FRONTIERS IN ALLEY CROPPING:
TRANSFORMATIVE SOLUTIONS FOR TEMPERATE AGRICULTURE

BY

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DISSERTATION

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ABSTRACT

Annual row crop systems dominate agriculture around the world and have considerable negative environmental impacts. Incremental improvements to the prevailing system have been the primary focus of efforts to reduce these negative impacts, though are likely insufficient in solving the ecological challenges of row crop agriculture. This dissertation explores alley cropping (AC) – an agroforestry practice integrating trees with crops – as a transformative land-use solution to mitigate climate change, restore ecosystem services, and improve agricultural profitability. Through an inventory of all field experiments of AC to date, I identify several major gaps in AC research. In particular, AC has held a narrow focus on systems that integrate only one timber tree species with one annual grain species. I explore broadening this focus and identify key considerations for the scalable implementation of woody polycultures and tree crops for food and fodder. To evaluate the direct benefits of such systems, I then assess the potential of diversified, food-producing AC to mitigate unintended nitrogen losses in a side-by-side field experiment with row crop agriculture. I show that transitioning to AC can rapidly tighten the nitrogen cycle even during establishment years. Finally, I evaluate the economic competitiveness of the most common temperate AC system – black walnut trees for timber with annual grain alley crops – against the widespread maize-soybean rotation. Even without monetization of environmental benefits, I demonstrate that AC can improve landowner profitability across a substantial portion of the Midwest US. By exploring the frontiers in temperate AC, this dissertation highlights a multifunctional, transformative land-use alternative for temperate agriculture.

INDEX WORDS: agroforestry, silvoarable, tree-based intercropping, nitrogen, land-use change, tree crops, multispecies systems, polyculture, permaculture, nitrate leaching, nitrous oxide

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CHAPTER 1

INTRODUCTION

BACKGROUND

Row crop agriculture covers over 1.28 billion hectares of land around the world (FAO 2017). Though extremely productive, these cropping systems degrade many ecological functions via a heavy reliance on external inputs of energy, nutrients, and pesticides. The agricultural sector accounts for 10-12% of global anthropogenic greenhouse gas emissions (IPCC 2014) and is also highly sensitive to future impacts from the resulting climate change (Mistry et al. 2017). Intensive management in row crops leads to a leaky nitrogen (N) cycle, in which leached N inputs have become the largest source of nutrient pollution in aquatic ecosystems (USEPA 2007). Extensive landscape disturbance and simplification leads to widespread biodiversity loss (Foley 2005). Furthermore, degraded soil fertility and high external inputs leaves row crops highly susceptible to volatile annual profitability (Brandes et al. 2016, Williams et al. 2016).

Incremental improvements to the prevailing system have dominated efforts to reduce these negative impacts in the US (DeLonge et al. 2016). These approaches include cover cropping (Dabney et al. 2001), precision management (Mulla 2013), no- or low-tillage (Lal et al. 2007), and organic production (Nandwani and Nwosisi 2016). Adoption of these approaches remains low (USDA 2011, Wade et al. 2015), and their impacts will likely be insufficient in reversing greenhouse gas emissions, reducing surface water hypoxia, fostering substantial biodiversity, and solving other ecological challenges of temperate agriculture (de Ponti et al. 2012, Powlson et al. 2014, Pittelkow et al. 2014).

Transformative solutions addressing the fundamental issues associated with vast monocultures of annual crops will be necessary for a robust and resilient temperate agriculture, especially in the face of global change (Tilman 1999, Malézieux 2012, Tittonell 2014). Jackson (2002) best stated this need in his call for a paradigm shift to focus on transformative solutions that can solve the "problem *of* agriculture" rather than the "problems *in* agriculture." Successful transformative solutions must be ecologically sustainable, economically viable, and culturally acceptable (Robertson and Swinton 2005, Jordan and Warner 2010, Foley et al. 2011).

Agroforestry, the integration of trees with crops or livestock, is one such transformative approach that has been widely studied (Gold and Hanover 1987, Leakey 2014, Wilson and Lovell 2016). Encompassing a diverse array of multifunctional practices, agroforestry is an ancient approach that has declined over the last century with the trend to remove trees from agricultural landscapes (Eichhorn et al. 2006, Nerlich et al. 2013). Recently, however, there is a growing awareness that agroforestry can provide many economic and ecological benefits that contribute to the call for sustainable intensification (Smith et al. 2012, Leakey 2014, Geertsema et al. 2016). Agroforestry has great potential as a tool for climate change mitigation and adaptation (Schoeneberger et al. 2012, IPCC 2014), and can improve many other ecological functions, such as yield resilience, biodiversity, nutrient use efficiency, pest resilience, and reduced soil erosion (Jose 2009, Quinkenstein et al. 2009, Tsonkova et al. 2012, Lorenz and Lal 2014, Torralba et al. 2016).

Although agroforestry encompasses a wide array of practices, alley cropping (AC) most closely integrates trees with crops. While other agroforestry practices, such as riparian buffers, windbreaks, or shelterbelts, are confined to field margins, AC integrates trees and crops throughout a field. This is a transformative departure from the monoculture row crop fields that currently dominate temperate agriculture. Research and adoption of AC has been higher in the tropics, though interest has grown considerably in the temperate zone (Mosquera-Losada et al. 2012, Smith et al. 2013). Temperate AC has the potential to sequester substantial amounts of carbon (Thevathasan and Gordon 2004, Udawatta and Jose 2012, Winans et al. 2016), increase land-use efficiency (Graves et al. 2007, Dubey et al. 2016), buffer crops from climate change impacts (Nasielski et al. 2015), improve soil structure and fertility (Udawatta et al. 2008, Torralba et al. 2016), increase biodiversity (Stamps et al. 2002), and improve farmer livelihood (Alam et al. 2014). This dissertation evaluates AC as a transformative agricultural solution for temperate agriculture, primarily through the lens of two underexplored frontiers that have the potential to expand the benefits of temperate AC: (1) augmenting AC with tree/shrub polycultures and (2) leveraging trees for food and fodder production.

OVERVIEW

While AC is inherently diverse in its composition and function, no comprehensive inventory of its many forms has been performed. In Chapter 2, I catalog the composition and function of all AC field experiments in the literature to understand the existing gaps and future opportunities in AC research. I review a total of 1,244 publications from 77 countries over the last 35 years. I found that tree diversity utilized in AC was high across all climate regions, with 410 species utilized from 192 genera. Dominant trees included *Populus* and *Juglans* in the temperate zone, *Eucalyptus* and *Populus* in the subtropics, and *Leucaena* and *Gliricidia* in the tropics. Alley crops were also highly diverse – 276 species within 181 genera – but were dominated by a few annual grains in each region. Despite the diversity in composition across systems, the agricultural function of both trees and crops were limited. Temperate systems emphasized trees for biomass production, while trees for food, fodder, and crop facilitation were more common in the subtropics and tropics. To best orient the growing interest in AC around the world and inform future research opportunities, I leveraged the results of this quantitative literature review to identify existing gaps in the literature. Four frontiers in the composition and function of AC were identified as (1) within-system tree diversity, (2) tree crops for food and fodder production, (3) perennial alley crops, and (4) trees for crop facilitation.

In Chapter 3, I focus on the two key frontiers identified in Chapter 2 – within-system tree diversity and tree crops for food and fodder production – as opportunities to expand the scope and potential benefits of temperate AC for climate change mitigation and adaptation. I describe the central concepts of climate change mitigation and adaptation in AC and discuss the primary opportunities by which tree diversity and tree crops could enhance these benefits. In addition, I identify four important considerations that could enhance the scalability of temperate AC and the implementation of these frontiers in the temperate zone: (1) strategic expansion from marginal lands via policy incentives, (2) well-developed tree crops compatible with the maize-soybean supply chain, (3) practical designs optimized for tree-crop interactions and mechanized management, and (4) complementary crop combinations that provide both early returns and long-term yields.

To directly evaluate the potential of a diverse, food-producing AC system to improve biogeochemical cycling, I examine the agricultural N cycle in Chapter 4. Since the two major avenues of N loss from agricultural systems are N leaching and soil nitrous oxide (N_2O) emissions, I focus on these two fluxes to evaluate the efficacy of AC in tightening the N cycle. To compare the N losses and N cycling of the conventional maize-soybean rotation (MSR) and AC, I (1) summarized literature values of N pools and fluxes in both systems and (2) directly measured N leaching and N_2O emissions in a side-by-side trial of MSR and an establishing AC over four years. Ample literature data on MSR allowed me to construct a robust working N budget, while a paucity of data on N cycling in AC revealed gaps and high uncertainty in our understanding. In the field trial, AC quickly reduced both N leaching and N_2O emissions compared to MSR. Even in just the first 5 years after establishment, AC reduced nitrate leaching by 82 to 91% and cumulative annual net N_2O fluxes by 25 to 83%. Overall, conversion of MSR to AC rapidly tightened the N cycle and reduced unintended N losses over four years by 83%.

While environmental benefits can certainly increase landowners' interest in agroforestry, they have failed to drive adoption due to the lack of robust market mechanisms to monetize their value. Profit remains the key driver for adoption of alternative agricultural strategies. Consequently, in Chapter 5 I evaluated the economic competitiveness of forestry and AC as two tree-based land-use alternatives to MSR. By combining publically available data on soil characteristics, timber prices, crop productivity, cash rents, and land cover in a novel, high-resolution spatial and economic analysis, I identified target regions where forestry and AC can be direct economic competitors of MSR without any monetization of environmental benefits or government assistance. I showed that black walnut plantation forestry and AC could be more profitable than MSR on 17.0% and 23.4% of cultivated land, respectively, assuming a 5% discount rate. These results revealed a strong economic case for landscape diversification and AC adoption. Importantly, the economic competitiveness of the tree-based systems was not correlated with MSR productivity, indicating that restricting evaluation of land-use alternatives to so-called marginal lands is inadequate. Instead, results revealed major opportunities for landowners and investors to increase profitability by investing in forestry and AC on both marginal and highly productive land.

Finally, in Chapter 6, I summarize the results of this dissertation and explore avenues for future research in this area. Overall, this work demonstrates that temperate AC has great potential as a transformative agricultural solution and demands further research. I conclude that effective AC systems are ready now for implementation as profitable enterprises with significant ecological benefits, although there are many opportunities for future research to optimize the productivity and management of these complex systems.

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CHAPTER 2

ALLEY CROPPING: GLOBAL PATTERNS OF SPECIES COMPOSITION AND FUNCTION

ABSTRACT

Alley cropping – the intentional integration of trees and crops – is one of the most common agroforestry practices around the world. To better understand its potential to provide economic and ecological benefits over separately cultivated trees and crops, alley cropping research has expanded significantly over the last few decades. While alley cropping is inherently diverse in its composition and function, no comprehensive inventory of its many forms has been performed. We analyzed historical and geo-climatic trends in species composition and function of all alley cropping field experiments in the literature. A total of 1,244 publications from 77 countries over the last 35 years were included. Tree diversity was high across all regions, with 410 species utilized from 192 genera. Dominant trees included *Populus* and *Juglans* in the temperate zone, *Eucalyptus* and *Populus* in the subtropics, and *Leucaena* and *Gliricidia* in the tropics. Alley crops were also highly diverse – 276 species within 181 genera – but were dominated by a few annual grains in each region. Despite the diversity in composition across systems, the agricultural functions of both trees and crops were limited. Trees for biomass were utilized in 82% of temperate experiments, while trees for food, fodder, and crop facilitation were more common in the subtropics and tropics. To best orient the growing interest in alley cropping around the world, this inventory was used to identify existing gaps in the literature and inform future opportunities in alley cropping research. Four frontiers in alley cropping research were

identified as (1) within-system tree diversity, (2) tree crops for food and fodder production, (3) perennial alley crops, and (4) trees for crop facilitation via shade, nitrogen fixation, and mulch production.

INTRODUCTION

Agroforestry encompasses a diverse array of multifunctional practices that intentionally integrate trees or shrubs with crops or livestock into a single agricultural system (Gold and Hanover 1987, Wilson and Lovell 2016). Many agroforestry practices are ancient and were widely utilized around the world, although these systems have declined over the last century with the trend to remove trees from agricultural landscapes (Eichhorn et al. 2006, Nerlich et al. 2013). Recently, however, there is a growing awareness that trees integrated into agricultural landscapes can provide many economic and ecological benefits that contribute to the call for sustainable intensification (Smith et al. 2012, Leakey 2014, Geertsema et al. 2016). Beyond their potential to improve agricultural productivity and resilience, agroforestry practices can promote carbon sequestration, biodiversity, nutrient use efficiency, pest resilience, and reduced soil erosion (Jose 2009, Quinkenstein et al. 2009, Tsonkova et al. 2012, Lorenz and Lal 2014, Torralba et al. 2016).

The inherent complexity in the structure and management of agroforestry systems is the primary hurdle to achieving their potential benefits. Care in species selection to avoid allelopathic effects (Jose and Holzmueller 2008) and strong interspecific competition (Jose et al. 2000a, 2000b) is critical. Management complexity can become more tractable by adapting and developing tools for use in integrated systems (Vandermeer 1989). The relatively large initial investment and long time to maturity for trees and shrubs is also a substantial economic hurdle to agroforestry adoption (Dyack et al. 1999), although leveraging multispecies systems (Malézieux et al. 2009) and high-value tree crops (Molnar et al. 2013) could lessen this burden.

Of the many common agroforestry practices around the world, alley cropping (AC) – the intentional integration of trees and crops – most closely combines these two components. AC is typically comprised of widely spaced rows of trees or shrubs with a range of agricultural crops grown in the intervening “alleys”. The close proximity of trees and crops in AC creates dynamic interactions between these components (Jose et al. 2008). The tree and crop components can include any one or more species, creating many variations of AC around the world (Nair 1991, Williams and Gordon 1992, Mosquera-Losada et al. 2009). Species can be applied across regions based on their productivity, market availability, and potential to improve agroecological function (e.g. Reisner et al. 2007). Beyond tree and crop composition, agricultural functions in AC are also extremely diverse. Products from both tree and crop components can include food, fodder, fuel, biomass, medicine, and floral products, while the trees can also produce timber, sap, and cork (Nair 1991, McAdam et al. 2009). The layering of these functions can vary from simple, two-function systems such as an annual grain rotation between timber tree species (e.g. Thevathasan and Gordon 2004, Cardinael et al. 2015) to complex homegarden systems that often produce a full range of agricultural products (e.g. Singh et al. 2016).

Despite the wide variety of AC systems around the world, no comprehensive inventory of species composition and function in AC has yet been performed. An understanding of AC composition and function around the world will orient the growing interest in AC and help identify research priorities. Therefore, our primary goals were to (1) catalog species composition and agricultural function in all publications of AC field experiments around the world and (2) use the resulting inventory to identify existing gaps and promising frontiers of AC research.

METHODS

This review considers AC, broadly defined, where the “tree” component can refer to one or more trees, shrubs, or other woody plants, and the “crop” component can refer to a wide range of plant functional types – both annual and perennial – both herbaceous and woody – that produce agricultural products. While “alley cropping” has been the term adopted by the agroforestry community in the USA and many other countries, other terms that refer to comparable systems are also widely used in the literature, including “agri-silviculture”, “tree-based intercropping”, “hedgerow intercropping”, “belt and alley systems”, “agrihortisilviculture”, “intercropped orchards”, “parkland systems”, “agri-horti systems”, and “multi-strata agroforestry systems” (e.g. coffee/cacao agroforestry and tropical homegardens) (Nair 1991, Williams and Gordon 1992, Mosquera-Losada et al. 2009, Liu and Zhang 2011). These systems are all considered here under the umbrella of AC.

This review considers publications on AC field experiments published in peer-reviewed journals. While an inventory of field experiments is not necessarily a direct reflection of AC being applied on farms, it nevertheless represents the depth and breadth of our scientific understanding of AC and is the best available approach to assess species composition and function in AC. Publications that did not include AC field experiments were not included in the review. Specific criteria for excluding publications, such as studies purely of *in silico* modeling, economic analyses, or landscape-scale dynamics, are provided in Table 2.1.

To find all publications on AC, a literature search was conducted on the Web of Science Core Collections requiring one or more of the following key phrases: “agroforestry”, “alley crop”, “silvoarable”, and “orchard” or “tree” with “intercrop”. The search query was constructed so studies that only examined other agroforestry systems (i.e. silvopasture, riparian buffers, windbreaks, and forest farming) but not AC were not returned (Table 2.2). The search returned 5,291 publications using a search window of 1900 through 2016, and included all major journals with AC-related publications (Fig. 2.2). All retrieved publications were screened to determine if the criteria were met for inclusion in the inventory, with a total of 1,244 publications meeting the criteria. For each included publication, the unique combinations of examined tree-crop treatments, along with the primary agricultural function of each component, were cataloged. For species with multiple uses, the primary use was determined from the description in the publication or inferred based on the agricultural practices of the region where the experiment took place. All analyses were conducted at the genus level since many domesticated trees and crops include multiple, similar species. Including this species-level diversity would unduly exaggerate the diversity of trees and crops in AC. Analyses of tree and crop composition and function were performed using the unique combinations of publication-tree genus or publication-crop genus as the experimental units (referred to here as “observations”).

