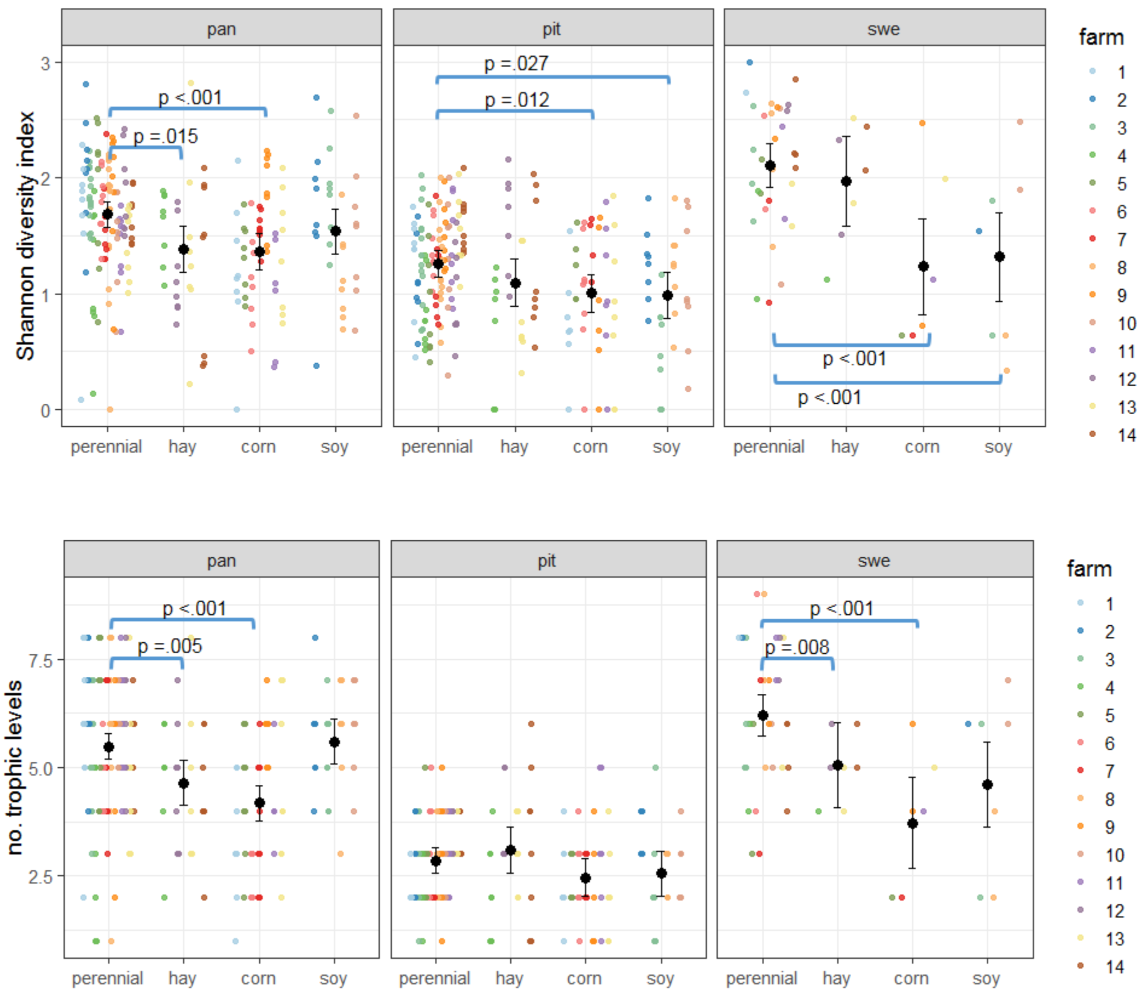


Figure S7: Invertebrate functional diversity. The number of trophic functions represented from invertebrate fauna (see Appendix B1 for details on how trophic functions were assigned). Points and error bars represent model estimates and 95% CIs. Estimates are averaged over the levels of trap type and visit; P-values are adjusted using the Dunnett method.

Appendix C - Chapter 4 supplement

C.1 Supplementary methods

Interview protocol

Introduction

I’m Maayan Kreitzman, a graduate student at the University of British Columbia, working with the Savanna Institute to better understand the stories, motivations, barriers, and livelihoods of perennial polyculture farmers in the Midwest.

Thank you for agreeing to do an interview with us and fill out a questionnaire. We’ll start with the interview portion. The beginning will be a discussion about perennial polyculture farming. Our conversation should take about an hour - is that ok with you? We will then proceed to the questionnaire, which will take about half an hour. It will ask about some basic demographic information about you and your family, and about your farm’s size, makeup, products, labour, revenue, and expenses. We can then also do a short walk around the farm, if you would like to explain how your farm has been changing and developing and your plans for the property. If you don't mind, I'd like to record our conversation. The recording is just for my use to make sure I understand everything correctly and will be kept confidential. I’ll turn on my recorder and we’ll get started!

B. General views on farming

1. I wanted to confirm that you mostly produce XXXXX (e.g. strawberries) and your operation is primarily based on YYYY (e.g. field crops). Have I got that right? Is there anything else that you would like to add about what you do with your land?

2. What are the main goals/objectives you have in farming?

    - Why do you continue to farm? (Mayberry et al., 2005) [1]

3. Can you describe a farm/ranch in this region that you admire and why, even if it’s your own though it doesn’t have to be? What is it about this farm or ranch that you admire? [no need to mention the name, but I’d like to know mostly what it is that you like about the way it’s managed] (Mollie Chapman protocol, 2015/6)

    - Are there many farms like this?
    - How unusual or usual is it?

4. Can you now describe a farm or ranch in this region that you dislike and why? [no need to mention the name, but I’d like to know mostly what it is that you dislike about the way it’s managed] (Mollie Chapman protocol, 2015/6)

    - Are there many farms like this?
    - How unusual or usual is it?

B. Adoption of specific perennial management practices

1. Can you give me an overview of the management practices you are using on your farm? (cultivation, mulching, fertilizing, cover cropping, weed control, rotation, grazing, pest control, irrigation)?

2. What are some practices that you are using on your farm that are unique to the polyculture enterprises? (I mean types of cultivation, pest control, harvest, fertilization, planting strategies, cover cropping/pasturing).

3. What are practices you'd like to adopt?

    - Can you tell me why you would like to start using this practice?
    - What considerations did you have in mind as you are deciding whether to use this practice?
    - What makes this practice difficult to adopt? Does it seem like a risky option?
    - What would make this practice easier to adopt? Would talking to other people who have adopted the practice make it easier to adopt the practice?
    - Do you think this practice has any benefits for fish, wildlife or habitat? Does this influence your decision to start or stop using the practice?

4. What are practices you've used in the past but would not use again in the future?

5. Are you enrolled in any payments for environmental services program or beneficial management practices program? If so, was this a motivation for perennial agriculture or a byproduct of practices that you were already doing/planning?

6. Do you know of existing programs that would support practices you are doing or planning to do on your farm?

- Does your type of farming fit or not fit within programs that exist to incentivize pro-environmental farming practices?
- If it doesn't fit, what practices do you think should be included?

C. Environmental worldviews

1. Do you think of the land's health and your own well being as being connected in any way? If so, can you describe that link? *How does it work? How do you know it exists? How strong is that link?*

2. Is what you describe for yourself also true for your community – that its well-being might also be linked to the land's health? Can you think of any examples that demonstrate or speak to that relationship? *These examples can be either things you've witnessed personally or that you've heard from other people.*

3. What does the phrase or idea of "a healthy agro-ecosystem" mean to you? What first comes to mind when you hear that phrase? *When you think of a "healthy agro-ecosystem" are their parts of that system that come to mind in particular? What are they?*

4. Do you think we need to improve or change how we manage agricultural land? Are there specific things you think we should be doing to manage the land's ecological health? *What are they and why do they matter? Feel free to recommend or think out loud about anything that's important that way.*

D. Adoption of perennial polyculture, motivations, bridges and barriers

The purpose of this section is to learn about your motivations and the things that undermine or support your perennial polyculture activities.

1. Can you describe how you started/transitioned to perennial polyculture?

2. What motivates you?
   Prompts if necessary:
   - having a sustainable household/ self sufficiency?
   - or producing large amounts of food for other people, or income?

3. Are you getting what you hoped out of this?

4. What are the main barriers you face to reaching your goals, and hopes?
   - do you feel that this is a temporary issue or that it is a chronic or permanent one?
   - have you found support for this, or do you mostly work through issues alone?

5. What makes it worth or not worth the effort?

6. Do you consider yourself a member of a community or movement? How does this play a role in your decisions?

7. Do you consider yourself an innovator or leader?

8. What was your vision of this enterprise when you started and what is your lived reality?

9. Are you going to expand this operation?

10. Do you have regrets? are there things you would have done otherwise? would you do the same thing now if you were starting from scratch?

11. How would you feel if you had to go back to your normal job or to farming in a more conventional way?

E. Demographics and Livelihood

I'll ask you now to fill out the attached questionnaire. It covers some demographic information about you and your family. It also covers livelihood related information including revenues, costs, labour, and land in production. The questionnaire is not meant to be very precise, but rather give contextual details about the interview. It shouldn't take more than 15 minutes.

F. Debrief

Those are all my formal questions. We can now go for a walk on your property and look at X, Y, Z that you mentioned in the survey and/or interview and you can tell me a little more about it. Thanks again for your participation.