RESULTS AND DISCUSSION

When & Where

The retrieved publications on AC field experiments spanned 35 years, with the earliest in 1981 (Fig. 2.1). This horizon corresponds well with the broader historical origins of agroforestry as a scientific discipline. After the term “agroforestry” was coined in the mid-1970s, the International Council for Research in Agroforestry (ICRAF, now the World Agroforestry Centre) formed in 1978 (see Huxley 1987). ICRAF’s work remains primarily focused on the tropics. The publication record similarly began in the tropics, expanding to the subtropics 5-10 years later, and then to temperate regions 5-10 years after that. Temperate AC field experiments only began to appear in the literature in the mid-1990s, which corresponds well to the development of the discipline in temperate regions. In the USA, for example, the National Agroforestry Center was established in 1990. Despite the expansion of AC research into the subtropical and temperate zones, the number of tropical publications continues to grow at a faster rate than in other regions. However, beginning in the early 2000s, the tropical research focus shifted sharply to the more complex coffee/cacao and homegarden systems (Fig. 2.1). This shift was likely driven by increasing consumer demand for extensively managed and shade-grown coffee/cacao and the resulting research funds contributed by the industry.

As the scientific literature on agroforestry grew, the journal *Agroforestry Systems* began publishing in 1983. By 2013-2016, the number of publications on AC field experiments across climate zones grew to just under 100 publications per year. Over all years, 28% of publications were published in *Agroforestry Systems*. The next most common journals were *Agriculture, Ecosystems & Environment; Plant and Soil;* and *Forest Ecology and Management* at 6.7%, 3.7%, and 2.7%, respectively (Fig. 2.2).

The AC field experiments in the reviewed publications took place in 77 countries across the globe. India and Brazil led the way, each contributing substantially to the tropical and subtropical literature, with almost twice as many publications as any other country (Fig. 2.3). The USA has the most publications in the temperate zone, followed by China, Canada, and France. The temporal trend of publications from each country has generally followed the overall trends shown in Figure 2.1 except for Nigeria and Kenya. Both countries led the way in AC in Africa in the 1980s but have not experienced the same growth in coffee/cacao research that has dominated tropical AC research since the 2000s.

Tree component: species composition & function

Across all publications, 410 species from 192 genera were represented in the tree component of AC field experiments (Fig. 2.4). Deciduous broadleaf trees accounted for 87% of observations across climate zones. Tree richness across systems increased towards the tropics, with 5.3 times as many genera found in the tropical compared to temperate zone. Temperate studies were dominated by just a few genera, with *Juglans* (walnut) or *Populus* (poplar) included in 55% of publications. Similarly, dominant in the tropics were *Leucaena* (leadtree) and *Gliricidia* (gliricidia), occurring in 42% of publications. *Leucaena* and *Gliricidia* are both nitrogen fixers and have been used extensively as a “chop-and-drop” fertilizer for annual grain crops in AC. There were 142 and 141 publications containing *Leucaena* and *Gliricidia*, respectively, more than double that of any other tree genus in any zone. *Eucalyptus* (eucalyptus) was the most common subtropical tree genus, although the subtropics contained a more even distribution of utilized tree genera.

Beyond composition, the functional role of the tree component in AC was different across climate zones (Fig. 2.5). In temperate experiments, the primary function of the tree component in 82% of observations was biomass production (primarily timber). The only other significant tree function in the temperate zone was food production, primarily by fruit trees. Biomass was also the top tree function in the subtropics, but this was closely matched by food and fodder together. Food production included both fruits and nuts, while fodder production was primarily green leaves and branches in “cut-and-carry” systems. In the tropical tree component, a similar split between biomass and food/fodder production was observed as in the subtropics. However, there was an additional emphasis on trees with the primary function of facilitating the crop component.

Crop facilitation in AC occurs when the tree component enhances crop productivity relative to monoculture yields (Vandermeer 1989, Cannell et al. 1996). In the reviewed literature, there were three primary ways in which trees were used to facilitate crop productivity: nitrogen fixation, shade, and mulch production. The top seven tree genera in the tropical literature – *Leucaena*, *Gliricidia*, *Senna* (senna), *Erythrina* (coral tree), *Acacia* (acacia), *Calliandra*, and *Inga* – are all leguminous nitrogen fixers. These trees were all commonly used in both chop-and-drop AC with annual grain crops as well as in multi-strata coffee/cacao systems, where they also provided shade. The abundant use of nitrogen-fixing trees in the tropics and subtropics demonstrates the emphasis in these regions on multi-purpose trees. Many trees that were classified as having non-facilitative primary uses were also nitrogen fixers and, consequently, likely contributed to crop facilitation as well (Fig. 2.5). Beyond nitrogen fixation, tropical systems commonly leveraged trees to provide shade on crops or on-site mulch production. In these tropical systems, multiple facilitation mechanisms were often provided by the same tree species.

Crop component: species composition & function

The crop component of AC field experiments was also very diverse across all publications, with 276 species represented within 181 genera (Fig. 2.6). There were 2.1 times as many crop genera studied in the tropical zone compared to the temperate zone. Temperate studies were dominated by the same three annual grain crops that dominate temperate production agriculture: *Zea mays* (maize), *Glycine max* (soybean), and *Triticum* sp. (wheat). Other common temperate crops included other grains [e.g. *Hordeum* (barley), *Brassica* (mustard), *Avena* (oat), *Secale* (rye)] and several herbaceous forages [e.g. *Medicago* (alfalfa, lucerne), *Trifolium* (clover), *Lolium* (ryegrass)]. *Zea* and *Triticum* were similarly dominant in the subtropics, although

Glycine was replaced by another leguminous genus, *Vigna* (bean), as the most common nitrogen-fixer in annual crop rotations. Other common genera in the subtropics were *Arachis* (peanut, groundnut), *Sorghum* (sorghum), and *Oryza* (rice) as food crops and *Pennisetum* (fountaingrass) as forage. In the tropics, *Zea* and *Vigna* were the main annual crops, but *Coffea (coffee)* and *Theobroma (cacao)* were also dominant. The 265 total tropical publications containing *Zea* as the alley crop pairs directly with the dominance of *Leucaena* and *Gliricidia* in the tree component discussed above. The *Leucaena*-*Zea* and *Gliricidia*-*Zea* systems constitute the most-studied AC systems to date.

Despite the diversity of crops utilized, alley crop function was similar across climate zones. Food production was the dominant crop function across all zones, with fodder production second (Fig. 2.7). The role of fodder decreased from 24% of observations in the temperate zone to 14% in the subtropics and just 2.8% in the tropics. Other minor crop functions were biomass production in the temperate and subtropical zones (primarily *Panicum*, switchgrass), a wide range of herbaceous (temperate) and woody (subtropical) floral crops, and fiber (mainly *Gossypium*, cotton) in the subtropics. While function was similar across zones, there was a clear difference in the relative use of plant functional types in the crop component, especially for food crops (Fig. 2.7). Almost all utilized temperate food crops were annual herbaceous species, with the proportion of perennials increasing towards the tropics. The large proportion of woody perennials in the tropics was driven by *Coffea* and *Theobroma*.

Frontiers in AC

A comprehensive understanding of the existing gaps in AC experimentation is critical to orient future research priorities. The remainder of this paper discusses four gaps in species composition and function in AC research that were identified in this analysis as opportunities for future research and application. While others have discussed some of these opportunities (Eichhorn et al. 2006, Smith et al. 2012, Nerlich et al. 2013), this comprehensive inventory of field experiments provides new and robust context for these frontiers.

Frontier 1: Within-system tree diversity

Diversity is inherent in AC, with the definition requiring at least two species – one tree or shrub and one crop. However, despite the diversity of trees utilized across AC systems (Fig. 2.4), diversity within the tree component of individual AC systems has been very limited (Fig. 2.8). Single-tree AC has remained dominant in all climate zones – 74% of observations – despite robust evidence of the economic and ecological benefits of multispecies systems (Malézieux et al. 2009).

Just as for mixing trees with crops in AC, mixing multiple tree species can also result in overyielding, where the tree mixture yields more than the component monocultures (Piotto 2008, Sapijanskas et al. 2014). Overyielding in multispecies woody systems has been studied much less than in herbaceous systems (e.g. Picasso et al. 2011, Yu et al. 2015), although the broad variation in woody plant architecture above- and belowground potentially allows for even greater overyielding. Furthermore, improved ecological function has been repeatedly demonstrated in multispecies woody systems (Perfecto et al. 2003, Malézieux et al. 2009).

The most common approach to leveraging multiple tree species in the reviewed temperate literature was the common forestry approach of mixing fast-growing (e.g. *Populus*) and slow-growing [e.g. *Fraxinus* (ash), *Quercus* (oak), *Prunus* (cherry)] trees. This approach spreads the revenue potential over multiple harvest events and uses the fast-growing trees to maintain straight trunks and discourage branching in the more valuable hardwoods. In contrast, multi-strata tree and shrub components were the most common approaches for diversifying AC in the tropics and subtropics. A major limitation of the typical the multi-strata systems is that they are rarely limited to linear rows, which makes mechanization and scalability difficult. Multiple tree and shrub strata confined to linear rows is an underexplored approach that could maintain mechanical management and harvestability of both trees and crops (Lovell et al. 2017).

The only substantial use of diversity within the AC tree component was observed in tropical experiments cataloged with diverse tree components of unknown or unreported richness (Fig. 2.8). These cases of unreported tree richness occurred almost exclusively in coffee/cacao systems with a high diversity of shade tree species or in homegardens with a high diversity of species in all canopy strata. The fact that species numbers and identities were commonly not reported in these systems illustrates that the use of diversity was likely not intentional within tropical AC. Often, the diversity in these systems was just a consequence of the remnant native tree population under which the system was established. Major research opportunities remain for the intentional integration and management of tree diversity within AC.

Frontier 2: Tree crops for food and fodder

Just as with diversity, food and fodder production is inherent in AC. However, this function has primarily been limited to the crop component (Figs. 2.5 and 2.7). Only 24% of AC experiments included trees for food or fodder, compared to 94% for crops. Smith (1929) reviewed the potential of a wide range of tree crops for food and fodder production; he described the "meat-and-butter" trees of *Juglans* and *Carya*, the "corn trees" of *Castanea* (chestnut) and *Quercus*, the "stock-food trees" of *Ceratonia* (carob), *Prosopis* (mesquite), *Gleditsia* (honey locust), and *Morus* (mulberry), and a "kingly fruit for man" in *Diospyros* (persimmon). Smith's work has inspired agroforestry for almost 90 years, and his vision for staple tree crops is no less relevant today (Molnar et al. 2013). Yet, the results of this analysis clearly demonstrate that little of Smith's vision of tree crops for food and fodder has translated into tangible research and field experimentation in AC.

Production of the seven most widely grown fruit and nut trees has increased dramatically over the last decade (FAO 2017) (Table 2.3), creating market opportunities and potential for grower adoption. Nevertheless very few AC field experiments have utilized these important crops and their expanding markets. Neglecting the productive value of tree crops, especially of tree crops that already have global markets, significantly undervalues the economic potential of AC (Lovell et al. 2017). Furthermore, the food-producing potential of agroforestry systems can be the primary driver of adoption, especially in low-income, subsistence agriculture communities (Jerneck and Olsson 2014).

The nut or fruit biomass of tree crops can also provide tree-sourced fodder production beyond the common tropical cut-and-carry approach using only vegetative biomass. For example, the most widespread silvopasture system, the *dehesa* of southwest Spain and Portugal, utilizes nuts as fodder (Eichhorn et al. 2006). One major benefit of using nuts or fruits as fodder is that no farmer intervention is typically required to bring fodder to the livestock. In AC, livestock could graze on fallen fruits and nuts directly beneath the trees once alley crops have been harvested, temporarily turning an AC system into a silvopasture system. Even when tree crops are harvested first for food, any crop remaining due to harvest inefficiencies can be foraged by livestock as a secondary yield.

Frontier 3: Perennial alley crops

Annual alley crops have dominated AC field experiments around the world – 66% annual, 13% herbaceous perennial, and 22% woody perennial (Fig. 2.7). Further research is needed on how perennial alley crops could further improve the economic and ecological functions of AC. In the tropics, the emphasis on woody perennial alley crops is almost completely driven by coffee and cacao. The lessons learned from these systems regarding habitat structure, tree arrangement, and species interactions can provide a starting point for research outside of the tropics.

There are many food producing shrubs, such as *Ribes* (currant, gooseberry), *Rubus* (raspberry, blackberry), *Vaccinium* (blueberry), *Sambucus* (elderberry), *Amelanchier* (serviceberry), and *Aronia* (chokeberry), that have global markets and could function well in AC alleys outside of the tropics. Some of these crops even have documented yield and fruit quality benefits when grown in the partial shade expected under trees in AC (Djordjević et al. 2014, Gallagher et al. 2015). Furthermore, the explosion of research in perennial grain crops over the last 40 years (Kane et al. 2016) provides promising opportunities for integration into AC, especially since these herbaceous crops are structurally similar to the annual grains typically utilized.

Frontier 4: Trees for crop facilitation

The design of multispecies agroecological systems has generally focused on niche complementarity rather than facilitation mechanisms to enhance overyielding of crops relative to monoculture yields (Malézieux et al. 2009). Temperate AC research seems to have maintained a similar emphasis (e.g. Jose et al. 2000a, Cardinael et al. 2015). For example, experiments have commonly focused on reducing the negative impact of tree shade on sun-adapted alley crops (e.g. by altering tree row orientation) (Chirko et al. 1996, Artru et al. 2017). In contrast, tropical AC field experiments have more often leveraged trees to facilitate alley crop productivity via nitrogen fixation, shade, and mulch production (Fig. 2.5).

Opportunities exist for expanding the use of nitrogen-fixing trees in AC beyond the tropics. Nitrogen is the largest and most expensive input to temperate row crops. Massive applications of highly mobile inorganic nitrogen lead to considerable negative impacts on water quality via nitrate leaching (David et al. 2010) and climate change via soil emissions of nitrous oxide (Hernandez-Ramirez et al. 2009). An on-site, biological source of nitrogen via trees in AC could drive substantial economic and ecological benefits. While there are fewer nitrogen-fixing tree species available outside the tropics (Menge and Crews 2016), the available species are nonetheless underutilized (Jose et al. 2004). For example, only 8 and 3 temperate publications utilized *Robinia pseudoacacia* (black locust) and *Alnus* sp. (alder), respectively. No other nitrogen-fixing trees or shrubs have been directly explored in field experiments of temperate AC.

Further research in utilizing shade-tolerant alley crops could substantially improve productivity in AC. Rather than settling for crops that are merely tolerant of tree shade, many opportunities exists in identifying potential alley crop species or genotypes that actually have enhanced yield or quality under shade (Armitage 1991, Pang et al. 2017a, 2017b). Further work in this area could lead to breeding programs dedicated to developing alley crops that better leverage the facilitation potential of tree shade.

On-farm mulch production is another facilitation mechanism that could benefit from further research in AC. Rapidly expanding around the world, organic crop production systems often utilize mulch as an important weed control strategy (Wilson and Lovell 2016). Placing these systems within AC could reduce the typically high transportation cost of mulch (Jordan 2004).

CONCLUSIONS

Integrating trees with crops through AC can transform agricultural landscapes, improving both ecological and economic function. Here, we cataloged the species composition and function in all AC field experiments published over the last 35 years. This inventory of the diversity of AC research provides robust context and direction for orienting future research across regions. Overall, AC field experiments to date have utilized 410 tree species and 276 crop species in 77 countries. Both trees and crops provided a wide range of agricultural functions, although tree and crop functions were focused on biomass and food production, respectively. Despite the immense diversity observed across AC systems, within-system diversity has been primarily limited to just a single tree and single crop species. Major frontiers for AC research were identified as (1) within-system tree diversity, (2) tree crops for food and fodder, (3) perennial alley crops, and (4) trees for crop facilitation. These frontiers should be the focus of future research, expanding our understanding of AC systems and opportunities for adoption around the world.

TABLES AND FIGURES

Table 2.1 Specific types of publications and systems that were not included in the review.