Questionnaire

Woody perennial polyculture in the temperate north: ecosystem services and livelihoods

Study team and contact information: Principal investigator: Dr. Kai Chan, Institute for Resources, Environment & Sustainability (IRES), University of British Columbia (UBC) [kaichan@ires.ubc.ca]. Co-Investigators: Maayan Kreitzman, PhD Candidate, IRES, UBC [kreitzman.maayan@gmail.com]. Adrian Semmelink, Msc Candidate, IRES, UBC [a.semmelink@alumni.ubc.ca]

1. How many adults are part of your household?

Male: Female: Other:

2. How old are the adults in your household?

Male: Female: Other:

3. Who is mostly responsible for the farm in your household? (indicate using percentages)

   person 1
   person 2
   person 3
   person 4

4. Total household income

6. Income earned from farming (Please indicate if farming income = net profit or gross)

7. Income from perennial polyculture enterprises (Please indicate if farming income = net profit or gross)

8. farm enterprises (list):

   1.
   2.
   3.
   4.
   5.
   6.

perennial polyculture enterprises (list):

   1.
   2.
   3.

8. Size of farm:

size of perennial polyculture enterprises:

size of each perennial polyculture enterprise:

1.
2.
3.
4.

9. Number of full time-equivalent employees:

10. Gross revenue from each perennial polyculture enterprise:

1.
2.
3.
4.

11. Planting date for each perennial polyculture enterprise

1.
2.
3.
4.

12. Estimated establishment time to full production for each perennial polyculture enterprise

1.
2.
3.
4.

13. Yield from each perennial polyculture enterprise:

1.
2.
3.
4.

C.2 Supporting quotes

Supplementary table 1: Livelihoods.

Livelihood category		Quotes
Farmer livelihoods	Money management over the long term	*I think the big one is having the wherewithal to weather the learning curve. [...] So, by having other income to weather the learning curves on the farm - you know, last fall we got completely flooded out, and so I had to buy carrots and beets for my CSA in the winter, you know, and that was an added expense that I wasn't budgeting for. That's just, that's going to happen and you know, there's been a 10-year, 18-year learning curve of building a perennial polyculture here.* *I remember I was taking care of the kids until 2001. The naturalist position opened up and I went and applied for it and got it. And they were like, "Oh, what do you see yourself doing in five years?" I said, "Oh, I'll be on the farm full-time because it will be making enough money." That was 15 years before I was able to leave that job for the farm. [2]*
	Profitability is important	*I think the goal right now is to within the next two to three years to get the farm profitable enough that [spouse 's name] can give up his fulltime job. Because his company doesn't really have retirement per se. So it would just be instead of working kind of two full time jobs, he'd be working one on the farm. [3]* *It doesn't, you know, it doesn't constitute a huge portion of our income right now, but we'd like to get to where it does. I think we'd like to get there because we want that. We want to be farmers. [11]* *It [the farm] provides our income. Because we're just now getting to the point where we are commercially successful. And just very recently. We were desperately poor people just a few years ago. I mean, we were like land rich, but in terms of income, we were very low. [2]*
	Profitability isn't required	*We didn't have those projections that [name of mentor] is giving out now about how much money you can make off of it. So I would say it really wasn't driven by money. It was more driven by what's the right thing to do for the land and we could just making hay on that ground, or we can put in some trees and see how it goes. [3]* *I think our position it's been, you know, we brought the idea here. That now it's up to the next generation or the next people who want to maybe expand on this. So that opportunity opens up for a lot of people. From an economic standpoint for us, we are in a position where we don't need that income. [6]* *It was never an intention that we would recover all of the cost of the input. And we didn't have to acquire the land. That was done, so those up-front costs would be considerable if someone were hoping to eventually recover all of them on what they grew and sold here. [5]*
Community livelihoods	*I mean I think about that every time I drive through the tiny towns that my farms are next to. I mean the towns are just totally desolate and devastated compared to what they once used to be. The little town between the two farms, Homer, has a really beautiful building right at the corner where we turn and it's the Homer Opera House. And since then it's just totally falling apart and has been abandoned for years. And it's like this tiny, little town in the middle of nowhere had enough wealth and community [...] to foster an opera house! And*	

	now, the only place to buy food is the gas station - there are no businesses there anymore. There's nothing. Because over time all the money in Ag has gone out of the community and there's nothing left there. So everyone there just drives over to Champaign-Urbana and works somewhere in the city, and then goes back, and there's literally no economy left there. *And so, yeah, if I can produce or I can work with a farm that is selling to the local community or employing the local community - none of these farms around here are employing the local community - that would be amazing. If we can put in a little processing plant there. Process all the berry crops. That would just, even the little, tiny positive things for a couple farms would be the biggest business in the whole town. [1]* *And I think that, you know, we live in a state where, and, a state in general, and then you know, a community in particular, where young people don't stay. Where there's often in many places, a brain drain, so to speak. And I think that successful family farms and other types of successful small businesses are what bring folks back into the community and make the community vibrant and healthy. And I think a lot of people know that. So, whether it's about the health of our land or, you know, the economic success of new stores in town or other types of businesses that operate in the area, I think folks know that that's important. And the extent that our businesses success or like our continuing to be here, and people like us, continuing to be here, is really closely linked to the health of our landscape. [11]* *I think there is a direct link between the health of the land around here, in general, and the, which is declining because of the industrial agriculture practices, and the decline of rural communities. I mean, the population of this county is significantly smaller now than it was in the 1870s. It's, I think one or two thousand smaller than it was in the 1870s. And there are towns that existed back then that are just corn and soybean fields now. And I don't think any of the cities in this county are really growing, with the possible exception of Columbus Junction because of the meat packing plant. [2]*

Supplementary table 2: Motivations. Each quote may apply to more than one motivation; additional motivations are noted at the end of each quote. Numbers refer to the interview.

Motivation	Quotes
1. to experiment, innovate, and educate	<u>Experimentation or innovation-focused</u> *But mainly, I think the first three years in the orchards in establishment, we did it more as an experiment, because we did get some grant funding to test, like does this combination of food forest work, or like plants in a food forest model work? And you know, we're building on the continuum, right? And there's been other growers we have chatted with who have been planting a lot of things like quince, aronia, red, white, and black currents, elderberry, serviceberry, seaberry, gooseberries and they were, kind of like, the top eight. So, we were like, "Well, let's test them here." [8]* *A major portion of what we're trying to do is the polyculture part of it. Yes, we are looking at that variety of species and we know some of them probably won't survive, but we want to have some information about it that we can share with people even if they don't do well here. So we can say why do they not do well here. Might be climate, might be exposure, might be soil type, it might be any number of things. [6]* *To do R and D, research and development. So, R and D not in the traditional, you know, way that we do that. As you know at the university I did research and development at the University of [name of university]. And went through the whole scientific process. [...] And here we didn't quite do the same thing. But, we were still working on ensuring that whatever we were doing was being thoroughly documented for very simple and practical reasons. So, what we tracked was only the stuff that mattered to us. A regular scientist would have had a problem with a lot of the stuff we're doing. But, a farmer wouldn't have any problem. [10]*

	Education or inspiration-focused *Yeah, I think that I probably would say, given the state of the farm now, one of my main goals is to illustrate to other farmers and aspiring farmers in Iowa that you can make a living in growing perennial tree crops and berry bushes in a diverse farm operation, where you also have annual crops and livestock. I'm really excited about that being, I don't think farmers believe it until they see it. And the more farmers that see it, the more likely they'll, at least stop saying there's no market for it. [4]* *The initial thing was just to try it. And in those first three years, we've learned that there's widespread, growing interest in it. And being on the somewhat cutting edge, and being able to help share whatever we learn here with other people, that has become a secondary goal and desire. It's evolving. We sort of plunged in, not recklessly, plunged in and said, "Well, let's try it and see what we get. It was never an intention that we would recover all of the cost of the input. [...] I think of us as some kind of pioneers in this. And that appeals to me. [5]* *But, like I said, my interest in getting involved in agriculture was to provide an example for other people to follow and that would eventually result in changing the world and to, from the modern industrial agriculture to perennial poly-culture all over the world. And we're not there yet. [2]* *Having a viable business as a farmer is my first priority here. The education component is a passion of mine and so it fits in where I have time to do it. Which isn't, you know, there's very small windows where that can happen. But also, I'm succession planning as well, so as I get creakier, and I hire a hot young farm manager, you know, to do all of the physical labor, you know, I'm probably going to be moving more into the direction of teaching off the farm. Or on the farm, I should say. [13]* *Yeah, I think education has always been part of what we do because by nature of having a specialty crop that not everyone is familiar with, you can, if you're selling direct, you're going to expect to spend 20 to 25% more time on just, "What is this? What do we do with it? What are some of the different roles it can play?" which I enjoy. Like, that's my background. So, it's what I do. between the farming habits I do some teaching. [8]*
2. to restore or be in harmony with nature	*Yeah, my main goal is to have the most ecologically healthy relationship with my land, as possible. And so, everything I'm doing is based on how can I better improve the ecology of this land. And in some cases, the products of my farm are basically the offshoots of that. I don't think about it as these are my markets so this is what I'm going to supply, and then the land fits around that. It's the other way around. So, I'm looking at, okay well this is heavier, wet soil, perennials make a lot of sense, animals make a lot sense. Summer weather market garden is what I need for cash flow, but to the extent that I can make that low till, that's what I'll do. So, that's my main goal. And then, obviously, secondarily to make a livelihood. To pay bills. [13]* (also includes motivation 4)
3. to create a healthy environment and grow healthy food	*Partner 1: I guess it's just to build a model that other farmers can use to grow like diverse, have a diverse farming operation and support a family on a 40 or 80 or 100 acre piece of land, I guess. [...] So and growing healthy, abundant food I guess.* *Partner 2: Right what s/he said at the end there is what I would add to it is health of the land and health, quality of the water, health of the people is obviously a goal of this model or this type of farming. And I would say that it's about building an industry based around more regenerative practices and trying to take back some of the poultry markets in a good way. [9]* (also includes motivations 1, 2, and 6) *...my personal main objective is to create a better lifestyle for public in general. My motto is, you know, get your wealth or health from the farm, not the pharmacy. So that's why we're really*

	concentrating on perennial crops because you have the Nutritional value there. Field crops produce a lot of caloric input, but we're concerned about health and well-being [6] *If you're talking about the availability of nutrients or healthy fats within, that the land has the capacity to absorb and uptake and give to your human body, and maybe you have healthier brain function or you have a healthier body which can lead you to be a more productive citizen or a healthier whole, more whole person. It's just like the scientific note of things. [9]* *I think we can taste it [the health of the land] in our fruit too. Right? I think when we taste our fruit that comes off of healthy land, we get the intensity of the flavor and the rich, you know, the nutrient richness in the flavor of the fruit is really apparent. [11]* Negative valence: *I almost cried this year when they pulled in across the road and tore up the hay and put corn in. Right across the street from my house, conventional corn was going to get. Oh, I've already seen it get sprayed multiple times. [...] I saw the sprayer before they even planted ...multiple sprays. It's emotional. When you've had cancer twice and they tell you it's environmental, you tend to want to change your environment to where you live. [3]* Negative valence: *Well, I can judge, the reason is the farming can be detrimental to our water quality. They're contributing to the high eutrophication in the Gulf. They're polluting Iowa's water and the Mississippi River. They're polluting the air. And they're producing inputs for corn oils, that are themselves a health hazard. They're producing inputs for, to make corn sweeteners, which is a major contributor to the health problems of this country. [4]* Negative valence: *A huge problem in the entire food system is we need to continue to educate people on the externalized costs of agriculture production on food system on different food products. People think that you can buy a pound of chicken for 79 cents. There's costs that have been externalized to the environment, to humans that work in the system. And so that would be the biggest. That's more like the food system in general, not necessarily agriculture production. But we have this false illusion of cheap food. And cost at the store doesn't reflect. Most of the time the cost at a retail food store does not reflect all of the aspects that go into human health and the planet health. [9]*
4. to have a successful, profitable business	*I mean, we're mostly trying to be a commercially successful farm. And I think that's like our, maybe our primary motivation. [...] our goals are to, you know, to create a farm that's economically sustainable, as well as environmentally sustainable. I think it's important to us. It doesn't, you know, it doesn't constitute a huge portion of our income right now, but we'd like to get to where it does. I think we'd like to get there because we want that. We want to be farmers.* [11] (also includes motivation 2) *Well, one is make money. Two is sequester carbon. And then three would be inspire others to do the same because numbers one and two work. [1]* (also includes motivations 1 and 2) *But in terms of, well like I said, I wanted to show that a more ecologically friendly form of agriculture could still be commercially successful. Not only commercially successful, but also attractive enough that people would want to change. [2]* (also includes motivations 1 and 2)

5. to grow food for their own households	*Yeah, I think first of all, it's a home, and this is permaculture ethic too, you feed yourself before you feed anybody else. [...] I feel like if I'm not eating from my land, number one, you know, then something is off in my system, and then the rest of it goes out for sale. Yeah, and so, homestead first, but the commercial layer is very important and I'm tracking that very carefully. And I have no interest in going back to a sort of, real world job ever again. And so, this better work. [13]* (also includes motivation 4) *It's feeding us, it's feeding our members, it's feeding our souls and how do we do that in a way that's optimal where we're not taxing our bodies, we're not taxing the land and you know, we're earning a living wage. [8]*(also includes motivation 2 and 4) *But I would tie it in, too, that, when we have food on our plates that came from our farm, I feel more energized and more provided for than when it's a matter of growing things and getting paid for it, and then I go buy the food. And we always take a lot of pride with all the things that we put on the table, like this evening, that come from our farm. [2]*
6. to establish markets and industries	*Well I mean most farms are set up with longer term leases and with investors. So and as I scale up over the next couple years, it's exactly how we're going to do it. So it's money that's not my money; it's land that's not my land, and that to me is really the only way we can scale this up as fast as it needs to be scaled. It's very rare for people to have land and money and ecological knowledge and farming experience. We need to be working in teams to do this. [...] And so that's as I work now towards scaling up, within a couple years, that's where all the work is happening is trying to identify landowners and identify investors. Put them, mesh them appropriately and catalyze new projects. [1]* (also includes motivation 4) *Well right now we're in the process of helping others set up similar systems. And the industrial infrastructure to aggregate product grown by producers, process it and consolidate it in the marketplace in a recognizable form. [...] One of the reasons why I'm involved in the start-up of aggregation companies, value-added product companies is because now we need to get others involved this way. And how do we get them involved? It's like if you produce this, we'll buy it, market it and sell it. You now have an income if you do this. There's an incentive right there. Now you have multiple businesses in multiple places currently working on a pool of this kind of perennial products pool in the New York state region and Nebraska region and the Upper Midwest region and the South Florida Georgia region that now starts to spread out. [7] (*also includes motivation 4) *By the time I got here I knew I was going to make a living off the farm. So, I started this place with the full understanding that I needed to protype something that I could turn into something very large. Not a farm but way, way beyond farm. And so I never did things here the same way I would have done them if I just wanted to farm. So, that was a very significant departure point for this place. [...] So I have been working now on setting up this, the systems and the infrastructure to scale. And that's what I want to be. I'm not interested in actually being a farmer anymore. I was interested in that before I started this work, the systems development. But once I move into systems development, I was also not interested on small stuff. I can go either way, but now I mean I don't really have a choice anymore. I feel really good because the acceptance of the system now is pretty large scale. We can go almost into any community and we carry the day. We have a really powerful word to communicate how people can do better. [10] (*also includes motivation 4) *We want to create a brand, the [name of company] brand. And we want to grow not just our farm, but other farmers that are using these types of practices and that can sell their products under our label. So at the same time that we're establishing a farm, we're also establishing a food company that can market these products. [...] we're working to build a production, a farm production model. And building the food business. And in building that business foundation to have processing and marketing and distribution and all of those pieces in place to be able to*

	*train other people and grow that supply chain with the same system. [9] (*also includes motivation 4) *We're product of necessity too at the same time, yeah, we're helping lead this new industry and innovate it. And sort of pioneering and being on the forefront. There's been other people who have gone before us and that's what's led us to this point. But there's a real truth and a reason behind why this needs to happen. And that's really the driving force. [9] (*also includes motivation 4)
7. to provide land access for the next generation of farmers	*That place started out as […] we had a windfall. We wanted to do something with it that made a difference. And to us, we had identified this problem; Iowa land is in bad shape, and young farmers need access to land. And between those two things, could we combine those efforts to get what we wanted, which was healthy, nature friendly farming, of food people eat. And affordable land for a young farmer***.** [4] (also includes motivations 1, and 3)
8. to share new and interesting foods and tastes	*I like to introduce people to different fruit. Especially stuff that grow, well, that does well out here. Because it seems appropriate that people eat some stuff that does well in the local area. And then also to just introduce them to different tastes and stuff. I mean even people that eat a lot of apples, they're not familiar with lots of the different varieties. They can name like ten varieties maybe. And they're all pretty common commercial things. [11]* *Another prime example of how people really don't know their food. This little girl, this mom and this little girl came to this stand. And we had seven different kinds of plums. And this mom said do you have any plums that are like the ones you get in the grocery store? He said no, not a one. Well my little girl likes plums, okay. Well have her try this one. And it was one of the sweetest ones we had, Chind River. This little kid took one bite and goes, blllghh. And mom walks off and goes I guess not. Because they weren't firm, and they weren't hard and tasteless. So this little girl wouldn't eat it. [...] Because basically a lot of people [...] don't have a taste for the other aspects. Our palette is so trained to sweet and sour. [6]*

Supplementary Table 3: Perennial polyculture management.