Publications on purely *in silico* modeling, stakeholder surveys, or economic analyses,
Experiments based in the laboratory or greenhouse
Reviews/syntheses of other studies
Studies at the landscape level in which AC was only one component
Mixed-species forestry and orchard systems in which no crop component could be identified
Studies that examined the effect of groundcovers in orchards if the groundcover was not harvested as a crop or had a direct facilitative effect on the trees beyond just covering the soil
Silvopasture systems or any agroforestry systems that integrated livestock, although AC in which a fodder crop was grown as hay were considered
Shelterbelts, windbreaks, hedges, forest farming, or riparian buffers
“Improved fallows” as part of crop-fallow rotation agroforestry, since these do not include trees and crops coexisting in space
Field studies on species regarding their potential in AC but that were not performed in AC

Table 2.2 The Web of Science search query used to retrieve the 5,291 publications screened for inclusion in this review. The timespan was restricted to include publications published between 1900 and 2016.

(TS=(agroforestry OR "alley crop*" OR "silvoarable" OR ((orchard OR tree) AND intercrop*))

NOT
TS=(silvopast* OR silvipast* OR "riparian * buffer*” OR windbreak* OR "forest farming”))

OR
(TS=("alley crop*" OR "silvoarable" OR ((orchard OR tree) AND intercrop*))

AND
TS=(silvopast* OR silvipast* OR "riparian * buffer*” OR windbreak* OR "forest farming”))

Table 2.3 Increase in global production (2010-2014 relative to 2000-2004) of the top seven most produced fruit and nut tree crops (Source: FAO 2017) and the number of cataloged publications by zone in which each crop was included.

Tree crop	Production increase (%)	# of cataloged publications		
		Temperate	Subtropical	Tropical
Fruits				
Apple (*Malus* sp.)	46	6	1	1
Banana/Plantain (*Musa* sp.*)*	41	-	-	23
Grape (*Vitis* sp.)	20	1	1	-
Mango (*Mangifera indica*)	51	-	6	9
Pear (*Pyrus* sp.)	55	5	3	-
Peach/Nectarine/Plum (*Prunus* sp.)	49	2	8	1
Citrus (*Citrus* sp.)	37	-	19	8
Nuts				
Almond (*Prunus* sp.)	71	0	0	-
Brazil nut (*Bertholletia excelsa*)	35	-	-	15
Cashew (*Anacardium occidentale*)	68	-	2	3
Chestnut (*Castanea* sp.)	109	0	-	-
Hazelnut (*Corylus* sp.)	13	1	-	-
Pistachio (*Pistacia vera*)	97	1	-	-
Walnut (*Juglans* sp.)	180	6	1	-

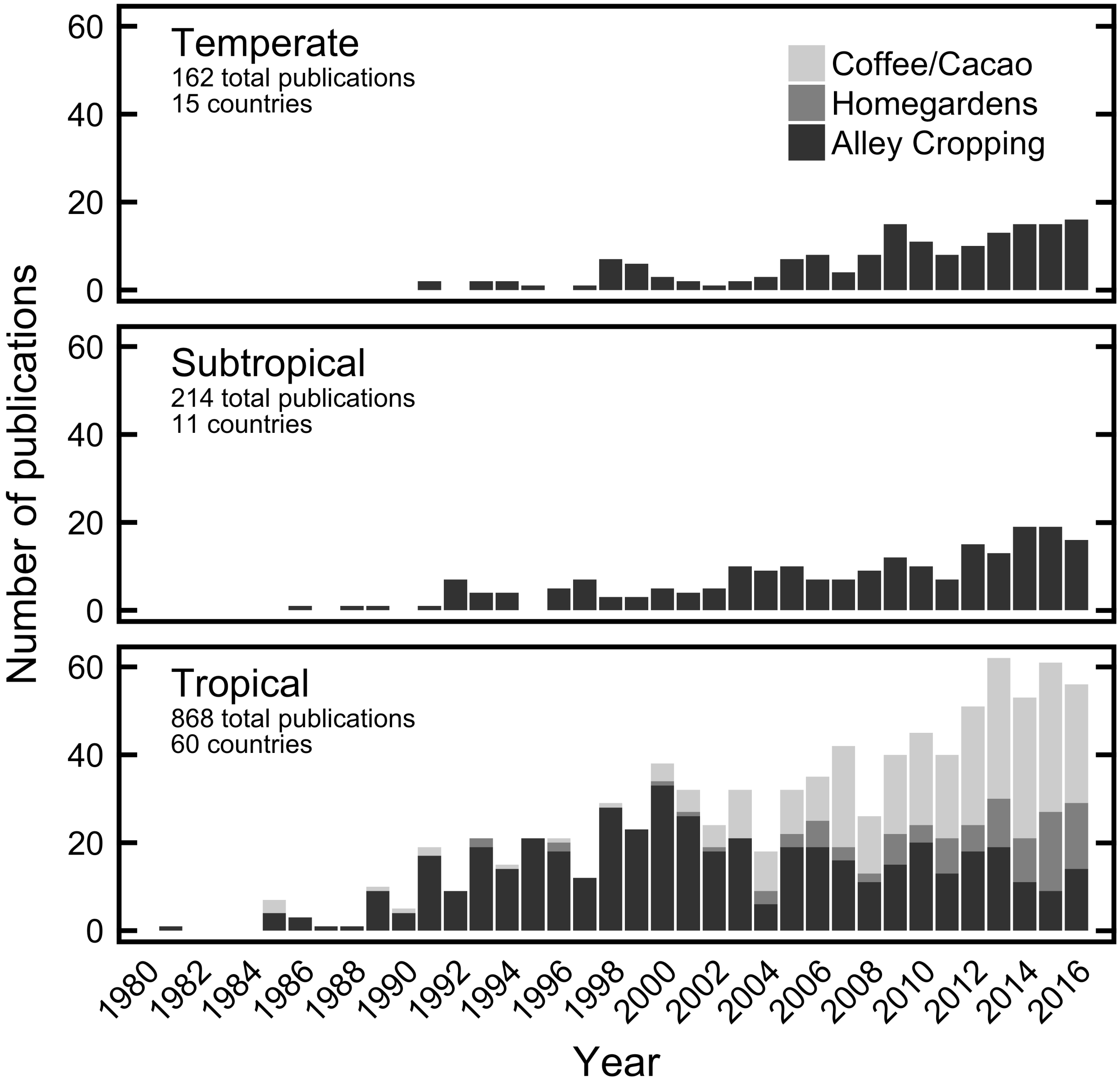

Figure 2.1 Historical trend of peer-reviewed publications on AC field experiments

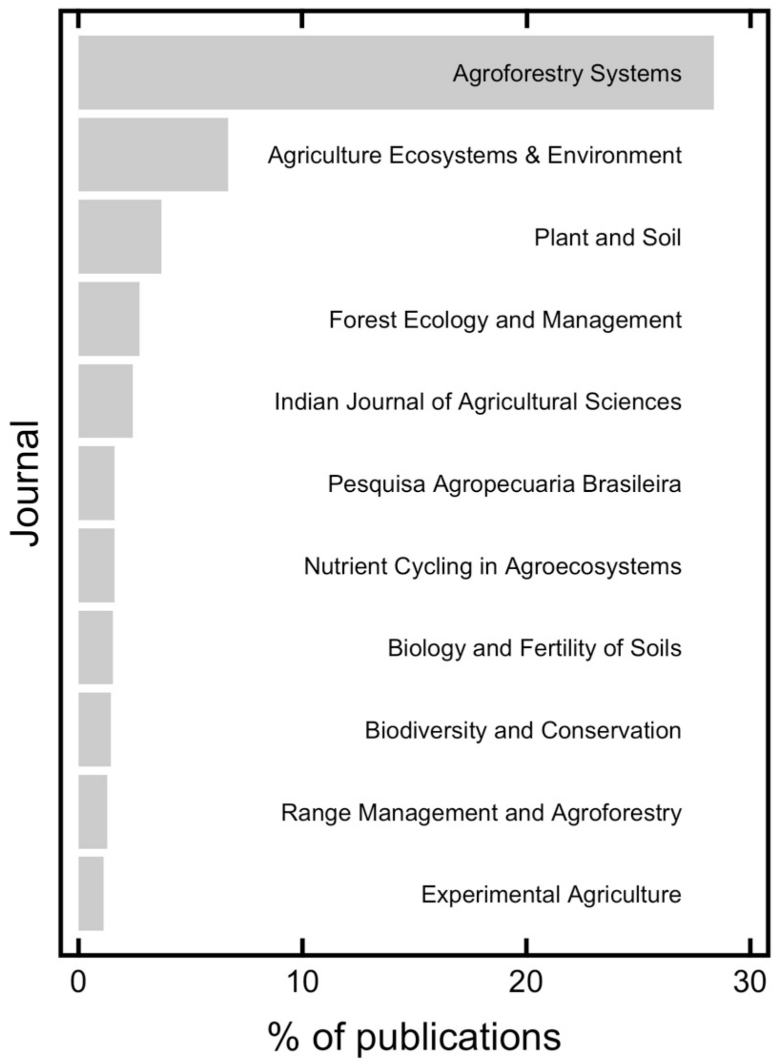

Figure 2.2 Proportion of reviewed publications published in the 10 most encountered journals.

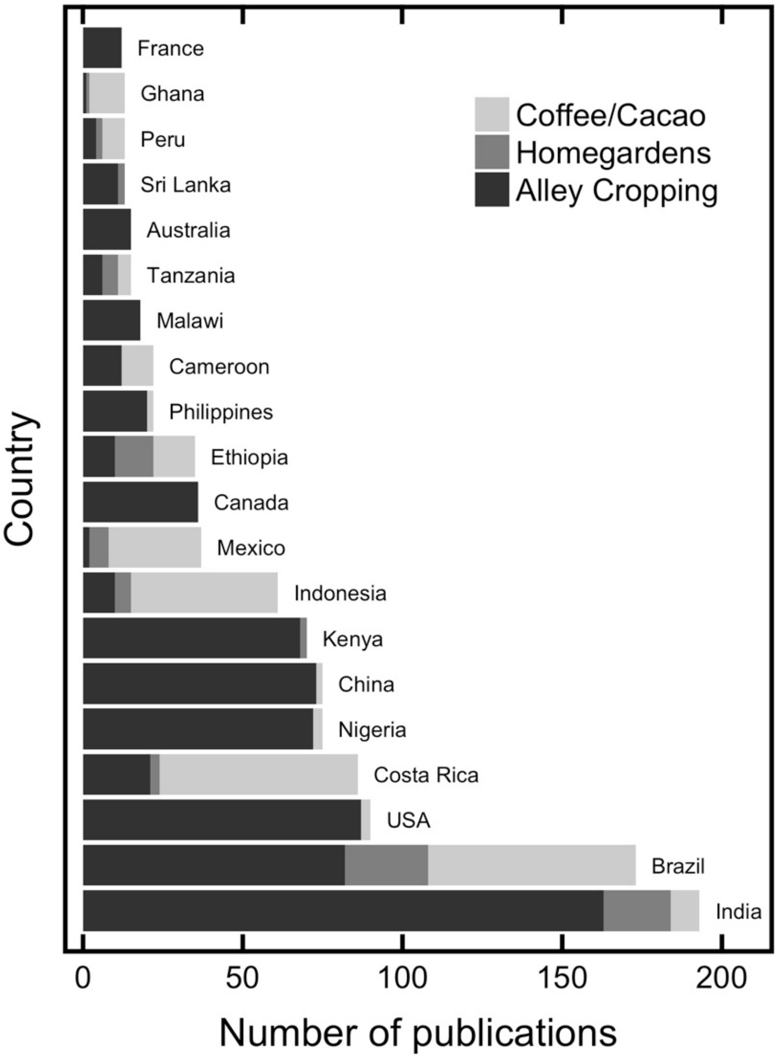

Figure 2.3 The number of reviewed publications with field experiments in each of the 20 most encountered countries by AC type.

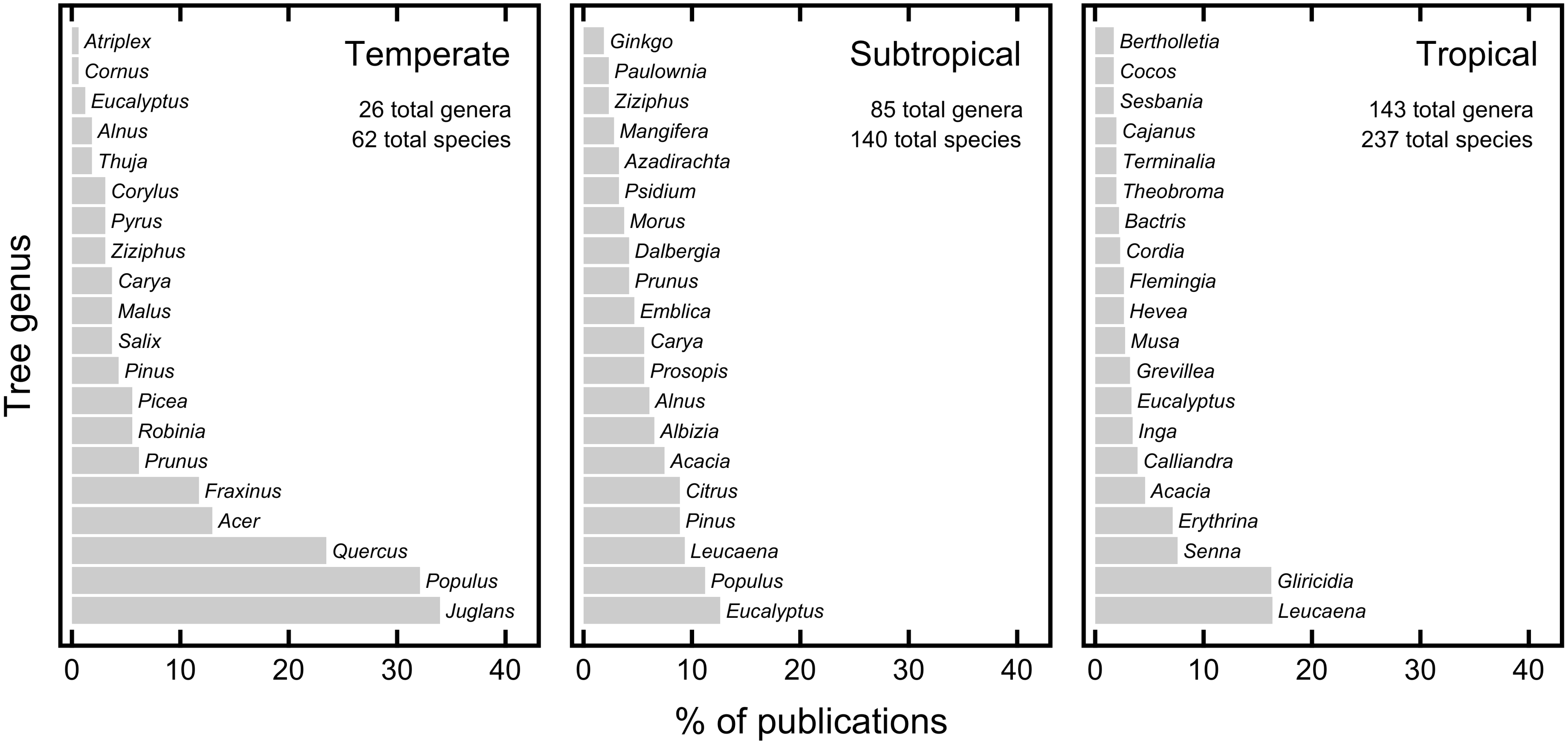

Figure 2.4 Frequency of genus occurrence in the tree component of AC field experiments within temperate, subtropical, and tropical climate zones. Since many experiments examined multiple AC systems, often with different tree species, the sum of values within each climate zone is not 100.