Management principle	sub-category	Quotes
Designing for diversity	Diverse interplanting and native mimicry	*Yeah, we interplant a lot of different things. In fact, we have, I don't have an exact count. I'm always remembering additional species that I haven't remembered before after making up a list. But probably somewhere around 70 to 75 different species of fruit and nut trees, shrubs and vines and perennial vegetables. And we're trying perennial vegetables under the trees where they're not normally grown, including things like asparagus, rhubarb and horseradish. [2]* *The way that we've outlined the farm is elderberry, hazelnut, hardwood, hazelnut, elderberry. And there's 15 foot spacing between the elderberries and that first set of hazelnuts and then there's 10 feet between where we put hardwoods. So right there, that's our polyculture. That's the footprint that we've modeled our farm after. And it's really based on what grew here indigenously or natively. And we believe that it'll create this forested canopy. It'll mimic a forested canopy even though it's in*

		rows. Really mimic that umbrella having the hardwoods above the lower shrub-like species. [9] *Oh it's absolutely systematic and what changed everything and made everything simpler was when it dawned on me that the systems that work in the past are where you imitate the natural plant community types of a region. And then you go imitate using improved varieties of whatever the individual plant species are in the plant community type. And then you just set them up, they've been living together for zillions of years, evolving together, whatever their pest and their disease and their predator and control cycles are all in sync. And it's what your place is designed to grow. And [name of the farm] Farm is a classic example of that. It's that oak savanna plant community type. It works. I can walk away from that and those species will all be there. Their populations are expanding and contracting based on the natural disturbances of the area. It's a natural system. If you leave it alone, it'll be all right. [7]*
	Integration of livestock	*I think it [having animals in the orchard - ed] is part of how we envision our orchard management proceeding. We want to use the animals to biological benefit in our orchard. So, for weed control, or for pest control, and for fertility. Like I think there's a lot of benefit that they bring. We're not necessarily managing them to optimal effect this year, but I think even what we're doing right now, which is not, which is far from optimal, is still beneficial. [11]* *I was lucky enough to have a moment to have thought through, "Alright, I'm planting all of the apples and the cherries in ripening succession." So, we're literally going down the field every week, or every two weeks, when it's harvest time and picking out, you know, one row at a time. And I deliberately planted so that there was that wave across the field. Which allows me to have a chicken tractor, that moves through that field, you know, as long as I'm aware of when the harvest that day is, and backing up 90 days from that, then those animals can move through that whole area without compromising one row or the other, you know, with fruit production. So, I'm giving 90 days of manure management window between the animals being there and the harvest, yeah. [13]* *And I also think that they're in our orchard because we have so many different species of fruit and so many different needs and timing of that. I think that, you know, that really plays into the way, for example, it plays into the way we're moving our animals around the orchard. Because certain things are harvested at certain times. it also plays into the way we mow and where we choose to mow, because it's like we need to mow the berries when we're going to harvest things. And you know, wait on other things. So, I think a lot of that really affects...the diversity of fruit species. Yeah, just in the orchard as a whole. [11]*
	Multi-strata vegetation	*So, you have your canopy trees, and then your trees like paw-paw under that and then you'd have your shrub layer, and then you'd have your echinacea and golden seal., and then under that golden seal you had ginseng. Ginseng and golden seal and a black cohosh. [2]* *Well, for example by incorporating like multi-levels of shade and canopy in this space. We went from seeing just basic crickets and very little life to having turtles, and crawdads. And like, I think when you see reptile life and stuff like that in an area where food's growing that's kind of a cool feeling. And all of the pollinator insects that we see here, that makes me happy. [12]*

		I wasn't doing agriculture when I came into this space. And perennial agriculture was the only way I was going to get back into agriculture. I had already grown vegetables and other monocultures in Guatemala as an agronomist and after school. And it was always wrong. I always knew that's not the way to use a landscape the most efficient way. The most efficient way is to grow vertically, not horizontally. And so from a purely mathematical perspective, I was very clear on the fact that I want to grow cubes not square feet. So I don't think of an acre as a flat space. I think of an acre three dimensionally. So if you think of it three dimensionally, you can't farm without perennial crops. [10]
Timing	Over short term	*Yeah, it's overwhelming. I mean when I set out the list for the year, you have to think about all the timing of all those crops and then it's difficult to say the least. But that's, I mean, for sure. When we fertilize, for example, the rows of chestnuts and currants, we have to … those two crops in an ideal world don't get fertilized at the same time. They're optimal fertilization with those is not at the same time. So you have to make a decision. Do you fertilize it when the currants prefer it or fertilize it when the chestnuts prefer it? Do you split the difference? What's the right way? [1]* *Observing the farmers around here who haven't begun harvesting yet, their corn or soybeans, although they've gotten wheat and they're taking in oats, we're sort of harvesting all summer, as different plants that we have are ripe. And we expected that. We planned for that. So, that's like monitoring what's ready and getting it picked. [...] So far, we're, it's pretty much when one thing is done, the next is coming. I think we finished the black currants today and the next thing will be blackberries and boy they're coming. They're growing on the vines. [6]* *all of the harvest seems to happen in clumps. Where like I can just focus on one, or maybe two different projects at a time. And then move on to the next thing. And each harvest usually lasts…Like it will last a few days or a week. The currants ran a little long this season. So, that was fun. The raspberries are going to go for a long stretch once they're going. But, yeah, in general like it's like very punctuated moments of the season.[12]*
	Over long term	*So, I feel like we're getting better, for, like in the beginning few years, it was just like well get stuff in the ground. And then it was start to, once we started harvesting and managing, like when there was fruit on things, like figuring stuff out that's from like years, I don't know, I guess years four through now. And then, now I kind of feel like we have an okay line of sight on what we need to do. So, we've had to make some changes, stuff like taking things out, replacing things, and that all, when you're dealing with perennials that takes a long time. To learn those lessons, you have to plant something and then get it to production and then maybe learn that you don't like it or it's not working for you, and then take it out and do something else. And so, that just takes a long time. So, I'm kind of thinking, originally, I was like, well by year 10 I think we'll be fully rolling. [11]* *I don't know if you'd call it a challenge or not, but trees grow and they keep on growing and when I put persimmons under or in between heart nuts, some years later, they're going to be under heart nuts instead of in between, and persimmons aren't shade tolerant, so, persimmons are going to get shaded out eventually, but that's just something that I expect to happen. And the same may be true of honey berries. Honey berries may eventually get shaded out because they're growing in between the rows of chestnuts. […] Yeah, but there's a lot of years that they'll be productive before that happens, so. [2]*

		...the first three years in orchard establishment, if you're growing perennials, it's almost more like seeding nitrogen-fixing annuals, or things like that, that are things that are really going to help support your soil. [...] that actually helps support plant establishment. And then you can kind of, after your two or three year design really starts to take shape, it's a lot more around shifting managements from intensive ground-cover and like planting, to more like grafting, or in winter, dormancy months we're pruning, we're collecting scion wood, we're taking cuttings, and we're kind of like at a place where we're able to grow out a nursery or do our own plant replacement and mix things up. [...] I do want to put a plug in for sequencing. I think it's a really important thing. [...] because what I've been learning is that now, like I'm intervening and interacting with the orchard in a different way because it's at a different level or stage of maturity. [8] *But actually what's interesting is that it's a time shot. It's a characteristic whereas when we first got started 20 years ago there weren't any woody crops at all, so it was all annuals and hay. So the amount of produce that we did once upon a time, I think I was doing like 12 acres of annual produce plus two acres of asparagus and through time as the perennials have come on board, the annual dropped off. [7]*
Intentional lack of management	*The woody perennials, very little [weed control - ed]. Usually we prefer to go with mulch and that sort of thing because eventually they'll break down. They'll create the habitat for beneficial insects which will make the nutrient value more available. [...] Yes, [we mulched - ed] when the plants were younger, remember this is a test plot. So we're trying to see how much stress these plants will survive and produce on. It's part of the test. [6]* *So taking excessively good care of my woody plants in the early years is something I'm not going to do ever again. Put them in the ground. If they're going to die, good riddance. I want the ones I put in the ground and they'll survive. They do all right. I'll mow on either side. And maybe if it's a drought year when I first put in a bunch of trees, I'll water them. [7]* *And quite honestly, weeding the trees is one of the most useless expenditures of time I can imagine. Because they're all old enough to hold their own against the weeds that are there right now, I think. Because they had been heavily mulched. As long as we can keep the hay down and the trees can get sunshine, as long as we get enough rain, they'll get the two out of three things they need. [4]* *But, one of the things we do is before we actually start implementing a practice for an activity we watch what would happen if we didn't do it all. [...] So, that the perennials…The one thing we got to watch is to make sure we are not doing work that is unnecessary. And honestly with a bush hog, as well as with push mowers, I mean two weeks ago we could have weeded. But we don't…One of the things we have done here is let things go to the very tipping point. Where you actually end up doing a lot of work like we're doing right now and then estimate what that work is like. [10]* *Bigger shrubs, because my style is just not to really do much with the grass. Other people will mow more or do a better job with mulching, you know, and it just hasn't happened. [13]*	
Tradeoffs in complexity	*The other thing we did in the past is that we put, and we still have those, oaks and sugar maples on the same row interplanted with the hazelnuts. And we don't want to be doing that because we want to be able to mechanize all of the hazelnut harvesting. And once you have trees on the same rows then you can't drive the machine through once the trees become taller than twelve feet. [...] So, in other farms that we planted after we planted this one we have a row of hazelnuts, a row of elderberries. And then in between both of those rows we have a row of interplanted trees. So, the tree row is definitely diverse but*	

	not the row of hazelnuts or the row of elderberries. Because others wise, you've locked yourself into manually having to do too much stuff. And that's not good. [10] *And so, having rows of things that are alike, that I'm picking in one patch at a time, and not going all over trying to find this tree or that tree, you know, is the production side of production permaculture. Yeah, and I'm not apologetic about that because I have so much diversity otherwise. I'm not really worried about the fact that I have a row of one kind of apple tree, you know? Or that all the black currants are planted in one row of the pears, you know? That's fine. But in terms of my harvest, that's critical. [13]* *And here, it was very hard to move them [the pigs] around because we have berries and pears because we have early and late season stuff. And we kind of can't. It's easier when you have things like in, okay, this is the harvest season, it's like these two weeks out of the year or four or whatever and then you can gauge appropriately. But when you've got multiple things and you're trying to do it and make it financially viable, you know, it's one thing if you just did it for your own use. [...] It's hard to do, I feel like we could do a mix of just woody perennial things and then just not have animals. There are some things that I'd like to try to do... maybe if I wasn't thinking about getting animals in there. I feel like eventually, once the trees are fully grown, it's going to be easier to integrate animals in there. I kind of, don't want to do it when they're young because they can do a lot of damage. But I feel like it's potentially eliminating some tractor use and doing more to help with pest and disease pressure, rather than just spraying, you know? [11]*
Holistic and adaptive approaches to management	<u>Holistic and integrated knowledge</u> *But I think like a lot of people, you sort of, when you're doing poly-cultures you're, kind of, forced to think in systems. And it's not to say that, yeah, I don't know how to discern whether or not we're going to gravitate more towards systems thinking than kind of a near reduction of sort of space, or like this then this, if you will. [8]* *Certainly, I mean if the farm ecosystem is working properly and the pollinators are doing their job. There are not weed issues because the niches are occupied with the plants that I want them to be occupied with. And either they're being managed appropriately if there's chickens in there reducing the disease pressure. If that's working then the whole system works better and more money will be made. And I'll be less stressed. [...] You're just fundamentally, you have to acknowledge and work with the system and make sure the system is healthy otherwise it will fall apart because it is more complex. Whereas if you're working over in a corn model culture, it's so just devoid of complexity, so devoid of life that not many things go wrong. Until the catastrophic thing goes wrong and like everything dies from a new bug that nothing is resistant to it. And so but on a day-to-day level it's so much simpler. [1]* *Let's just take our language that we've been using here. For one, I've stopped every once in a while saying well that's monocrop language and that's not how I'm thinking. So it's a different way of thinking here. What would it take for you to all of a sudden start to examine how you approach all these situations? Say whoa, this is total conditioning based on monocrop thinking. That this is not the right question. [...] It's* as *important. It's* as *important. [7]* *I have a pretty strict schedule of spending an hour or two in the orchard in the morning. And then spending a little bit of time on the computer during the hot part of the day. And then getting in the south field and spending time with the goats. Like, it's kind of like the circus performer with the spinning plates. Like, you just have to keep moving and catching each plate. Because all of them kind of will lose momentum if they don't have a little bit of push behind them. [12]* <u>observation</u> *I grew up watching birds and trying to learn about the animals that I could. I just spent a lot of time in the woods. And I didn't have a lot of friends. I grew up in the country. And so, I spent a lot of time just*

	kind of observing things and always thinking that was kind of a waste of time. And then like years later encountering stories like Joel Salatin, and David Brown. And all these interesting minds that are using like that kind of passive, just observation of land and life and applying it in a way that's really poetic and cool. And so, if I can figure out how to make money doing that then that would be a really noble life full of purpose. [12] *I have enterprises that I've created after observing what's best on the land here. I don't think of myself as someone, I don't, I'm not coming in with a vision that I'm wedded to that has to happen on this land, no matter what, I guess is what I'm saying. So, I really want to learn from what the landscape is teaching me, which is, you can't really have tractors here. You know, you can have them for mowing or you know, doing some yard work or something, but it's not going to work for agriculture, for tillage or weed management. [13]* *Right, so you know, we're in transition. And we don't have the equipment to do what we need to do and we don't... and we're spending the whole summer just regrouping to figure out what's out there and to observe the farm and learn more about the land itself. [4]*

Supplementary Table 4: Community relationships

Relationship	Quotes
Farmer networks and organizations	*I've always worked very closely with our other groups. We work with, I gave a lot of presentations and we work with a lot of groups trying to promote perennialization even before it became a term. It's now become a thing. It wasn't even a thing back when I started 50 years ago. [6]* *Yeah this community's actually full of farmers who I absolutely admire. Yeah, this community's just full of heroes. And it's like, I think I've talked to a couple of people about this. I don't know if you and I have talked about it. But, the idea that your friends are also your heroes. That's kind of an exciting thing to be able to look up to your friends. [12]* *My sister and I are fairly active with the Savannah Institute, which really has grown phenomenally, in terms of members and outreach, and its diversity. There's all kinds of people with all different sizes of operations, growing and learning about various, various things that you can enjoy and use that aren't just corn and soybeans. [...] And then there's a network of the members that are helpful to learn from, and enjoyable to get to know. And there are opportunities with graduate students who want to use and learn about what we're learning about. And we enjoy that educational aspect. We enjoy working with them. [5]* *Wouldn't you say PFI [Practical Farmers of Iowa] is kind of our community? A lot more than local people around here. And PFI has gotten so big, not everyone recognizes us anymore. That's kind of weird. [2]* *I also joined Iowa Nut Growers Association and then the Northern Nut Growers Association, and especially the Norther Nut Growers Association has very wide range and interest in all kinds of nut trees, plus persimmon and paw-paw trees. So, and because I joined and they would send me their newsletter and annual reports and it would have all these fascinating articles about all these other perennial trees and shrubs that produce interesting crops. And so, I started gradually learning about and then planting other things besides chestnuts. [2]*
Women's farmer networks	*I feel really connected to some women grower groups in the area. And I, also on a more regional level, you know, there's sort of a farmer's solidarity piece; I feel pretty connected to the flower farming network. So, I think overall, yeah, I feel pretty well dialed in. [8]*

	I started attending something called women food in Ag network and I do enjoy that because it is all women. And it's really involved women, which I consider myself. It's not like, the example I'll give you is I attended something this year called Annie's project that Iowa State puts on. And what I would say in that group of women, the majority of them are farm wives who really know hardly anything about their operation. Their spouse does it all and they maybe drive a tractor or do something in the fall to help, but they're not involved in decision making. They don't really know the numbers of anything. And so that is, to me, a direct contrast over the people that attend the women in food Ag network because those women are doing it all and know it all. [3]
Neighbour relationships	*But it was last year sometime after we had planted the blueberries and I stopped there. He [my neighbour] said to me, I just want you to know that I really admire what you guys are doing. That was nice to hear. I'm sorry I'm getting emotional, but I feel like people think that we're just like freaky weirdos. So having that validation for my neighbor was nice [4]* *Well, they [the neighbours] see me doing it, and they probably think I'm nuts to do stuff that's so much work, right? But I guess they could also see the result though. It looks better. It's not a big huge dirt patch, you know. And then, there's another big huge pile of manure that has to be scraped up all the time. [11]* *We did have a farm visit day last summer. It was advertised locally, and a number of local neighbors came by to find out what it is that we're doing, with an interest in doing, "Something like that, " on land that they had. It hasn't been promoted much locally. I wouldn't say that many people around here, except those who drive by, have much of a sense for what we're doing. [5]*
Broader or local community relationships	*I think that generally for most of the population, this kind of farming isn't very visible. I think most people, like even at this stage, a lot of people assume that farms are dairy farms. [...] I think both things can be true. That we feel really connected to a community that really values the kind of work that we and other folks are doing. And it's true at the same time that there's a lot of ways in which our type of farming is invisible too. It lacks recognition in the larger population [11]* *And as an example, or if you go more than 1/8th of a mile from our farm and ask "Where is [Name of the farm]?" They'll be like, 'What?" Or "What are chestnut trees." Yeah. People in [neighboring village], "Where is [Name of the farm]?" [2]* *There's, you know, there is still a lot of diversity of opinion, and political perspective and all of that. I think, at least for a lot of people though, there's an understanding that if some of us are not all right, we're, all of us are not all right. [13]* *One person told me this and I don't know if this will happen, but if it happens to us, great. They said that once you invite people to the farm, [...] like if you've got eggs. Somebody's coming to your farm for eggs if you've got blueberries. Then people might say I'd love it if you could raise some sweet corn for me. Or I'd love it, you know, if you have animals if I could buy half a pig from you once a year. And if that happens, I think we're open to that kind of thing especially if [spouse's name] can be here full time. But I think it's about establishing relationships with people. And finding the people that care about where their food comes from and understands the stuff at the grocery store shelves and where it comes from. [3]*