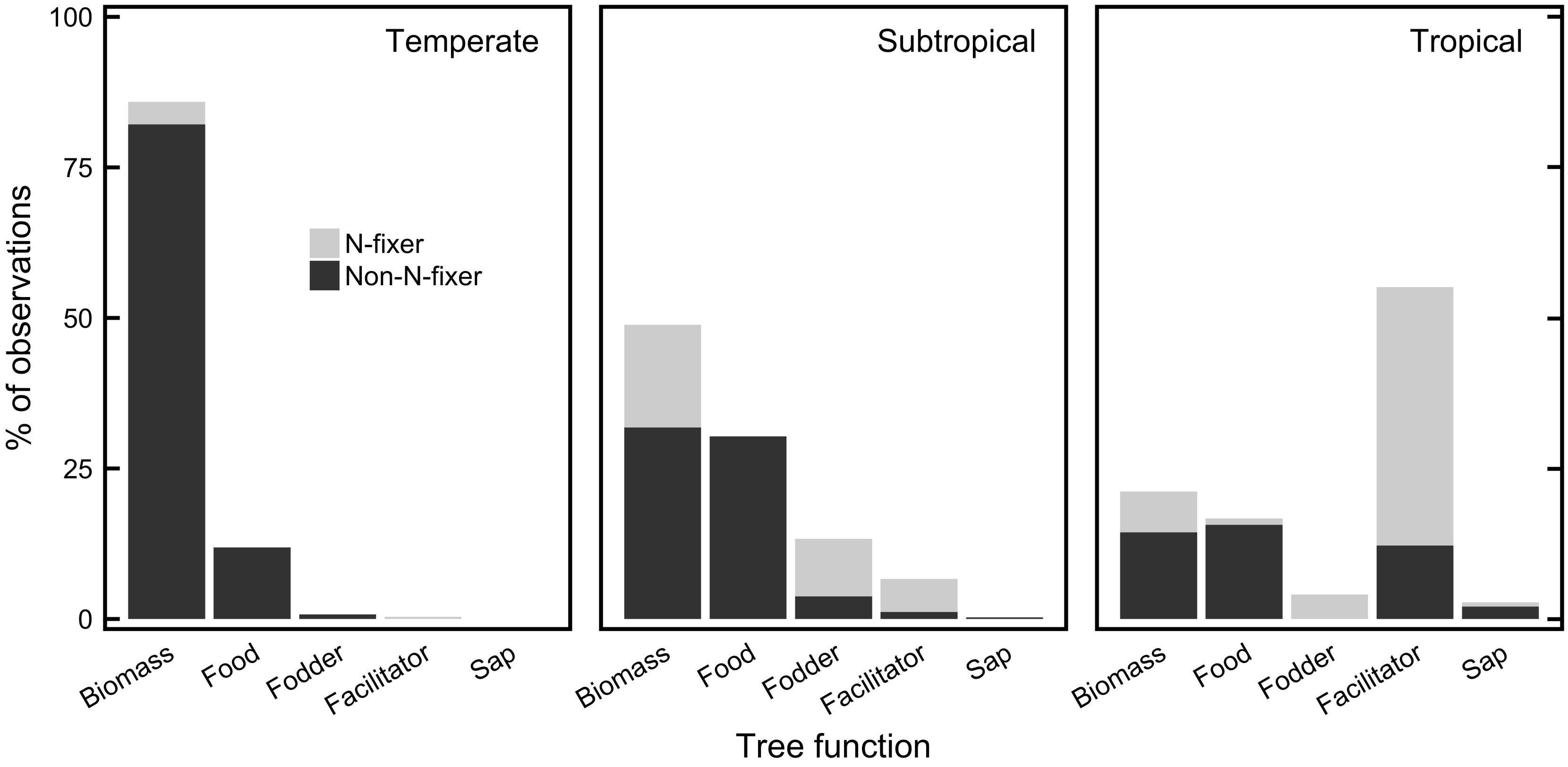

Figure 2.5 Frequency of tree function in temperate, subtropical, and tropical climate zones.

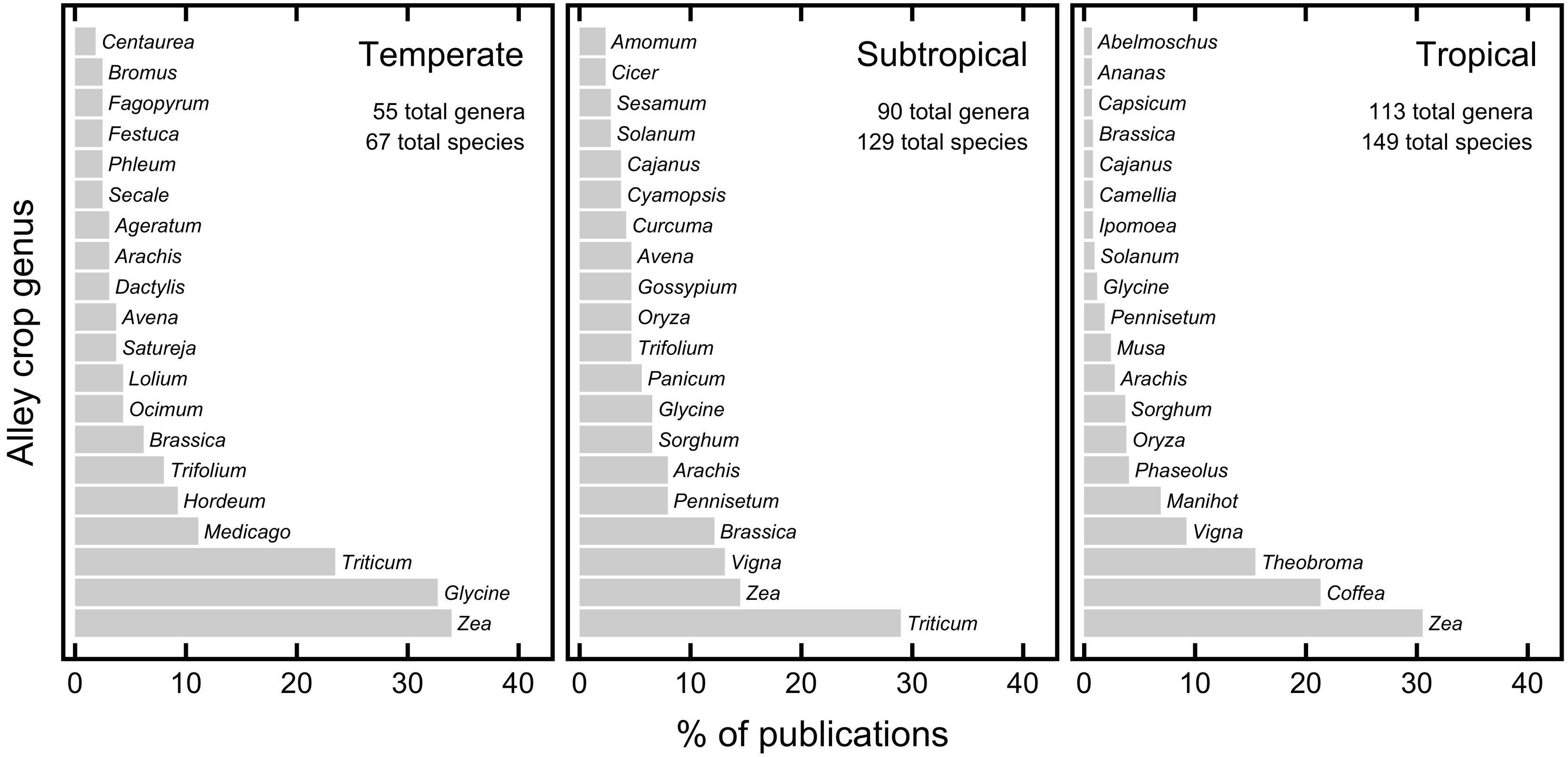

Figure 2.6 Frequency of genus occurrence in the alley component of AC field experiments within temperate, subtropical, and tropical climate zones. Since many experiments examined multiple alley cropping systems, often with different crop species, the sum of values within each climate zone is not 100.

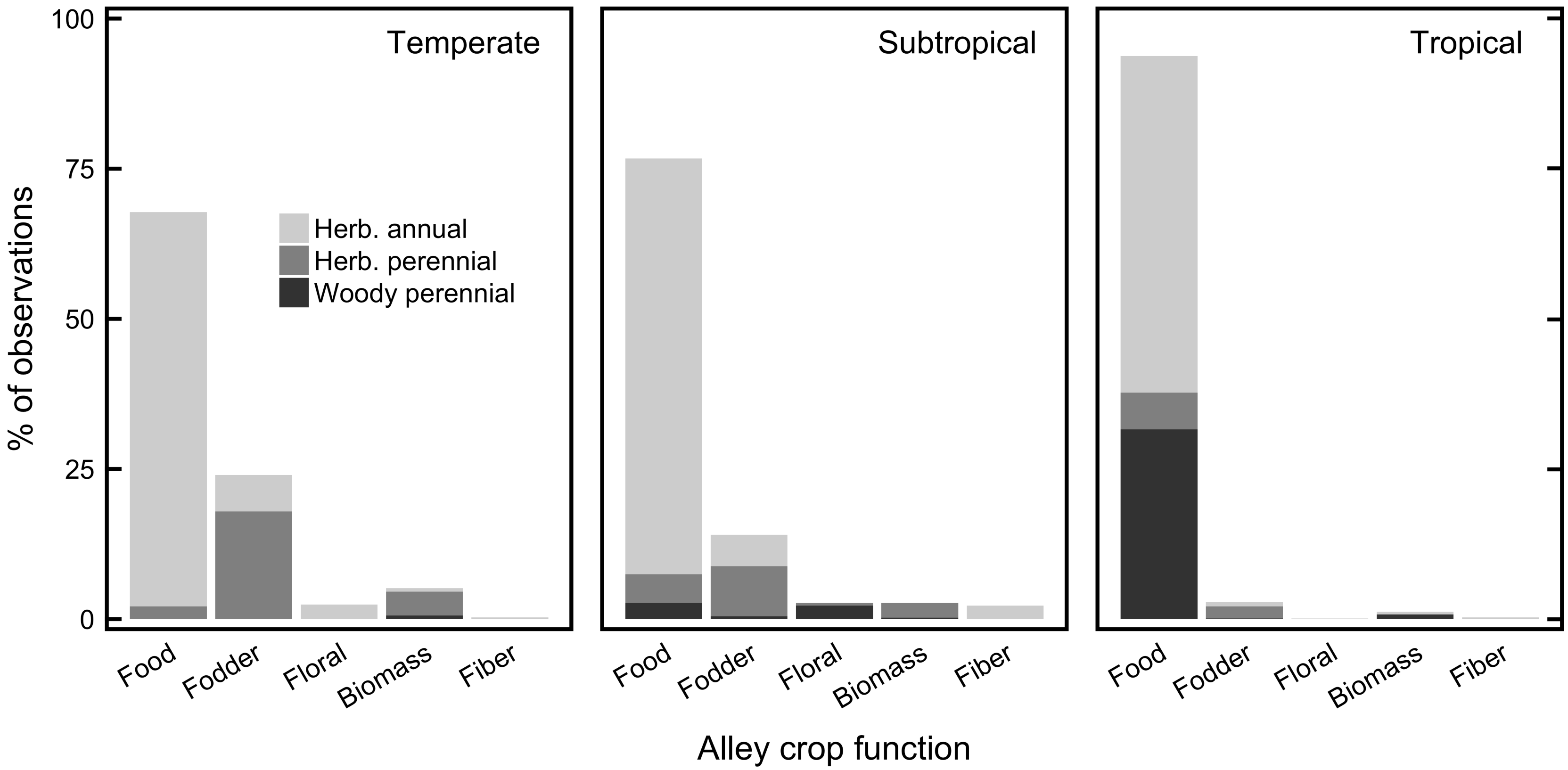

Figure 2.7 Frequency of alley crop function in temperate, subtropical, and tropical climate zones.

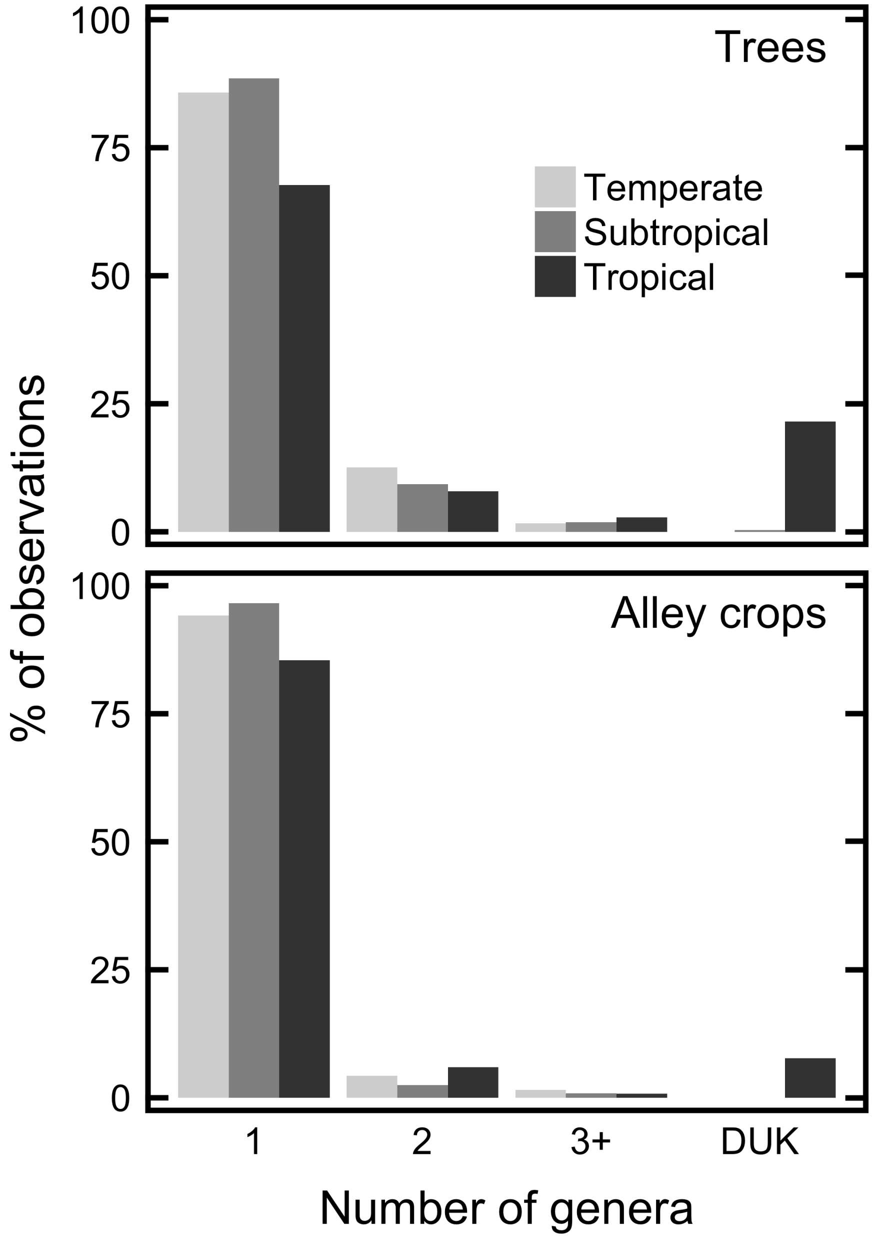

Figure 2.8 Number of genera included in the tree and alley crop components within individual AC field experiments in temperate, subtropical, and tropical climate zones. DUK (diverse but unknown) refers to diverse treatments containing an unknown number of genera.

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CHAPTER 3

FRONTIERS IN ALLEY CROPPING AS CLIMATE CHANGE MITIGATION AND ADAPTATION TOOLS FOR TEMPERATE AGRICULTURE

ABSTRACT

Annual row crops dominate agriculture around the world and have considerable negative environmental impacts, including significant greenhouse gas emissions. Transformative land-use solutions are necessary to mitigate climate change and restore critical ecosystem services. Alley cropping (AC) – the integration of trees with crops – is an agroforestry practice that has been studied as a transformative, multifunctional land-use solution. In the temperate zone, AC has strong potential for climate change mitigation through direct emissions reductions and increases in land-use efficiency via overyielding compared to trees and crops grown separately. In addition, AC provides climate change adaptation potential and ecological benefits by buffering alley crops to weather extremes, diversifying income to hedge financial risk, increasing biodiversity, reducing soil erosion, and improving nutrient- and water-use efficiency. The scope of temperate AC research and application has been largely limited to simple systems that combine one timber tree species with an annual grain. We propose two frontiers in temperate AC that expand this scope and could transform its climate-related benefits: (1) diversification via woody polyculture and (2) expanded use of tree crops for food and fodder. While AC is ready now for implementation on marginal lands, we discuss key considerations that could enhance the scalability of the two proposed frontiers and catalyze widespread adoption.

INTRODUCTION

Row crop agriculture – primarily maize (*Zea mays*) and soybean (*Glycine max*) – covers over 1.28 billion hectares of land globally (FAO 2017) (Fig. 3.1a). Though extremely productive, these cropping systems rely heavily on external inputs of energy, nutrients, and pesticides, leading to many unintended ecological consequences. The agricultural sector accounts for 10-12% of global anthropogenic greenhouse gas emissions (IPCC 2014) and a striking 55% of global N_2O emissions (USEPA 2012). Fertilizer applied to row crops has become the largest source of nutrient pollution and eutrophication in aquatic ecosystems (USEPA 2007). Extensive disturbance and landscape simplification leaves little permanent ground cover or habitat for wildlife, leading to soil erosion and biodiversity loss (Foley 2005).