Supplementary Table 5: Barriers to success and expansion

Barrier	Quotes

Capital and insurance	*we can establish 100 acres of some perennial crop, but it's not going to mature and produce a full yield for, you know, 5 to 7 to 10 years. And there's really not financing systems that are even set up to think about that. And there are some starting to develop out there in the world. […] But you can't go to a conventional bank and tell them you're going to plant hazelnuts and say we'll have a yield in six years. And we can't pay that loan back for six years. You just can't do that in a conventional financing system [9].* *And the next generation - we're relatively economically independent at this point - but the next generation is going to have to move forward and move this from an environmental and social approach that benefits the future. They're so restricted by the economic restraints that's their difficulty right now. I mean [farmer's son's name] can't move forward aggressively with some of these things even though we have a pretty good idea of what combination of perennial food crops that would be the future of agricultural production. You can't afford to do it because it's too much investment involved and too much time involved. The economic restraints are really what are holding back these sustainable approaches. [6]* *You're probably familiar with the treadmill of production? Like growth for growth's sake, or just having to constantly innovate until you get stuck in this sort of poverty trap because you're always sort of hustling. On the flip end, you could get into hyper management and just rigid and you can't break free of that. So, what's that balance of what do you need? So, we're kind of like, what do we need to creatively destroy or send back to the Earth in a humble and great way, and what do we sort of need to take a leap on? And you know, when I ask people who have expertise in this area, they're kind of like, "Oh, I don't know." So, I'm asking like is it a customer thing, or a market thing or is it an investment support? Or a combination of both? It's things where you're like you don't have to take on a huge debt load. [8]* *At the federal level, you know there's no account, everything is built for annual crops so there's no accounting for the fact that it could be five to seven years before you get your first crop. Besides depreciation, I guess. I'm not sure how it would work, but you could imagine that some kind of crop insurance program that would deal with trees. Because there's a big substantial, a substantial initial outlay of money. That won't return for what, five, seven, ten years. So, some cost share with that would help. Or some insurance program, so if all the trees died, you'd get reimbursed. Something like that. Because an Ag Department documents, the only crops are corn and soybeans. Everything else is what they call a specialty crop. And they have all different treatments for specialty crops than for real crops.[5]* *But I think that overall, there's, it just you know, we don't qualify for crop insurance and we don't qualify for a lot of things that would help stabilize, you know, help stabilize other types of farms. [11]*
Labour / time management	<u>Lack of time; lack of resources to hire paid labour</u> *Labour. Labour is a big barrier. Yeah, just physical demands. [8]* *My age. My time. And with my age comes my energy. The fact that we live a hundred miles from here, it's, there's always the back and forth. And the time spent doing that. [6]* *Time. I think, you know, every year and in every season there's things we're not getting to that we know if we did them or did them better, would make our farm more successful, like economically more successful, but also ecologically more successful, and also, just kind of run better from a work day perspective. In some cases, it's a mystery, but like we don't know what's the problem here. But in other cases, it's like we know, if we could manage the canopy on our grapes, then we could grow grapes. But we can't manage the canopy on our grapes, so we're not going to. So, that's one of the biggest barriers. [11]* *I would say the big limit is harvest labor. So, that's where the big money is, you know, in your labor. [13]* <u>Availability of paid labour</u> *The hardest thing has been that I mean I'm obviously not a full time farmer and the hardest thing has been trying to find employees, part-time employees. Seasonal and/or part-time employees because people don't*

	want those jobs and they want a fulltime job. And so it's hard. So that has been the hardest thing about it. So many people kind of pass-through and we invest in training and retraining people. And so. [1] *Right now, honestly, there are two barriers. The first one is enough people to do the work, so I don't have to be doing all the day-to-day work. That's one big thing. [10]*
Marketing and processing	*I'm thinking of if people really are wanting to grow hazelnuts, or chestnuts or walnuts even, like are there some small-scale shared tools, or processing things that you can use? It's either like your home-grown backyard, or it's giant. There's not a lot of middle. And I think in Missouri there's some, they have some cool tools and equipment that are really designed for people who maybe have, like are in the two to five-acre realm, and not bigger than that. So, I'd like to play a little bit more with that or just kind of finding other folks where you can. [8]* *I would like to have taken this farm finances class that I took this past fall back in the beginning where they kind of teach you more about doing enterprise budgets or projecting things out on paper. I would have liked to have done more of that type planning. I did that with the blueberries. We did not do that over there [for the fruit and nuts]. You're still going to come up with things that you don't really plan for, but I think it gives you a better idea on one acre of blueberries after X amount of years, this is what you can expect in return. I have no idea what we're going to get. I mean [name of mentor]'s given some numbers on the chestnuts, but like on the fruits and stuff, I have no idea. I feel like we're just kind of in the dark. And I feel like unless we do you pick we have no idea how we're going to sell this stuff except for the chestnuts because you've got the cooperative as an option. But if you're going to, haven't talked to the grocery stores. [...] I don't know if they buy the nuts, you know, if they were organic chestnuts or hazelnuts. I haven't talked to them about it. I guess I felt like I was going to wait until I had some production. [3]* *I think markets are another barrier. I think we still have some market space to grow into with a lot of what we're growing, but I think when it comes to things like apples, we're going to pretty quickly hit a ceiling when it comes to the way that we've been marketing. And so, we're going to have to figure out how, once we hit that, we move into a more mid-size farm space. Or we can use wholesale markets. And I think one of the problems for farms like ours is that those markets don't exist very well in our country today. There's a lot of, you know, there are, depending on where you are, but in various communities there's a lot of support for small farms. And there's this gigantic infrastructure of the USDA that's dedicated to giant farms and it's, there's a lot missing or how to be a successful farm in the middle of that. And that's something that really worries me. [11]* *People are not real familiar with a lot of these fruits. So the next step is you've got to have some way of processing the fruit that you harvest. So that processing plant doesn't exist or if there are places out there like in cranberry production. You could feasibly use a cranberry processing facility and it's transporting fruit, you know, your fruit to them. But they're afraid to try it because there's not a market for it yet. So that becomes a huge barrier. So okay, who's going to invest X number of dollars in making a processing plant and people can take their fruit to and do the juicing or whatever you're going to do. I mean it's, that is the issue in it. Then if the processing plants is 500 miles away. That really [adds to] your carbon footprint. [...] So there's still a lot of barriers out there that have to be met. Economic barriers primarily. [6]* *I mean it's a matter of money. It was a lot of work to establish the full production system, a lot of work and a lot of money. And we can't sell chicken for $6.00 a pound. We have to work within the market pricing structure that is out there in the world. And so it's been a challenge to sell. It's been a challenge just to get into markets and be competitive with the amount of investment and time that goes into building this system. [9]*
Uneven playing field	*The broader work that needs to be done, is we have to change the Federal Farm Bill. No farmer is ever going to make a living in this country until we change that farm bill. And that is going to be generations of work to get it to change, because there's so much money stacked against us. [...] Well, and it's confusing and a lot of people don't understand what the Farm Bill does, or where the money is going. You know, we've had some increases in organic funding there, and we've had increases for young farmers getting started, and we've had some conservation money, but compared to where that money is going, no. The scale*

	is tiny, and if you even look at the market distribution, so the percentage of agriculture that is organic, is not reflected in the way the money is split up in the Farm Bill. So, the Farm Bill money is like .1% of the market share of organic. Organic, you know, standing in for perennial production and many other things that fall under its umbrella. [13] *Well the conventional agriculture system is so well established; the markets are so well established that you can go to a bank and without much. I mean you can go to a bank and say I'm going to grow corn and I'm going to get this many dollars per acre and I need this much money to start it off and do it. And the banks have been working with that system for 50 to 70 to 100 years. So it's very well established. There's very little risk. [9]* *Well, I would start by doing a very republican thing and actually leveling the playing field by just removing all the subsidies. So star with a level playing field. [1]* *First thing we need to do is stop subsidizing the overproduction of corn and soybeans. And the subsidizing the animal, industrial animal operation. It's ridiculous. I mean when have this huge, I don't know if you read about that considering you're from Canada. But just last summer or the summer before there was a huge death in chickens in Northern Iowa. Got some disease wiped out, I mean they killed millions of birds. They called in people from fire departments.[...] Yes, they created the fricking problem and then our government paid them. And we, who paid all these people to come and deal with it? So you take the risk out of it for them, there's no consequences. They just can be as careless as they want. It's like the attitude of my neighbor. No skin off his back. [...] They get all the subsidies. And then every farm bill they say they're going to cap that. So that these big guys can't get more. They all figure out a way around the system. And then you're a little guy and you're going in there trying to figure out how to get $400 worth of trees paid for and they can't figure it out. I mean for crying out loud. It's so stupid. It's so backward and screwed up. We should be promoting people to grow food whether it's organic or not. We should be promoting people to grow food. But I think the problem is they see these animals as food, cheap food, really cheap food. Somebody's making a killing somewhere. And it's not the people choring those buildings. [3]* *Well my personal, political philosophy is we should have no welfare programs for any farmers, period. So that means all the big payments to all the big Ag goes out the window. All the industrial support for the industrials, all the chemical companies and fertilizer companies, all of the corporate welfare goes out the window, absolutely all of it. Let's have a level playing field in the real fair market. So that's where I'm starting from. [7]* *Well, anybody doing conventional corn and bean on a D slope...ought to just be jailed or something, or shot. Probably even a second amendment solution. I mean, there's just no excuse. This hill right here, 15 to 18% slope and it was corn and bean when we bought it. It's ridiculous. And why? Because they can't lose money on it, so why not go ahead and farm it and see what happens. So, yeah, anybody who's driven by, well you know, everybody is driven by a bottom line. [4]* *But I'm of the opinion that if, that we'd all be better off if the government just got out of the way instead of trying to help. Because whenever they try and help, they always mess it up. So, the government is subsidizing the rape and pillage of the land. They're literally subsidizing 50 tons per acre, per year of soil erosion in places. They're paying farmers to apply practices that result in 50 tons per acre of soil loss. They subsidize corn and soybean production on land that should have never been taken out of, from the vegetative cover in the first place. [2]*

Supplementary Table 6: Values. Each quote may apply to more than one value; additional values are noted at the end of each quote. Numbers refer to the interview.

Relationship	Value	Quotes
	Self-sustenance	*I've eaten, I have not bought a vegetable or fruit from a supermarket in, for as long as I've lived here, so 18 years. And now I'm meat independent. I'm fat independent, even*

Individual to land		*though we buy olive oil and things like that, I have enough lard that I could do stuff with. But all of that means that my entire body is from this farm, like 99%. And so, I really think that has a huge impact on just a simple thing as bugs, getting bit by bugs. I don't get bit by bugs in the way that visitors to the farm get bit by bugs. Because I don't think that I'm visible anymore. You know, just a walking piece of soil out there, you know? So, like that's a really concrete way that I think about all the time. Because I see people come on the farm and they're swatting away, you know? And it's not bothering me [...] The plants that show up on this land are medicine. So, we make bitters, you know, for digestion and I'm harvesting clover blossoms for a tea that's also helping improve my liver and blood. And so, there's really concrete things, medicine-wise that I'm also getting from being here. [13]* *And mostly in my case, not as much now since I'm traveling so much, but for 25 years, that land is my body. I'm eating the food that comes of it. [7]* *But I would tie it in, too, that, when we have food on our plates that came from our farm, I feel more energized and more provided for than when it's a matter of growing things and getting paid for it, and then I go buy the food. And we always take a lot of pride with all the things that we put on the table, like this evening, that come from our farm. [2]* *It's feeding us, it's feeding our members, it's feeding our souls and how do we do that in a way that's optimal where we're not taxing our bodies, we're not taxing the land and you know, we're earning a living wage. [8]* (also includes Other-sustenance, and Stewardship, care of farmland)
	Stewardship, care of farmland	*Of the 22,000 plants that we planted in 2015, lots more of them lived than I thought would. [...] And then watching things grow and seeing these crops that I wasn't familiar with, grow, nurturing them, harvesting them, and monitoring and maintaining have been very rewarding now, in my post, in my retirement. It wasn't anything I ever dreamed of or planned on, but it's working out very well from that aspect. [6]* *Well, what I mean by that is leaving the land in better shape than we started. And that to me includes the environment, the diversity, the aesthetics, as well as just curbing soil erosion and clean water, and standard conservation practices of crop rotation and strip farming, and grassed waterways and stuff. [6]* *I think our ability to use our land to grow food, to sell, you know, to grow our business is really based on the health of the land. And I think about, erosion is a really good example. Erosion is something that, with the landscape around here, that we see on a lot of farms. And we basically don't see on our farm. A little bit, on the side of our driveway. But I think that erosion washes away topsoil. It washes away, you know organic matter and everything that you've spent time building. And it washes away like the economic potential of your land too, if you're thinking about it that way.* [11] (also includes self-sustenance) *But I think like many farmers, this is also my home, and it's a deeper home, maybe than if I just had a house somewhere in a town. Because I am so entwined with giving care to the animals or plants and then receiving food back that, you know, it's like a family. It's a family member or it's a part of me. It's not, like there's no separation. So, for example, I cannot imagine selling this farm to retire. I just can't picture, it may happen, but I just can't picture that you know? I would sell off a business but I wouldn't be leaving.* [13] (also includes Eudaimonia/connection to identity) *I mean you just see, the more I'm here farming, the more I just, I've learned to observe and see that the plants and the things that are showing up in our lives seem to be*

		exactly what we need when we need them. And I'm just learning to, I mean it's finally maybe open more to paying attention to that observation. Especially in terms of making my own plant medicines or doing my food preservation. And I guess, you know, farming, you grow something and you're tending to the soil and putting in that effort, you know, it rewards you with food and nourishment. [8] (also includes Eudaimonia, Self-sustenance) *Well, and also, I feel like if we're doing an okay job and you can tell that the stuff we've done has allowed the fruit to come in, it looks pretty nice, and we have a good crop, then it also makes just things go smoother and you feel better about yourself when you come to harvest, and you're picking all this nice stuff. And also, it's like you're, you know, you're sustaining your business and you're feeling good about what you do. Plus, it's also less work. Which, we're always strapped for time and working really hard, so if there's anything that makes work go easier, and be more enjoyable, that's really nice. [11]* (also includes Eudaimonia) *I think that how we're treating the soil totally comes back to how we feel. And it's totally all interconnected. I guess the only example of that I can give is down on our other farm where we've done a lot of soil building and I just feel like when you look at those crops this year, you can, it's like the ground telling you thank you. And everything about it is enjoyable and fun to see. I think [farmer's spouse 's name]'s enjoyed working the ground down there and everything, but then we have to look across the street at a hog confinement and then it just depresses us and deflates us at the same time.*[3] (also includes Eudaimonia) *Yeah, I think we just need so much more attention to soil health. And I think that has to come from a university that has confirmed research institutions. And it has to come from our government programs and they have to start prioritizing it because we just, we've lost so much topsoil and we lose so much organic matter and there's just so little health. And so much of our productive land, and our farming system today, it just makes everything so precarious and it leads to needing all of these inputs and it leads to being on the precipice of a disaster when it comes to climate change and weather events. [11]* (also includes Connection to nature and wildlife) *Soil erosion and fertility managing right off the bat, in one, and then nutrient management goes right along with that. Because this one particular farm, an example, I was just there two weeks ago on a Tuesday. And in 1905 I think it was, one, two, three, four generations ago it was undisturbed. Had never been disturbed by modern civilized human beings until that point in time. [...] It was a dry, scrubby oak Chaparral grassy Savannah kind of thing. And they plowed up the soil for the past 100 years or so and they washed it all the way. Blown it all away in the wind. Oxidized the rest of it. And it's a wasteland today. Wasteland. That's what we've got to turn around. We got to stop. There's land like that all over this country. [7]* (also includes Connection to nature and wildlife)
	Connection to nature and wildlife	*Well, I get personal value out of the diversity of birds and insects that have returned, in a short time, I think, to what we're doing. Everything we've got growing seems to be pretty much thriving. It was deliberately varieties that were of native origin, so they should be able to prosper here and they seem to be. That's rewarding. I've always liked growing things, so when growing things grow and come back every year, and then produce things that are fun and delicious to eat and good for you, that's an immeasurable but valuable good result that I'm aware of. [5]* (also includes Eudaimonia, Stewardship and care of farmland) *And I don't know about [spouse 's name], but when I see the trees growing well, and even if it's not well managed, because the grass is too tall, or we didn't get his tree*

		taken care of, [...] or we didn't get this harvested. But we can see the trees, in general, growing and we have lots of diversity, and there's lots of birds singing. So, we know we have a healthy environment, it's so much better than when we're walking through our neighbor's ground where it's so different. [2] (note that in midwestern parlance, "different" is often used as a criticism) (also Stewardship and care of farmland) *Migratory patterns of birds and insects, and butterflies, and a lot of that stuff that we are seeing kind of fluctuate in population - I think that when you have a healthy system you're creating habitat for them to rest and recoup before they get back on the road. And from what I've learned from our partners with the DNR and the fly over initiative I'm really, really excited to contribute to, like, pollinator species and migratory birds as they move. Like that's I think a really big one for me, is like allowing niches to be filled by the appropriate actor in the environmental world. You know, like having no real chemical solutions for mosquitos here is okay because of all of the birds that we've attracted and provided safe space for. That's my favorite I think.* [12] (also Stewardship and care of farmland) *Well, for example by incorporating like multi-levels of shade and canopy in this space. We went from seeing just basic crickets and very little life to having turtles, and crawdads. And like, I think when you see reptile life and stuff like that in an area where food's growing that's kind of a cool feeling. And all of the pollinator insects that we see here, that makes me happy.* [12] *And then I'm cognizant that I'm in a really pristine water shed and I feel really lucky about that and the more that I can protect that, that's also keeping my drinking water clean. I mean, that's very transactional, understanding of our, my relationship to the land. But I think it's also spiritual.* [13] *I'm a deeply spiritual person that really believes that there's no real division between myself and the land and we're all working together as one organism. And I see it up here in ways that, it's like the land is listening to us. Or it's like I really wanted a willow tree in that pond behind you because I remember having one there 20 years ago as a child. And one year a willow tree started growing there. I thought that was pretty magical. And I thought we're not so distant from each other in that there was some element of me that manifested or created that. Put that on record, would you?* [9] (also Eudaimonia, Connection to identity) *Well the intangibles, oh my gosh. The peace and the beauty of waking up to birds, not just one or two birds, but hundreds of birds of dozens of species. Birds singing all over the place. You're taking a dry dusty cornfield and turning it into a place that's singing with crazy frogs and toads. That's just all, what an incredible rush of beauty that is. I got choices, again, in the day if I'm going for a walk somewhere. Where will I go for a walk? Why would I go anywhere else? It's one of the most rich, luxuriant habitats around. The only thing I'm missing is a big pond to go swimming in and a stream with a babbling brook and stones. It's perfect. It's beautiful.* [7] (also Eudaimonia, Connection to identity)
Individual to community	Other-sustenance	*I guess it's just to build a model that other farmers can use to grow like diverse, have a diverse farming operation and support a family on a 40 or 80 or 100 acre piece of land. That isn't just growing commodity crops in the current agriculture system that we live in or that we have in the United States and in the world. So and growing healthy, abundant food I guess [9]* *It's feeding us, it's feeding our members, it's feeding our souls and how do we do that in a way that's optimal where we're not taxing our bodies, we're not taxing the land and you know, we're earning a living wage. [8]*