Incremental improvements to the prevailing system have been the primary focus of efforts to reduce these negative impacts in the US (DeLonge et al. 2016). Cover cropping, for example, extends soil cover beyond the primary cropping season to reduce erosion, capture excess nutrients, and improve soil quality (Dabney et al. 2001). Precision management leverages high-resolution positioning and remote sensing technology to apply inputs more accurately only where needed (Mulla 2013). No- or low-till practices reduce the level of annual tillage to improve soil stability, reduce erosion, and sequester carbon (C) (Lal et al. 2007). Organic production aims to minimize the use of synthetic inputs that have adverse ecological effects (Nandwani and Nwosisi 2016). Despite the perceived benefits, adoption of these approaches remains low, with only 39% of US cropland using reduced tillage, 1.7% utilizing cover crops, and 0.8% in organic production in 2010-2011 (USDA 2011, Wade et al. 2015).

Incremental approaches are unlikely to reverse greenhouse gas emissions and solve the ecological challenges of row crop agriculture (de Ponti et al. 2012, Powlson et al. 2014, Pittelkow et al. 2014). For example, while no-till management and cover cropping exhibit lower net global warming potentials (14 to 63 g CO_2-eq m^{-2} yr^{-1}) than conventional crops (114 g CO_2-eq m^{-2} yr^{-1}), net emissions remain positive (Robertson et al. 2000). In simulations with ideal cover crop adoption across the Midwest, nitrate losses to the Mississippi River were reduced by approximately 20% (Kladivko et al. 2014), falling short of the estimated 40-45% decrease necessary to meet hypoxia reduction goals in the Gulf of Mexico (Scavia et al. 2004).

Transformative solutions that address the fundamental issues associated with vast monocultures of annual crops will be necessary for robust and resilient agricultural land use, especially in the face of climate change (Tilman 1999, Jackson 2002, Malézieux 2012, Buttoud 2013, Tittonell 2014). Successful transformative solutions must be ecologically sustainable, economically viable, and culturally acceptable. Ecological sustainability requires robust functioning of regulating and supporting ecosystem services alongside the provisioning services at the core of agriculture. Economic viability means profitability for farmers and prosperity for rural communities. Cultural acceptability entails meeting the aesthetic, ethical, and practical needs of rural communities while producing the carbohydrates, proteins, and oils that are the basic components of food systems and industrial supply chains (Robertson and Swinton 2005, Jordan and Warner 2010, Foley et al. 2011, FAO 2016).

Agroforestry, the intentional integration of trees or shrubs with crops or livestock, is one such transformative approach that has been widely studied over the last four decades (Gold and Hanover 1987, Leakey 2014, Wilson and Lovell 2016). By integrating trees throughout the landscape, agroforestry has great potential as a tool for climate change mitigation and adaptation (Schoeneberger et al. 2012, Buttoud 2013, IPCC 2014). Although agroforestry encompasses a wide array of practices, alley cropping (AC) most closely integrates trees with crops. Unlike other agroforestry practices, such as riparian buffers, windbreaks, or shelterbelts, AC is not confined to field margins. Instead, AC integrates trees and crops throughout a field; this is a transformative shift from typical monoculture row crop fields (Fig. 3.1b). Interest in temperate AC has grown considerably in recent years with the recognition of its potential benefits (Mosquera-Losada et al. 2012, Smith et al. 2013, Mosquera-Losada et al. 2016).

In this paper, we discuss the potential of AC as a transformative agricultural approach for climate change mitigation/adaptation and economic/ecological sustainability in the temperate zone. First, we identify two important frontiers that have the potential to expand the benefits of temperate AC: (1) augmenting AC with woody polyculture and (2) leveraging tree crops for food and fodder production. Next, we review the central concepts of climate change mitigation and adaptation in AC, emphasizing the opportunities by which the two frontiers could enhance these benefits. Finally, we develop four important considerations that could enhance the scalability of these frontiers and catalyze adoption. Throughout the discussion, we emphasize practical application of AC in the temperate zone and incorporate a range of novel, quantitative yield analyses.

FRONTIERS IN TEMPERATE AC

In temperate regions, the environmental benefits of AC do not reach their full potential because systems are typically composed of only one timber tree species with one annual grain species [e.g. walnut (*Juglans* sp.) or poplar (*Populus* sp.) with maize, soybean, or wheat (*Triticum* sp.)] (Chapter 2) (Fig. 3.1b). The potential economic and ecological benefits of temperate AC could be expanded by refocusing AC to (1) combine multiple tree/shrub species into “woody polyculture” and (2) include “tree crops” that produce food or fodder (Figs. 3.1c and 3.2).

Integrating multiple species in space is inherent in AC, as it requires at least one tree and one alley crop. However, diversity within temperate AC has rarely gone beyond this minimum requirement. Tree diversity was limited to a single genus in 86% of temperate AC studies over the last 35 years (Chapter 2) (Fig. 3.3). This minimal use of tree diversity dominates temperate AC despite the widespread use of woody polyculture in other agroforestry practices around the world. For example, coffee and cacao agroforestry systems in the tropics leverage suites of canopy trees that cast beneficial shade, yield supplemental fruits, fix nitrogen, provide wildlife habitat, and produce mulch on site (Tscharntke et al. 2011). Multispecies windbreaks and riparian buffers with multiple strata can more effectively block wind or capture runoff (Schultz et al. 2004, Bird et al. 2007). Tropical homegardens take diversity to the extreme, often containing dozens of productive species (Méndez et al. 2001, Zaman et al. 2010, Abebe et al. 2013). Furthermore, the use of woody polyculture in agriculture takes inspiration from the structure and function of natural ecosystems (Senanayake 1987, Lefroy 2009, Malézieux 2012), where much more research has explored the benefits of diversity. Increasing diversity within the tree component of temperate AC is a major frontier that remains underexplored.

Temperate AC has also been largely limited to timber trees. Only 13% of temperate AC studies have utilized tree crops (Chapter 2) (Fig. 3.3). This narrow focus developed despite numerous ancient and contemporary temperate agroforestry practices that leverage tree crops. Examples of tree crops in temperate agroforestry include berry production in hedgerows across Europe (Baudry et al. 2000), nut production for fodder in the *dehesa*/*montado* silvopasture of Spain/Portugal (Eichhorn et al. 2006), the heterogeneous fruit-crop and fruit-livestock combinations of the *streuobst* in Germany (Herzog 1998), and several examples of nut trees in AC in the US (Zamora et al. 2007, Stamps et al. 2009). In his visionary work, Smith (1929) reviewed the potential of tree crops as alternatives to row crops on marginal land. This vision of productive tree crops has yet to be widely incorporated in temperate AC (Chapter 2). Emphasizing tree crops, therefore, constitutes another major frontier in temperate AC.

AC FOR CLIMATE CHANGE MITIGATION

The expanded benefits possible via these frontiers in temperate AC build on agroforestry's potential in climate change mitigation. Temperate agroforestry can drive substantial C sequestration in woody biomass and soil (Mosquera-Losada et al. 2011, Udawatta and Jose 2012), as well as reduce non-CO_2 greenhouse gases (Amadi et al. 2016, Kim et al. 2016). Over the initial 13 years of a long-term AC field experiment in Guelph, Canada, sequestration was estimated at 25 Mg C ha^{-1} in soil and 14 Mg C ha^{-1} in woody biomass (Thevathasan and Gordon 2004). In a review of C sequestration in temperate agroforestry systems, Udawatta and Jose (2012) estimated the total sequestration potential of AC as 3.4 Mg C ha^{-1} yr^{-1}. In addition to direct C sequestration, lower nutrient loss in AC due to the "safety-net" role of deep tree roots can translate into reduced dependency on fossil fuels for fertility (Udawatta et al. 2002, Allen et al. 2004).

Incorporating woody polyculture could enhance the climate change mitigation potential of AC. A meta-analysis of C storage in tree mixtures demonstrated higher storage in polyculture compared to monocultures (Hulvey et al. 2013). While studies of diversity impacts on C storage in AC are limited, diversity has been shown to increase C sequestration in other agroforestry practices (Häger 2012, Islam et al. 2015). Refocusing AC from timber trees to tree crops is unlikely to substantially alter its C sequestration potential. However, nitrogen cycling in AC with tree crops is likely quite different compared to AC with timber trees since higher levels of nitrogen fertilizer are typically applied to tree crops. Higher fertilization levels are often associated with increased nitrous oxide emissions (Dusenbury et al. 2008) in agroecosystems, so focusing on tree crops could exacerbate these emissions. However, if the annual row crops common to temperate AC (e.g. maize, soybean, wheat) are fertilized conventionally, additional fertilization of tree crops may be unnecessary.

Beyond direct reduction or sequestration of greenhouse gases, AC can also provide climate change mitigation by reducing the total area required for agricultural production via overyielding – where the combination of trees and crops in AC exhibits higher productivity compared to tree and crop monocultures (Jose et al. 2004). Overyielding can result from niche differentiation (i.e. interspecific differences in utilization of resources such as light, soil nutrients, pollinators, etc.), facilitative interactions among species (e.g. legumes fix nitrogen that is used by other species), and reductions in negative plant-soil feedbacks (Vandermeer 1989, Tilman 2001, van der Putten et al. 2013). Even the simple two-species systems typical of temperate AC can increase land-use efficiency via overyielding by 40% (Graves et al. 2007) to 200% (Dubey et al. 2016), compared to trees and crops grown separately. When leveraging tree crops rather than timber trees in AC, it is critical to examine overyielding in terms of reproductive yield (i.e. fruits and nuts) rather than woody biomass, as the response of biomass and fruit yields can be very different when mixing tree crops (Rivera et al. 2004).

Increasing the number of woody species in temperate AC could further enhance overyielding. Diversity-productivity relationships have already been shown in herbaceous mixtures (Tilman 2001, Picasso et al. 2011), although woody polyculture has received much less attention (Malézieux et al. 2009). A meta-analysis of 14 studies of forestry plantations found significantly higher biomass accumulation in multispecies versus single-species plantations (Piotto 2008), but that work did not explore the relationship for different levels of species richness. Promising diversity-productivity relationships observed in natural systems further support the use of woody polyculture in agroecosystems. For example, a global meta-analysis of productivity in forest ecosystems revealed 24% higher productivity in polycultures than monocultures (Zhang et al. 2012). Specific mechanisms that drive overyielding in woody polyculture have been difficult to disentangle. Documented mechanisms include mycorrhizal mediation of nutrient competition (Perry et al. 1989), heterogeneity in shade tolerance (Zhang et al. 2012), species density and evenness (Collet et al. 2014), plasticity in crown structure, and phenological differences among species (Sapijanskas et al. 2014).

AC FOR CLIMATE CHANGE ADAPTATION

In addition to climate change mitigation, agroforestry can help adapt agriculture to global change (Verchot et al. 2007, Schoeneberger et al. 2012, van Noordwijk et al. 2014). More volatile and extreme weather patterns predicted with climate change are expected to have direct impacts on agricultural management and productivity (IPCC 2014, Tomasek et al. 2017). Agroforestry practices can buffer the effect of weather extremes by protecting crops from wind stress (Böhm et al. 2014), stabilizing air and soil temperatures (Lin 2007), increasing soil water infiltration and storage (Anderson et al. 2009), and reducing evaporation of soil moisture (Siriri et al. 2013). For example, soybean grown in temperate AC experienced no significant yield decline under a season long drought treatment that reduced soil moisture by approximately 15% (Nasielski et al. 2015). In contrast, monoculture soybeans receiving the same treatment experienced a 40% yield reduction. Similarly, temperate AC can stabilize crop performance by reducing erosion and improving soil structure and fertility (Udawatta et al. 2008, Torralba et al. 2016).

Temperate AC also provides many ecological benefits that can further adapt agriculture to global change (Thevathasan and Gordon 2004, Jose 2009, Tsonkova et al. 2012). Resilience of ecosystems to ecological disturbance can increase with biodiversity (Oliver et al. 2015). Increased biodiversity has been demonstrated in temperate AC for many organisms, such as arthropods (Stamps et al. 2002), mycorrhizal fungi (Bainard et al. 2011), and birds (Gibbs et al. 2016). For example, by supporting higher populations of pest predators and parasites (Stamps et al. 2002), temperate AC could reduce the impact of increased crop pest outbreaks predicted with climate change.

Many of the climate change adaptation benefits of AC could be improved by integrating woody polyculture. For example, a greater distribution of roots in polyculture both spatially and temporally can further increase resilience via improved nutrient cycling and water-use efficiency (Jose et al. 2006). Diversification can also stimulate biodiversity of associated insects, pollinators, birds, mammals, and soil microbes (Perfecto et al. 2003, Malézieux et al. 2009). Further evidence from forest ecosystems suggests that tree diversity can increase drought resilience (Pretzsch et al. 2013) and nitrogen retention (Schwarz et al. 2014, Lang et al. 2014). Insights from a wide range of woody systems illustrate that diversity can enhance resilience to ecological disturbance, tighten biogeochemical cycling, stabilize productivity over time, and diversify income to hedge financial risk (Scherer-Lorenzen et al. 2005, Nadrowski et al. 2010, Cubbage et al. 2012).

Tree crops can also improve the climate change adaptation potential of AC over timber trees. Although overyielding can occur in AC with either timber trees or tree crops, using tree crops as staple sources of carbohydrates, proteins, and oils diversifies food sources in a system that is more ecologically resilient and drought resistant than row crop monocultures. The relatively short time to reproductive maturity and predictable annual yields in tree crops can also provide a faster economic return on investment compared to timber harvest rotations that span decades (Campbell et al. 1991). Furthermore, longer harvest intervals make timber returns more susceptible to natural disasters, climate variability, and changes in market preferences compared to tree crops (Taylor and Fortson 1991, Hanewinkel et al. 2011).

SCALABILITY AND IMPLEMENTATION

AC could be applied on marginal land, as an alternative to non-yielding conservation programs, and as widespread, transformative systems with tree crops analogous to existing staple crops. In the remainder of this paper, we develop four key considerations that could enhance the scalability and catalyze adoption of AC as a transformative solution for temperate agriculture. These considerations emphasize effective approaches to leveraging the two frontiers in temperate AC discussed above: woody polyculture and tree crops.

(1) Start with marginal lands

To catalyze cultural acceptability and encourage adoption, AC could initially be established on limited areas of farmland that are marginal or unsuitable for conventional row crop agriculture, and which contribute disproportionally to negative externalities such as greenhouse gas emissions, erosion, nutrient loss, and water quality degradation (Richards et al. 2014, Brandes et al. 2016). A wide range of drivers can motivate land owners to establish agroforestry practices on marginal lands, with soil health often a top factor (Mattia et al. 2016).

Valuation of C sequestration benefits in AC shows particular promise as an economic driver of adoption in the temperate zone (Winans et al. 2016). Niu and Duiker (2006) demonstrated that afforestation of marginal lands of the Midwest US could sequester more than 1000 Tg C over 50 years. Even if AC applied to the same land area deployed fewer trees and resulted in less C sequestration, AC would permit continued food production in these areas via tree crops and alley crops. This is a prime example of "land-sharing" and landscape multifunctionality, which have received increased interest in recent years (Lovell et al. 2010, Fischer et al. 2017). Redesigned conservation programs (e.g. the USDA's Conservation Reserve Program) that value the provisioning services of AC could further incentivize adoption.

These initial systems on marginal lands can then serve as nodes for expansion onto more productive lands. This expansion could be accelerated by policy mechanisms to lower the economic barriers to farmer adoption and provide direct economic rewards to farmers for the ecological benefits of AC. Incentivized ecological benefits could even produce more than twice the revenue directly generated by agricultural products in AC (Alam et al. 2014). Integrating the perspectives of both agricultural and conservation stakeholders (Atwell et al. 2010), as well as redesigned subsidy programs that support production of nutritious, high-value fruits and nuts, are just a few mechanisms that could further accelerate adoption. Even with increased economic supports, the relative permanence of woody crops can be a major limitation for risk-averse potential adopters (Frey et al. 2013). However, AC, and especially AC that includes tree crops instead of timber trees, can lower the risk in adoption by leveraging the faster return from alley crops and fruit/nut yields. For example, Mattia *et al*. (2016) demonstrated that more landowners were open to perennial cropping systems focused on fruit or nut trees than on timber trees.

(2) Staple tree crops

Among the diverse array of species used in temperate AC, widespread implementation will require well-developed tree crops that are highly productive and have robust markets. Many tree crops have longstanding global markets and have garnered increased investment by industry and academia over the past two decades. Though their potential growth beyond niche markets remains largely overlooked, many tree crops – especially nut trees – have great potential as staple food crops and animal fodder (Smith 1929, Molnar et al. 2013). Dominant tree crops will vary by region based on environmental suitability of tree species (Reisner et al. 2007), while also anticipating future climate conditions (Iverson et al. 2008). Furthermore, it will be critical to select tree crops that are already supported by a solid base of agronomic knowledge, foundational breeding work, and existing germplasm repositories.

The scalability of AC in the temperate zone could be more efficient with combinations of tree crops that produce comparable carbohydrates, proteins, and oils as maize/soybean and which can leverage the existing network of storage, transportation, and processing infrastructure. In the current industrial system, maize is grown as the carbohydrate source for livestock feed, ethanol, sugar additives, and bio-polymers. Soybeans contribute complementary protein and oil for livestock feed, biodiesel, and soy-based food products. Combinations of nut crops in AC could provide functional analogs for maize and soybean as industrial sources of carbohydrate, protein, and oil. Staple nut crops once served as the foundation of a number of civilizations (e.g. Michon 2011), and modern research continues to develop the potential of nut-sourced carbohydrates (Jozinović et al. 2012), proteins (Xu and Hanna 2011), and oils (Benitez-Sánchez et al. 2003) as staple food constituents.

An analysis of the global average yields of the five most widely grown temperate nut species demonstrated that the per-hectare caloric yields of these crops are currently lower than that of US maize and soybean (Fig. 3.4a). Closing this yield gap, likely via higher allocation to nuts, is a major opportunity for focused breeding efforts in tree crops. The six- and four-fold increases in US maize and soybean yields, respectively, over the last century (USDA NASS 2016) have been accomplished through massive investments in breeding and agronomic research. Analogous investments in tree crops can also be expected to substantially improve their performance. Beyond caloric yield, further comparison of carbohydrate, protein, and oil constituents from the same nut crops demonstrates that a combination of complementary nut crops, each specializing in production of certain dietary components, will be required to attain production comparable to the maize-soybean system (Figs. 3.4b-d).

Modern breeding in temperate nut crops has so far prioritized disease resistance and nut quality over yield gains (e.g. Mehlenbacher 2003, Molnar and Capik 2012). Only recently in hazelnut (*Corylus* spp.), for example, successful development of disease resistant genotypes with high nut quality has led breeders to refocus on productivity (Molnar and Capik 2012). The deficit of breeding efforts, combined with breeding cycles spanning decades, make the development of new tree crop varieties a slow process (Mehlenbacher 2003, Molnar et al. 2013). New biotechnology techniques, such as the use of plant growth regulators and transgenes to stimulate flowering on juvenile tissue or high-throughput genomic screening of offspring, could greatly accelerate the development of superior tree crops (van Nocker and Gardiner 2014). Plant material and technology from countries with the highest yields may direct the next generation of breeding and management innovation (Fig. 3.4). For greater compatibility in the agroforestry context, tree crop breeding could focus on conditions of interspecific competition and shaded environments for understory species.

The scalability and economic return of tree crops could be further improved by technological developments in management and harvesting automation. With long harvest rotations and minimal maintenance needs, timber trees and their interactions with alley crops require minimal management (Thevathasan and Gordon 2004, Cubbage et al. 2012). In contrast, the annual harvests and more intensive pest management in tree crops create potential conflicts between trees and alley crops in management timing and mechanization. Sensors that automate the detection of fruit location and quantity can aid in precision management of pests, yield estimation, and harvest timing (Gongal et al. 2015). Furthermore, robotic harvesters could ensure compatibility of tree crop and alley crop harvest activities. Tree crops, such as apple (*Malus* sp.) and citrus (*Citrus* sp.), were the top, high-value targets of robotic harvester development over the last 30 years, behind only tomato (*Solanum lycopersicum*) (Bac et al. 2014).

(3) Practical multispecies designs

The major limitation of woody polycultures in AC is that their inherent complexity makes management difficult, especially in a mechanized manner. Polycultures must be managed as a whole, such that interventions intended to benefit individual species may not necessarily be optimal for the overall system. For example, pesticides used on one tree species may cause harm to or may not be approved for use on adjacent species in a polyculture. Farmers, therefore, must be skilled in the management of several crops, remain aware of multiple markets, and manage for interactions among species. While mechanical implements already exist for management activities (e.g. pruning, harvest) in tree and shrub crops, these tools were developed for use in monoculture settings. Adapting and developing tools for use in polyculture is necessary to enable these more complex systems (Vandermeer 1989). Furthermore, robotic automation and advanced image processing in agriculture can overcome complexity by having machines automatically identify different species within a field, thereby permitting precision management of each species (Hamuda et al. 2016). Proper design and selection of tree crop-alley crop combinations with complementary management and harvest periods could circumvent potential issues altogether.

The inherent complexity of woody polyculture allows systems to take many forms. At the core of the knowledge gap in managing woody polycultures is the deficit of relevant research in temperate regions. Although high diversity agroforestry has been studied frequently in the tropics, many of these systems are predominantly small-scale homegardens that differ substantially from systems that could be implemented in the temperate row crop landscape (Chapter 2). In tropical regions, diversified AC commonly takes non-linear forms. By constraining trees to rows, designs are more scalable and easily mechanized (Fig. 3.5a). Maintaining this linear configuration when adding multiple tree/shrub species in temperate AC will likely be the most effective approach of diversifying AC.

There are several practical and scalable approaches to begin implementing woody polyculture within the linear framework of temperate AC. Additional tree species can be added via within-row diversification (Fig. 3.5b), between-row diversification (Fig. 3.5c), or both. Within-row diversification would more strongly leverage any niche complementarity among tree species, whereas between-row diversification would be preferred if management efficiency was much higher with monospecific rows (e.g. with some types of mechanical harvesting). Further diversification could also leverage multiple canopy layers (Fig. 3.5d). For example, planting shade-tolerant shrubs such as currant (*Ribes* sp.) or blackberry (*Rubus* sp.) (Djordjević et al.

2014, Gallagher et al. 2015) between the canopy trees could increase space utilization, light capture, and early yields. An understory shrub crop could be planted at the same time as the canopy layer or by adding the shrub under established AC/orchards. Diversity could be further increased by adding additional canopy layers or species within a layer. The development of practical multispecies designs optimized for yield, profit, and resource use will require iterative feedback from farmers via operational-scale demonstration plantings (Lovell et al. 2017) and separate long-term trials that leverage complex response-surface designs (Vanclay 2006, Leakey 2014). Furthermore, new and improved agroforestry models will be required to efficiently explore planting layout options and identify designs to be tested in the field (Malézieux et al. 2009).

(4) Complementary crop combinations

Since tree crops take years to reach productive maturity, it will be critical for AC to include complementary, early-yielding crops during the establishment phase. The annual alley crops typical of temperate AC are an important approach for early yields. Early revenue could also be provided by pastured livestock grazing on a forage alley crop, with young trees protected by fencing, tubes, or cages. This approach can mature into silvopasture, with integrated management of livestock, forage, and tree crops. Yet another approach to increasing early yields is to include fast-maturing understory shrub crops with high-value fruits. While the productivity of alley crops and understory crops may decrease as the canopy tree crops mature, these complementary combinations may improve profitability early in the transition to AC compared to the traditional approach solely using timber trees. Furthermore, early-yielding crops can complement tree crops even at system maturity by diversifying farm revenue, enhancing overyielding, and introducing nutritionally dense crops high in vitamins and antioxidants. The associated diversity of harvest and management activities in polycultures could even increase year-round employment opportunities in rural areas, which could help stabilize rural communities.

To illustrate an example of complementary combinations when leveraging woody polyculture and tree crops, we estimated the caloric yield of a theoretical AC system in Central Illinois. This example is based on an experiment described in Lovell *et al*. (2017) over the first 20 years after conversion from row crops. Combining Chinese chestnut (*Castanea mollissima*), European hazelnut (*Corylus avellana*), black currant (*Ribes nigrum*), and a hay alley crop in a design similar to Figure 3.5d, this system is projected to reach over half of the modern maize-soybean yield at maturity (Fig. 3.6). In this example, the nut trees are assumed to be unaffected by interspecific competition – the ideal case in an optimally designed polyculture – although currant and hay yields are assumed to decrease as the nut trees reach maturity. The resulting yield trajectory illustrates the complementary productivity of component crops.

CONCLUSIONS

Row crop agriculture continues to drive ecological challenges around the world, including significant contributions to greenhouse gas emissions. In a transformative shift from vast monoculture fields, AC closely integrates trees and crops to mitigate climate change, adapt agriculture to disturbance, enhance yields, and improve ecological functioning. Temperate AC has been underutilized despite its many economic and ecological benefits. Augmenting traditional AC via woody polyculture and tree crops for food and fodder enhances the potential of AC as a transformative solution to the problem of agriculture across the temperate zone. These frontiers expand the limited focus of temperate AC to date and provide many economic and ecological advantages over conventional row crop agriculture. Key economic drivers of these frontiers in AC include overyielding, utilization of crop analogs compatible with existing staple crops, and resilience via crop diversification. Key ecological benefits include enhanced C sequestration, soil and nutrient stabilization, biodiversity, and resilience to ecological pressures. Currently, the primary barriers to adoption of AC are the high establishment cost, insufficient tree crop breeding, and relatively high management complexity. These barriers, however, are surmountable with investment in research and updates to agricultural policy. Effective integration of woody polyculture and tree crops in temperate AC will require strategic implementation beginning with marginal lands, an emphasis on highly productive tree crops, practical and optimized multispecies designs, and complementary crop combinations for early productivity and management efficiency.

FIGURES

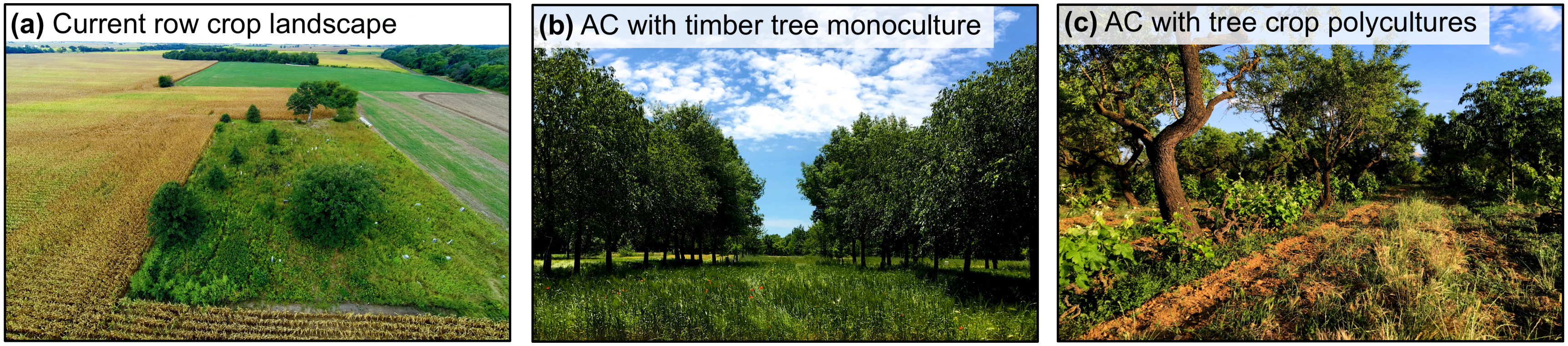

Figure 3.1 (a) The existing land management paradigm in most temperate regions: a landscape dominated by annual row crops and distinctly separated from the small patches of remaining natural areas. (b) Mature, traditional AC in France, with hardwood tree rows and an alley crop of small grains. (c) AC augmented with tree crops and woody polyculture, using both nut trees and grape vines within tree rows.

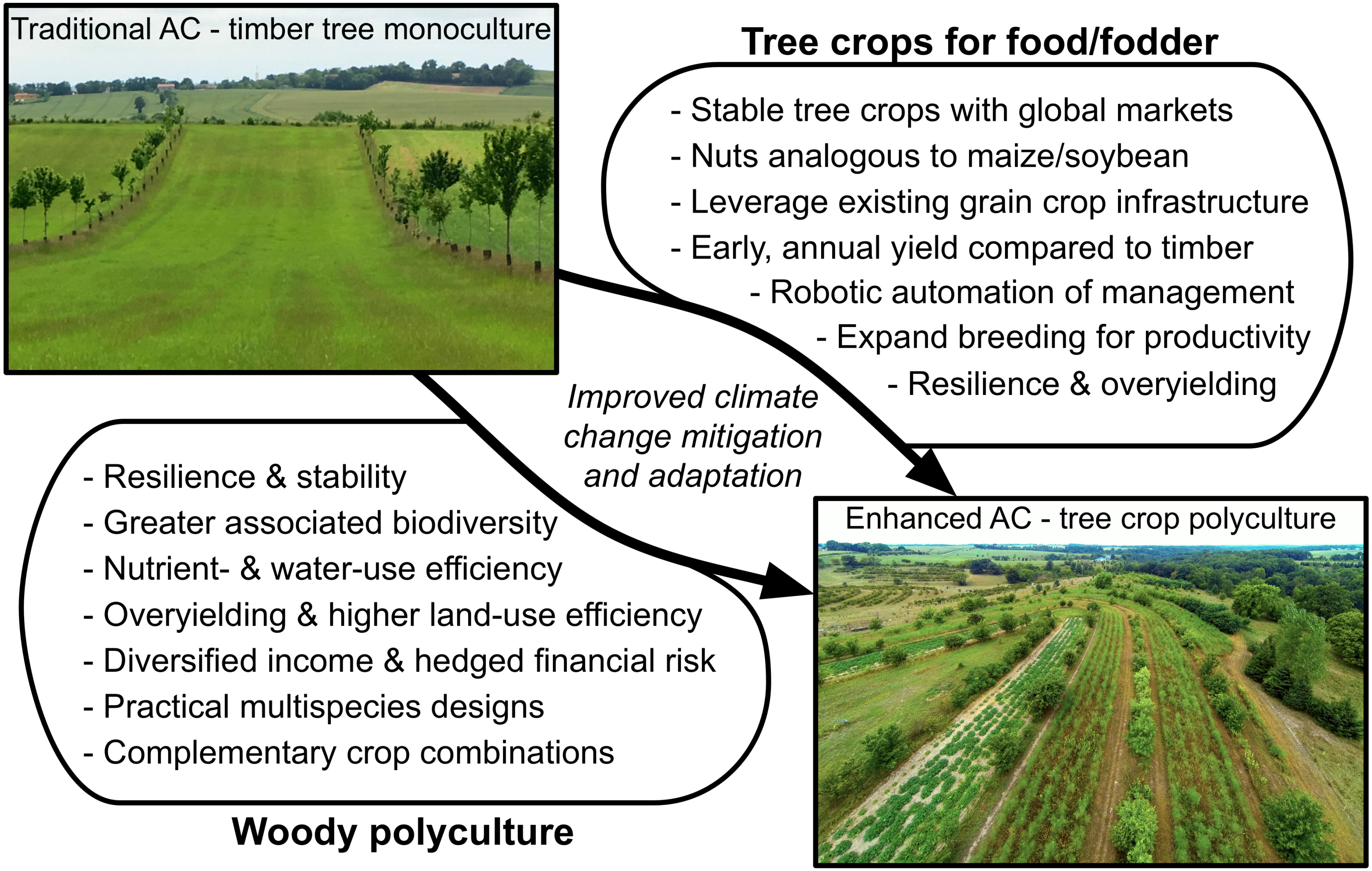

Figure 3.2 Schematic summary highlighting key concepts of enhancing traditional AC through (1) diversification via woody polyculture and (2) expanded use of tree crops for staple food and fodder production.

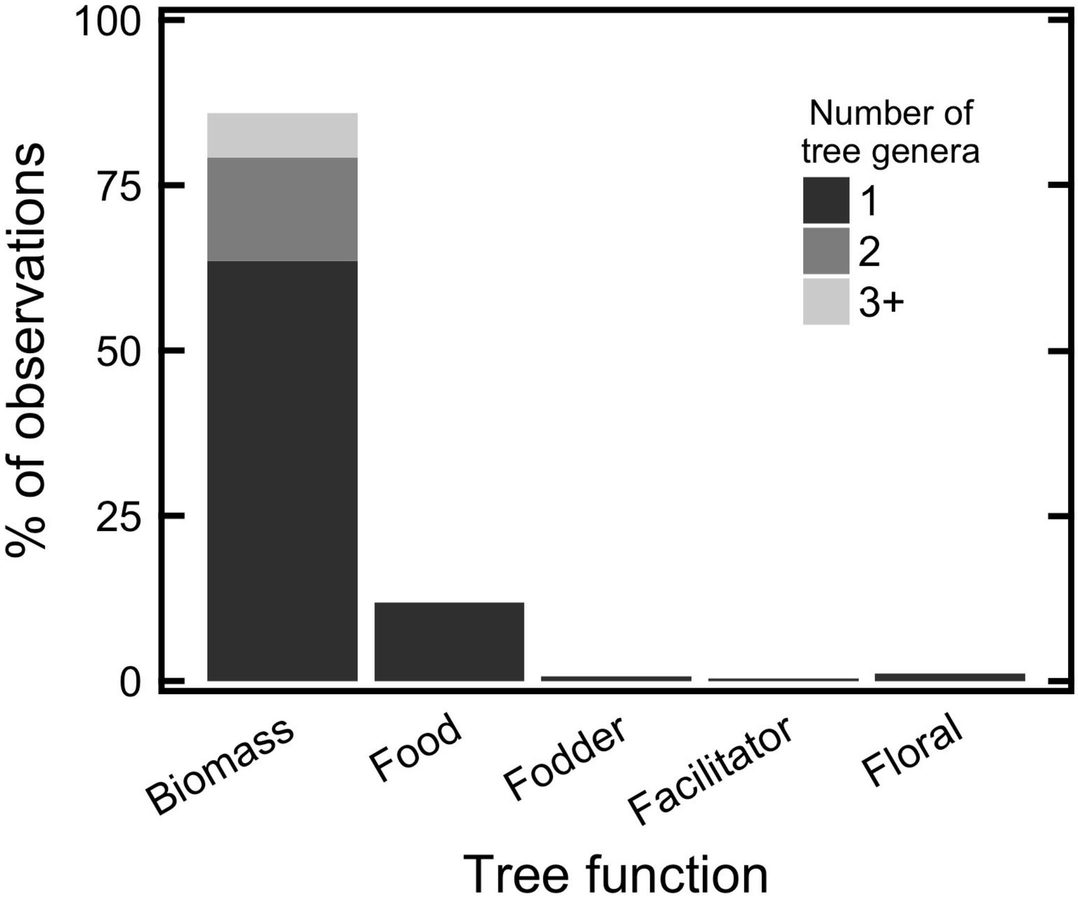

Figure 3.3 Proportion of publications on temperate AC field experiments classified by the primary agronomic function and genus-level diversity of the tree component. Data is from a catalog of 162 publications from 15 countries over the last 26 years (reproduced based on Figs. 2.5 and 2.8).