		I get a lot of satisfaction from sharing what we grow. Without always asking for the money. My philosophy is if we have it, we should share it. Because … it's been so good to us. The land, you get this deep appreciation and yes, you put in a lot of hard work. There's a lot of labor and all that blah, blah, blah. However, the benefits that you reap from that far exceed the effort that goes into it. And you know, it's just a, I don't know. It's very rewarding. [6] (also includes Eudaimonia)
	Learning and sharing	*I think one of things that I'm grateful for in this way of farming is we get to ask more creative questions than like what antibiotic I should give this cow that's standing in three feet of shit. Like, why does it keep getting sick? You know? [12]* *Yeah. I don't think there's…There's no one that's particularly egregiously offensive to me up here. Like, I think most of the practices that I see are pretty understandable. But, I think they're boring and…I think the people that do them aren't excited about it. [12]* *And then as we got started, we just got really excited about fruit and learned a lot about the different things we could grow and decided to try to grow every single one of them. [11]* *Well, I feel like life is, I know, what I know about myself is I like to continually learn and I do feel like there's some areas where I'm like, all right, the farm is flowing in a good way and there's certain, there's a few things that I kind of know how much time I'll need in terms of interfacing with it. And I'm also kind of like, I feel like I need a sabbatical. I just need a break. I think everyone should, in any profession in the work, should get a seven year, or ten year, or whatever it is for you, just a break to explore the things that you're curious about or interested in. [8]* *Again, I guess this is a learning experience. [...] Every year we learn something new about different crops. [6]* *Interviewer: Could you tell me what your main goals are in farming?* *Male Interviewee: I like to learn stuff. [11]*
Individual to land & Individual to community	Eudaimonia & connection to identity	See quotes in other sections tagged "also includes Eudaimonia" *But all in all, farming teaches you how to be, it really does. You have to have a real strong self-awareness and a sort of keen observation of the land and what it's telling you and how to best intervene, so that's my view, or my view right now. [...] You know, it's taxing, the isolating part, it can be isolating. There's, yeah like, you're never really alone, but at the same time you're alone. It's sort of a weird thing, but anyway. I guess like, to me it's sacred. [8]* *I mean, we're mostly trying to be a commercially successful farm. And I think that's like our, maybe our primary motivation. [...] our goals are to, you know, to create a farm that's economically sustainable, as well as environmentally sustainable. I think it's important to us. It doesn't, you know, it doesn't constitute a huge portion of our income right now, but we'd like to get to where it does. I think we'd like to get there because we want that. We want to be farmers.* [11] (also includes Self-sustenance) *Well actually it's interesting. I'm 55. And kids are all grown up. Everybody's moved out of the house. It's like life change times. Like well what do I do now? And why am I motivated to do anything? I think as far as living that way is concerned, I can't imagine not interacting with my environment in such a way that it's helping to produce*

		my food and my fuel and my medicines and all that kind of stuff. I can't imagine not interacting with my environment that way for one. [7] *I would rather just let it go wild than rent it back out to another conventional farmer. No, I think that someday I'm going to have children and those children are going to have children and I want to leave them with healthy land and clean water and my little 42-acres isn't going to do that. We need the whole neighborhood, the whole state, the whole country to rally behind it to really clean up some of the problems that we have. So, you know, I'd rather just let it go wild. [9]* (also includes Stewardship and care, Connection to nature and wildlife, long-termism) *I love how it's all starting to come together and financially it's all starting to come together, as well. So, I'm grossing about $25,000 off the farm, 10 of that is going right back in, and then I have other income that supplements me to have a viable livelihood. Not a rich one, financially, but I eat like royalty every day. And I'm in great physical health. And love being outside and being my own boss and there's you know, all those other benefits that you get. [13]* *Yeah, I think first of all, it's a home, and this is a permaculture ethic too, you feed yourself before you feed anybody else. [...] I feel like if I'm not eating from my land, number one, you know, then something is off in my system, and then the rest of it goes out for sale. Yeah, and so, homestead first, but the commercial layer is very important and I'm tracking that very carefully. And I have no interest in going back to a sort of, real world job ever again. And so, this better work. [13]*
	Diversity	<u>Ecological</u> *It just got me excited about plant diversity and like all of the amazing things that plants do that we kind of overlook. And I grew up in the woods. So, yeah. Like designing a food system that incorporates diversity and imitates like the ecological shape of a forest was something that was really, really appealing to me as soon as I started to learn about it. [12]* *I would say a healthy agroecosystem needs to be, needs to have a high level of biological diversity and, except on perfectly flat land, that should be covered with permanent vegetation all the time. And it should have high levels of wildlife, insects, and perennial vegetation, and bacteria and fungi and nematodes and anilines and arthropods, non-insect arthropods, and everything else. Even viruses and chlamydia and rickettsia. [2]* *And when it comes to poly-culture, it's also you know, like [spouse 's name] mentioned, it was a hay field and we never replanted the ground cover. So, you know, I think that our management of our orchard floor is pretty different from most other people. Some of it is just we don't have enough time to mow and some of it also really is, I think we have a diverse mix of ground cover species. Some of them I would prefer not to have in there, but I think the diversity is overall, of benefit to us. [11]* *So keeping a healthy agroecosystem is keeping it in that phase where we are still showing increases in soil health, fertility, biodiversity and the whole entire system and it's actually still paying a return for whoever the manager is. That return does not necessarily mean the top yields for the agricultural production per commodity. And it does not necessarily mean the top dollar as is you're making a million, crushing it. It's keeping in that, the aggradation phase of ecosystem development before you close canopy. Once you close canopy, you're going to start to lose parts of the system. It will actually become less biodiverse and more specialized, depending on which direction*

		you go successionally. So I like to keep it in that mid-successional phase, most dynamic phase. [7] *I really admire his diversity. And s/he was the first farm where I looked around and I said, "Oh, he's got lots of little different patches of stuff. This feels really good. [13]* <u>Financial</u> *Like, resilient income streams that wouldn't all hinge on the success or failure of one or two things a season. I think it's…stuff can be pretty unpredictable. Especially, when you're not super experienced. And so, scaling up at the right time is important. Well for the success of each individual project, and for my quality of life, and for the quality of life of the animals that we bring onto the scene. You know we want it to happen when I know that there's enough time to make it all go correctly. [...] And that's one of things that I think is the most enjoyable about a diverse system. If you can pace it out like that. But, it's also one of the things that makes it the hardest. [12]* *I think there's more opportunity for those smaller acreage farmers to do the diversity. That's, and so I think there's more of a push to do the agri-forestry or the perennialization sort of thing for those particular farmers that can bring in some different income stream for them. [6]* *We're both very much into local and regional marketing to reduce the environmental footprint and to try to establish enough diversity so you have different income streams so you're not … so many people in order to afford to farm you have to have these jobs to earn income off the farm. And that shouldn't be right. We should be able to earn a living on the farm. We should be able to be sustainable. You should be able to have contact with your customers. [...] And so I guess the contrast is more in terms of philosophy, but you've got to follow up on the philosophy and implement it and make it affordable. [6]* *I feel like that'd be pretty much, I can generally say that people who do poly-cultures are thinking of a risk management strategy. And that could be related to scale. And some are market driven, like maybe you're trying to find niche markets. I don't know. That's a good question. Yeah, that would be my two other things. The market interest and then risk. [8]*
	long-termism	*And I think it's just really satisfying to see, because you know, the perennials are such a long-term game and especially things like, now, I mean last year we had a pear harvest for the first time. Which was really exciting because we planted those pears a long time ago. So, that's just really gratifying to have those things start to produce and produce well and be delicious and wonderful and something that we are really feeling like has great value. [11]* (Includes stewardship and care) *See for me that means perennial things. That means doing long crop rotations. It means feeding the soil, not just depleting the soil. [3]* (Includes stewardship and care) *It takes time, soil rehab is a long process and so, I would also at the same time, like to better align agriculture policy and not have it be so tied to politics, like a four-year cycle does not work in a perennial or a soil health system. Maybe seven years, but definitely not two or four.[8]* *There's also, I'm in the middle of a process right now, in my farming trajectory, we're thinking of like, alright succession planning to probably a non-family person and what would that look like, in like thinking the ten-year plan, if you will. So, we're asking*

		those questions together, about alright, what's the next ten years on the farm look like? Can we just take a sabbatical and think of how to integrate some of these things that we've been learning and not have to feel like we're always in hustle mode. [...] I think right now, I'm a little tired. [...] in terms of my own kind of, lifetime path, if you will. [8] *Well, I mean, that's the thing about perennials. You, kind of, end up inheriting what the last guy did. It's not like you just get to tear it all under and start over. Like with corn or beans, or squash, or watermelons. But, that said, I don't think we're going to leave it to us. [...] I think we get somebody who's got a long-term investment in it, like a really long-term lease, and let them figure it out. They can study up. They're going to be the ones doing the work. [4]* *So right now I've still got a lot of energy to be in the field. I should be doing a lot. And then teaching some but not yet focusing on that. Building and deploying, yes. And then 15 more years and I'm going to start moving more into teaching and less into this other space. According to the appropriate ancient way that my communities have of transferring into your elder years which is where you are supposed to be doing the teaching. [...] I have it planned out. And I'm just evolving right now. That's why I'm anxious for the next 15 years to deploy this at scale. [...] If s/he doesn't take off, someone else will have to do it. Because I need to move into my new stage of life. [10]* *So, we started from scratch planting a perennial polyculture. So, that's what, I mean, we explored a lot of different ideas when it came to farming [...] trying to decide what to do, and we decided to start with planting fruit, partly because we weren't going to be living here, as we got started. And fruit was something we could manage in the beginning, in the early years, like with being here part time compared to raising animals or growing annual vegetables. [11]* *The last six years of being on this farm full time, has taught me so much more. So, you know, better organization of the way the animals move through the system, and what exactly the perennial fruit needs to be, and where, and what my harvest windows are and all of, you know, trial in different varieties of things. All of that stuff, the learning curve has jumped up at that point here. And then, so, it's now moving into, "Okay, I've got some final things to tweak, some final things I need to add, some infrastructure I still want to add", and then I will have sort of plateaued out, in terms of, my infrastructure, and what I want to manage. [...] it's interesting because when I did my dissertation and talked to women farmers, there was about a 10-year mark where people sort of, settled into exactly what they wanted to do, and let the other stuff go. I was like, okay, I'm kind of on that trajectory. [13]*