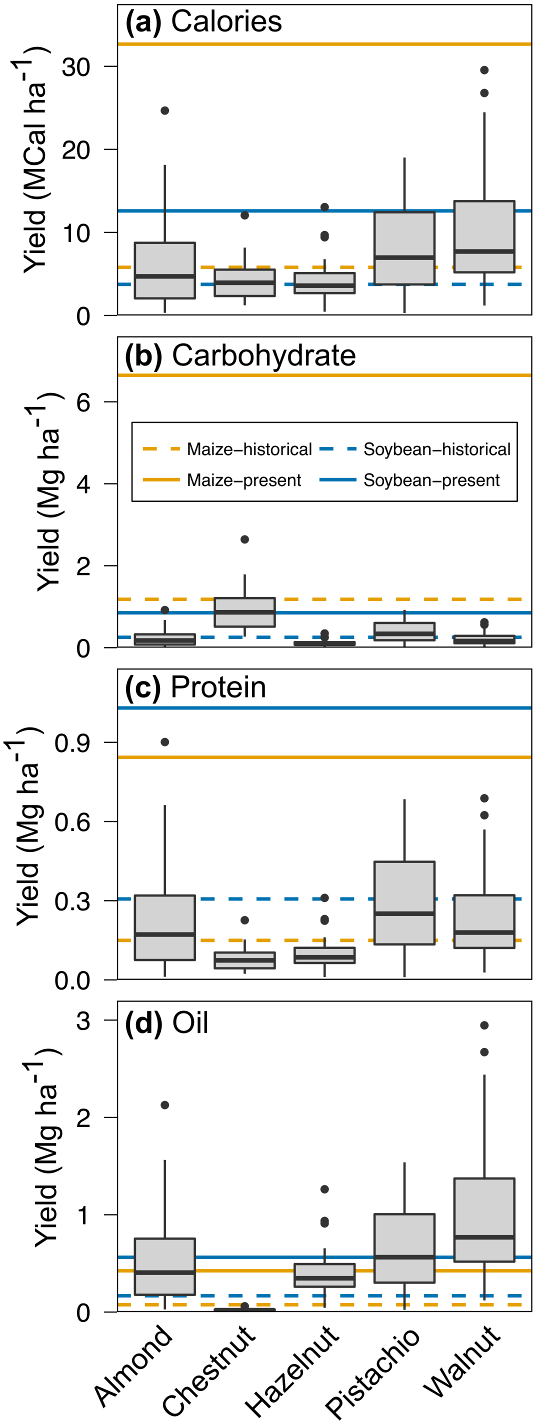

Figure 3.4 Global productivity of the five most grown temperate nut crops [almond – *Prunus* sp. (n = 47), chestnut – *Castanea* sp. (n = 22), hazelnut – *Corylus* sp. (n = 29), pistachio – *Pistacia vera* (n = 18), and walnut – *Juglans* sp. (n = 50)] compared to that of present and historical US maize and soybean in terms of (a) calories, (b) carbohydrate, (c) protein, and (d) oil.

Figure 3.4 (cont) Individual nut crop data points are 3-year country means (2011-2013) [yield, FAO (2017); constituent composition, USDA (2016)]. Maize and soybean data are US means for 2011-2013 (present) and 1925-1930 (historical) [yield, USDA NASS (2016); constituent composition, USDA (2016)].

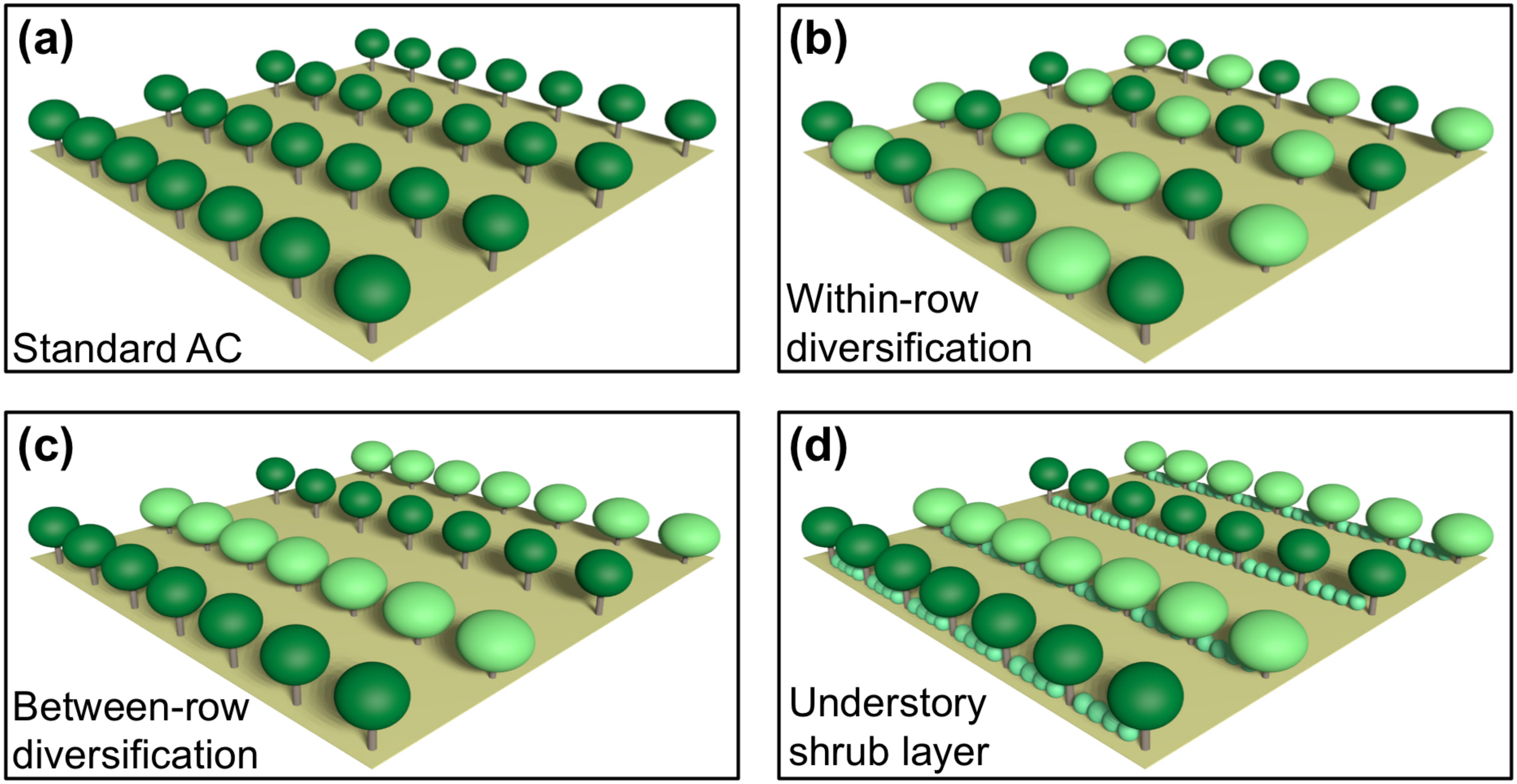

Figure 3.5 Conceptual diagram depicting practical designs for the within-row diversification in AC: (a) traditional temperate AC design with rows of a single tree species, (b) within-row tree diversification, (c) between-row tree diversification, and (d) an understory shrub layer within tree rows.

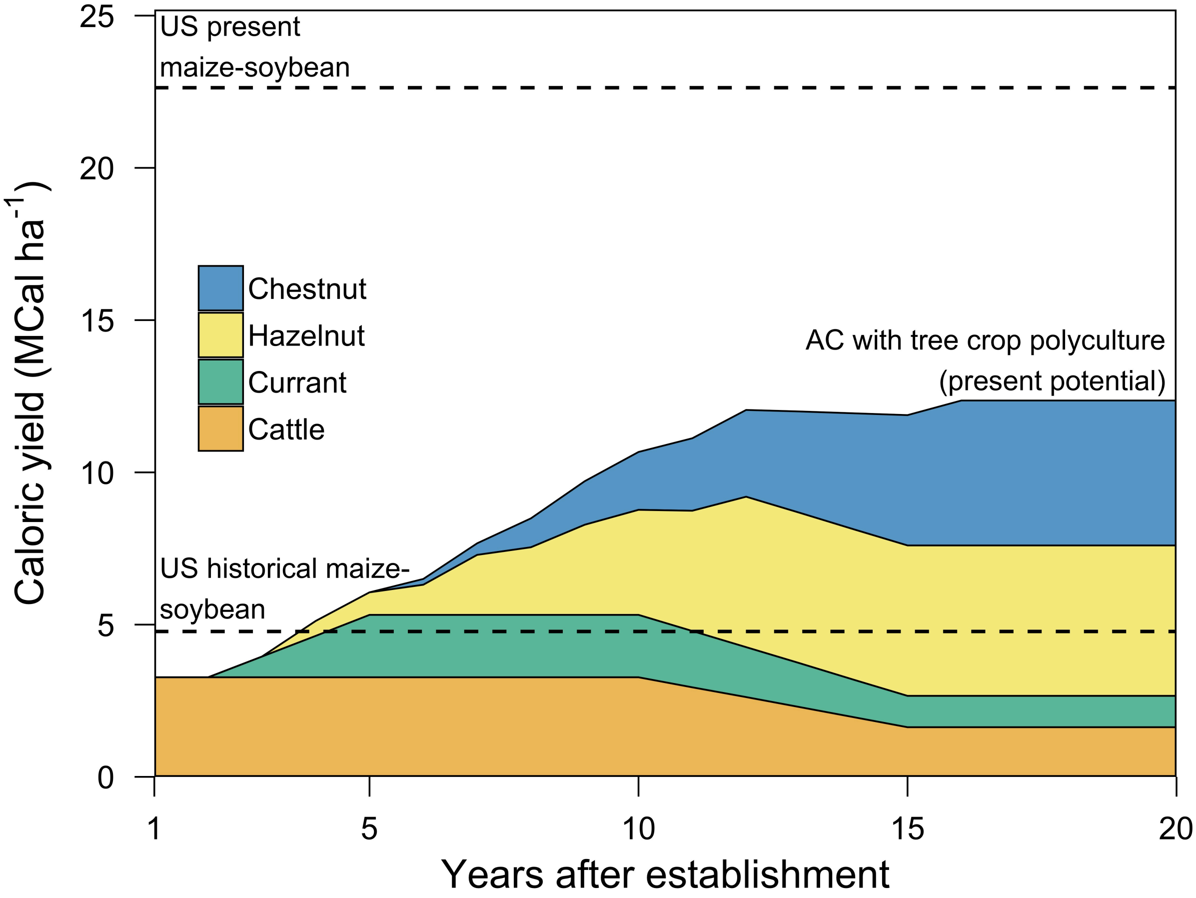

Figure 3.6 Yield projections for a theoretical AC system that combines tree/shrub crops in polyculture. Tree rows contain chestnut or hazelnut with currant in a design similar to Fig. 3.5d. Per-plant mature yields (chestnut: 33 kg, hazelnut: 5.9 kg, currant: 2.3 kg) and yields trajectories are from US extension bulletins. The hay alley crop is assumed to support two beef steers ha^{-1} (250 kg beef steer^{-1}). Currant and hay yields are assumed to decline by 10% each year from years 11-15 due to tree competition. Caloric composition is from the USDA (2016)]. Present and historical US maize-soybean mean caloric yields are also shown (from Fig. 3.4a).

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CHAPTER 4

REDUCED NITROGEN LOSSES AFTER CONVERSION OF ROW CROP AGRICULTURE TO ALLEY CROPPING WITH MIXED FRUIT AND NUT TREES

ABSTRACT

Agriculture across the temperate zone is dominated by a maize-soybean rotation (MSR) characterized by a “leaky” nitrogen (N) cycle. MSR N losses have considerable negative impacts on water quality via N leaching and climate change via soil emissions of N_2O, a potent greenhouse gas. Alley cropping (AC) focused on food- or fodder-producing tree crops has the potential to substantially reduce environmental N losses while maintaining agricultural productivity. To compare the N cycling of MSR and AC, this study (1) summarized literature values of N pools and fluxes in both systems, (2) directly measured N leaching and N_2O emissions in a side-by-side trial of MSR and an establishing AC over four years, and (3) used AC yield projections to estimate the trajectory of yield-scaled N losses as AC grows to productive maturity. Ample literature data on MSR permitted the construction of a robust working N budget, while a paucity of existing data on N cycling in AC revealed gaps and high uncertainty in our existing knowledge. In the field trial, AC quickly reduced both N leaching and N_2O emissions compared to MSR. Nitrate leaching at 50 cm depth in MSR ranged from 21.6 to 88.5 kg N ha^{-1} yr^{-1}, whereas leaching was reduced by 82 to 91% in AC. Cumulative annual net N_2O fluxes in MSR ranged from 0.4 to 2.0 kg N ha^{-1}, but AC reduced annual fluxes by 25 to 83%. Overall, conversion of MSR to AC reduced unintended N losses over four years by 83% from 240 to 41 kg N ha^{-1}. Even when accounting for the low yield in AC during the establishment years studied here, yield-scaled N leaching in AC and MSR were not significantly different. In contrast, yield-scaled N_2O fluxes were an average of 4.8 times higher in AC across years and were only estimated to reach a comparable range to MSR after reaching productive maturity. Our results demonstrate rapid tightening of the N cycle and a competitive trajectory of yield-scaled N losses as row crop agriculture is converted to AC.

INTRODUCTION

Row crop agriculture, primarily the maize-soybean rotation (MSR), is a dominant agricultural land-use around the world. MSR relies on large nitrogen (N) inputs and intensive disturbance, which can increase environmental N losses. The two major avenues of unintended N loss from agricultural systems are N leaching and soil nitrous oxide (N_2O) emissions (David et al. 2009, Hernandez-Ramirez et al. 2009). In North America, agricultural N leaching contributes around 80% of the 1.2 million tons of N entering the Gulf of Mexico and results in hypoxia (USEPA 2007, David et al. 2010). Produced via nitrification or denitrification of soil inorganic N, N_2O is a potent greenhouse gas (IPCC 2014). The leaky agricultural N cycle produces 55% of global N_2O emissions (USEPA 2012). Many agronomic techniques have been proposed to reduce N losses from row crop agriculture, such as split fertilizer applications, application of nitrification inhibitors, and cover crops. A meta-analysis of the many techniques intended to reduce N losses in maize found that they can reduce N leaching by 14–37% and N_2O emissions by 5–40% (Xia et al. 2017). However, much greater reductions are needed to meet hypoxia reduction goals (Scavia et al. 2004) and climate change mitigation goals (IPCC 2014).

Alley cropping (AC), the integration of trees with crops, is a transformative departure from the incremental improvements to MSR that focus on minor agronomic improvements or field margins (Gold and Hanover 1987, Wilson and Lovell 2016). In particular, AC with food- or fodder-producing “tree crops” (e.g. nut or fruit trees), could maintain high agricultural yields while promoting substantial ecological benefits in a “land sharing” land-use approach (Anderson-Teixeira et al. 2012, Lovell et al. 2017). By integrating trees and crops throughout a field, temperate AC can promote carbon sequestration, improved soil structure, increased biodiversity, and soil stabilization (Thevathasan and Gordon 2004, Jose 2009, Tsonkova et al. 2012). In addition, AC has potential to reduce N losses.

Like cover crops or buffer strips, tree roots can provide a “safety-net” by catching N that leaches beyond the crop rooting depth or growing season (Allen et al. 2004). For example, AC reduced nitrate (NO_3^-) leaching compared to monoculture crops by 46% at 0.3 m depth and 71% at 0.9 m depth (Allen et al. 2004). The greater leaching reduction with depth illustrates the cumulative effect of tree roots. Lower in the soil profile, Dougherty et al. (2009) found 46% lower NO_3^- levels in tile effluent under AC than monoculture maize, which directly translates into impacts on surface water quality. Even compared to perennial pasture, which has deeper roots and a longer growing season than annual crops, integrating trees reduced peak NO_3^- concentrations at 1.2 m depth by 56% (Bambo et al. 2009). The efficacy of leaching reductions in AC varies with alley crop species (Dai et al. 2006) and soil texture (Bergeron et al. 2011).

Agroforestry also has potential as a mitigation tool for climate change through reduced N_2O emissions (Schoeneberger et al. 2012). For example, studies of hedgerows and shelterbelts found up to 74% lower N_2O emissions compared to adjacent cropland (Amadi et al. 2016, Baah-Acheamfour et al. 2016). However, in a synthesis of N_2O emissions in agroforestry, Kim et al. (2016) reported an increase of annual N_2O emissions of 0.64 ± 0.26 kg N ha^{-1} in AC compared to adjacent agricultural fields. This value was based on only a single study (Guo et al. 2009) – the only study of N_2O emissions in AC with sufficient sampling to generate annual flux estimates – and clearly demonstrates the paucity of data on N_2O emissions in AC. Although not providing an annual total, Beaudette et al. (2010) found that AC reduced soil N_2O emissions by 72% on four dates without impacting alley crop yields.

Studies of N cycling in AC have focused on mature systems, leaving uncertain the trajectory of N losses during establishment. Other perennial crops can reduce N losses soon after conversion from MSR. For example, perennial grasses grown as bioenergy crops reduced NO_3^- leaching and N_2O emissions by over 90% in just four years (Smith et al. 2013). Young woody bioenergy crops can reduce NO_3^- leaching by more than 99% over the first 11 years (Syswerda et al. 2012) and N_2O emissions by 81% over the first nine years (Robertson et al. 2000). It is important to note, however, that perennial bioenergy crop are typically not fertilized due to the wide C:N ratios of the harvested biomass. Instead, fertilization can increase N losses unnecessarily (Behnke et al. 2012, Balasus et al. 2012). In contrast, AC with tree crops will likely require greater N replenishment due to the narrower C:N ratios of fruit/nut yields. These higher N inputs could negate the potential of AC to reduce N losses.

As a land sharing approach, a complete comparison of AC with MSR requires the use of yield-scaled N losses (Linquist et al. 2012), in which N losses are scaled by caloric food yields to determine N loss per unit yield. The yield-scaled concept has only recently been applied in perennial crops (Schellenberg et al. 2012) but is especially important in AC due to the low yields of immature tree crops. Many years of high yield-scaled N losses during the establishment phase could outweigh lower values at maturity.

Understanding the N cycle of AC is critical for its evaluation as a viable agricultural practice in the temperate zone. The objective of this study was to quantify changes in the N cycle when transitioning from MSR to AC. Three approaches were used: (1) To provide context on the possible range of N pools and fluxes in temperate MSR and AC, we constructed working N budgets from literature values and agricultural statistics. (2) We conducted a side-by-side trial of AC and MSR to evaluate changes in the N cycle over the first 5 years after AC establishment. (3) Using projections of AC yield, we estimated the trajectory of yield-scaled N losses as AC grows to reproductive maturity.

METHODS

Working N budgets

Working N budgets for MSR and temperate AC were constructed using a combination of agricultural statistics, climate statistics, and literature values. Literature values were primarily gathered from existing reviews of various components of the N cycle. All budget values were summarized as ranges, with values greater than 20 kg N ha^{-1} yr^{-1} rounded to the nearest 10 units. Complete details on the derivation of N budgets are provided in Appendix A.

Site description and experimental design

Our study site was located at the University of Illinois Pomology Research Farm (40°4′45.05″N, 88°12′57.45″W, ~220 m above sea level). The site previously grew soybeans (2009-2011), silage maize (2006-2008), and alfalfa (2002-2005), although was historically in a traditional MSR. Average annual temperature for the region from 1981-2010 was 10.9˚C, and average annual precipitation was 1051 mm (Illinois State Water Survey). Mean monthly temperatures during the study ranged from -8 to 24˚C. Monthly precipitation data are shown in Table A.1. Soils are a Flanagan silt loam (Fine, smectitic, mesic aquic agriudolls), typical of the deep, poorly drained mollisols of central Illinois. Mean soil pH was 7.3 at the time of establishment. The study site has a ~2% slope and contains four-inch drain tile oriented E to W at 30 m spacing.

The two treatments studied were: MSR and an establishing AC. Plots were established in spring 2012 in a randomized complete block design with four 0.2-ha replicates and 9-m mowed grass buffers. MSR was managed using typical practices of central Illinois. The AC design was based on Shepard (2013), containing six different food-producing tree and shrub species with 7-m grass-clover hay alleys (Fig. A.1). Neither treatment was irrigated during the study period. Detailed information on site design, establishment, and management can be found in Appendix A.

Soil N pools and fluxes

To characterize baseline (2012) conditions and quantify the total soil N pool, 3.8-cm-diameter soil samples were collected from 10 random locations to 100-cm depth in each plot. Each sample was air-dried and weighed to calculate bulk density, and a subsample was oven-dried at 105°C to correct for moisture content. Subsamples were then crushed, sieved (2 mm), finely ground with a modified coffee grinder, oven-dried at 65°C, and analyzed for total C and N concentrations with an elemental analyzer (Elemental Combustion System, Costech Analytical Technologies, Inc.).

Maize was fertilized each year with 200 kg N ha^{-1} using 28% urea ammonium nitrate at the time of planting. Soybean was not fertilized. AC was not fertilized during the first three years after establishment (a standard practice allowing trees to establish) and then uniformly fertilized with 100 kg N ha^{-1} of granular urea on 22 May 2015 (year 4) and 5 May 2016 (year 5). The fertilization rate used in AC is comparable to recommended rates for the various woody crops and was selected so that the mean annual N fertilizer input was the same in MSR and AC over 2015-2016.

Total N inputs from N_2 fixation were estimated using empirical relationships with aboveground [N] for soybean (Gelfand and Robertson 2015) and clover (Høgh-Jensen et al. 2004). Clover biomass was visually estimated as 20% of hay biomass. Wet N deposition (NH_4–N + NO_3–N) was obtained from the National Atmospheric Deposition Program at Bondville, IL (~15 km from the study site) for 2013-2016, and dry deposition was estimated as 70% of wet (McIsaac et al. 2002, USEPA 2007). N deposition in Jan-Apr 2017 was estimated as the 1980-2016 mean.

Annual N leaching fluxes were measured using resin lysimeters at 50-cm depth (Susfalk and Johnson 2002, Smith et al. 2013). Each lysimeter holds 10 g dry resin (Rexyn I-300 H-OH Beads, Fisher Chemical) within a 5.1 cm-diameter PVC pipe. Three lysimeters were randomly placed in each MSR plot, and one lysimeter was randomly placed within each of the three zones (two tree row types and the alley crop) in each AC plot. Lysimeters were initially installed on 7 May 2013 and replaced annually. Lysimeters were only retrieved annually to minimize damage to the perennial crops. Ammonium and NO_3^- loads in the resin were obtained via KCl extraction followed by colorimetric flow injection analysis (Lachat QuickChem 8000). Annual fluxes on an area basis were calculated by dividing the extracted loads by the lysimeter cross-sectional area.

N_2O flux was measured using vented static PVC chambers with 20-cm diameter and 3.2-L volume (Smith et al. 2013). Chambers were placed on PVC ring bases (20 cm diameter, 10 cm height) that were inserted ~5 cm into the soil and maintained free of vegetation. The bases remained in the soil throughout the experiment, though temporarily removed in MSR for tilling. In each MSR plot, one ring was randomly placed in each of three zones: within row, between rows, and splitting these two. In each AC plot ring placement was stratified as for lysimeters. Sampling occurred in late morning to minimize soil temperature variability, and measured fluxes were assumed to represent the mean daily flux. Sampling began in early spring and continued throughout the growing season approximately every two weeks. Sampling frequency increased surrounding fertilization events and slowed in late summer to once every three to four weeks. For flux measurements, chambers were secured on the rings for 30-min incubations, with 15-mL gas samples collected into evacuated vials every 10 min. Gas samples were analyzed by gas chromatography (Shimadzu GC-2014 Greenhouse Gas Analyzer, Shimadzu Scientific Instruments) alongside known gas standards (Scott Specialty Gases). Cumulative N_2O fluxes were linearly interpolated.

Harvested and standing biomass

To quantify N removed in yields, aboveground biomass samples were collected from three randomly placed 0.5 m^2 quadrats in each plot during harvest of MSR and AC alleys. Yield subsamples were analyzed for total C and N concentration as described above. All harvested fruits and nuts from AC were weighed during harvest. N content of harvested crops was found in the literature. All woody biomass removed via pruning was weighed.

To quantify net annual N uptake by woody plants, standing aboveground woody biomass in AC was estimated each year using stem caliper measurements and species-specific allometric relationships. Allometric relationships were constructed using pruning events and several destructive harvests (Figs. A.2 and A.3). Belowground woody biomass was estimated from literature values, when available, or using root:shoot ratios measured during destructive harvests. To estimate N content of woody biomass, above- and belowground wood samples of each species were harvested in Mar. 2013 while all species were still dormant. Collected samples were analyzed for total C and N concentration as described above.

Yield-scaled N losses

To calculate yield-scaled N losses during the four study years, measured N losses were divided by measured yield. Yields from top individuals were used rather than site means because of high yield variability due to rodent damage. For each tree crop, yield biomass was converted to caloric yield using standard conversions {USDA:2016wj}. Hay alleys were assumed to support production of zero, half, one, and one beef steer per hectare (550 kg of beef per steer) in years two through five, respectively. To estimate trajectories of yield-scaled externalities of AC beyond year six, N losses were assumed to remain equivalent to the mean of years four to five and yield projections were taken from Figure 3.6.

Statistical analyses

All statistical analyses were performed on plot-level means. AC plot means were calculated as area-weighted means of the stratified samples. Statistical analyses were performed using the R statistical computing software version 3.3.2 (R Core Team 2017), with differences in means significant at a probability level of $p < 0.05$. Prior to comparing treatment means, all data were assessed for normality (Shapiro-Wilk) and variance homogeneity (Levene). All data exhibited a normal distribution and homogeneous variance, except for unequal variance in NO_3^- flux data between treatments. One extreme outlier value for NO_3^- leaching in AC in 2015 was replaced by a mean of the remaining three blocks. Nitrate fluxes were analyzed for significant differences between treatments for each year using a Welch modified two-sided t-test with unequal variance. The same test was performed for differences in ammonium fluxes, cumulative N_2O fluxes, and yield-scaled N losses except that a pooled variance was used. Significant differences across years for each treatment were assessed using a one-way ANOVA. When overall F-tests were significant, Tukey's HSD was used to separate means. A blocking factor was not used since preliminary analyses revealed that blocking was non-significant for all tests.

RESULTS

Working N budgets

Ample available data from crop statistics and literature reviews made it possible to construct a robust working N budget for MSR (Fig. 4.1). Fertilizer and N fixation dominated N inputs for maize and soybean, respectively, with N deposition much smaller. The largest output in both crops was harvested N in grain, though N leaching was the largest unintended loss. In contrast, net N_2O emissions constituted negligible N loss, underscoring its disproportionate impact as a greenhouse gas. Ranges for all pools and fluxes were wide due to the variable climate, soil, and management in MSR across the temperate zone.

A paucity of data on N cycling in AC revealed gaps in our knowledge and generally low precision in the estimated ranges of N fluxes (Fig. 4.2). Net N_2O emissions were comparable to those of soybean, but lower than in maize. Leaching losses exhibited an extremely wide range, although data were derived from only three studies. Overall, the high variance in all estimates also represents the broad array of trees, crops, designs, and management regimes that can constitute AC.

Initial soils and harvested biomass

Initial soil C and N content was consistent between treatments (Table A.2). Organic C content in the top 30 cm of soil ranged from 17.3-25.2 g kg^{-1} and declined to as low as 3.0 g kg^{-1} at 50-100 cm depth. Total soil N followed the same pattern, ranging from 1.71-2.65 g kg^{-1} in surface soils and declining to a low of 0.46 g kg^{-1} at 50-100 cm depth. Organic C and total N pools in the top meter of soil averaged 140 Mg C ha^{-1} and 14.0 Mg N ha^{-1}.

Grain yields constituted the only biomass harvested from MSR and were typical of the region (Table A.3). Fruit/nut yields in AC generally increased throughout the study, although peak yields were not reached for any crop. Hay dominated AC harvested biomass, with yields increasing each year and more than doubling after the initiation of fertilization in 2015. Woody biomass prunings also generally increased throughout the study.

Standing biomass

Standing woody biomass in AC generally increased throughout the study, with some irregularities due to pruning regimes (Table A.4). The shrub species dominated the standing biomass as they were the most numerous and fastest-growing species, occupying the space in the bottom canopy strata in each tree row. Root:shoot ratios for woody components in AC species ranged from 0.78-2.00, with the large shrub species exhibiting the largest ratios. N content in aboveground woody biomass ranged from 0.7-1.1% across species, with the range in belowground N content slightly higher from 0.9-1.8%.

Environmental N losses

Large quantities of NO_3^- leached in MSR at 50 cm depth in all years, ranging from 21.6-88.5 kg N ha^{-1} yr^{-1} and representing a substantial portion of the annual N inputs to the system (Fig. 4.3). Leaching under MSR did not vary significantly across years except for leaching between the two soybean years (2013 and 2015), which were the highest and lowest leaching rates recorded in MSR. In the second and third years after establishment of AC, NO_3^- leaching was significantly lower than in MSR at just 2.7 and 3.9 kg N ha^{-1} yr^{-1}, respectively. Once fertilization commenced in AC in 2015 and 2016, NO_3^- leaching rose to 15.5 and 8.2 kg N ha^{-1}

yr^{-1}, respectively, but was still significantly lower than in MSR. Nitrate leaching at 50-cm depth was significantly reduced in AC compared to the MSR by 87, 91, 82 and 88% in 2013-2016, respectively. Ammonium leaching rates remained low (1.5-5.0 kg N ha^{-1} yr^{-1}) throughout the study (Fig. A.4).

Net N_2O fluxes in AC and soybean were low throughout each growing season, generally remaining below 0.5 μg N m^{-2} min^{-1} (Fig. 4.4). In contrast, net N_2O fluxes in maize were frequently greater than 1.0 μg N m^{-2} min^{-1}, reaching as high as 10.9 μg N m^{-2} min^{-1} in 2016, and only remaining consistently low in the fall season. Prominent spikes in net N_2O flux lasting approximately 20 days were observed after all fertilization events in maize and AC. In maize, these initial spikes accounted for 28% and 50% of 2014 and 2016 N_2O emissions, respectively. Additional but smaller spikes were observed in maize fluxes throughout both seasons, typically after heavy rains. In AC, the initial post-fertilization spikes accounted for 37% and 31% of 2015 and 2016 N_2O emissions, respectively. No additional large spikes were observed in AC fluxes, even after large rain events.

Cumulative annual net N_2O fluxes in MSR ranged from 0.4-0.9 kg N ha^{-1} in soybean and 1.4-2.0 kg N ha^{-1} in maize (Fig. 4.5). Cumulative fluxes were reduced in AC compared to MSR by 55, 83, 25 and 65% in 2013-2016, respectively ($p < 0.05$ for all years except 2015). While cumulative net N_2O flux in AC increased more than three-fold with the onset of fertilization in 2015 and 2016, the difference was not statistically significant. Net N_2O fluxes varied significantly between years for MSR, with fluxes higher in maize compared to soybean.

Overall N fluxes

Overall N budgets were developed for both experimental treatments (Table 4.1). Fertilization in maize was comparable to the annual N fixation in soybean. Together, these dominated N inputs for MSR. In AC, fertilizer was also the major N input, followed by clover N fixation. Atmospheric deposition added little N to both treatments. The largest N outputs were grain yield for MSR and harvested hay in AC. Fruit/nut yields and woody biomass prunings removed relatively little N from AC. Nitrate leaching was the largest unintended export of N from both systems, constituting 29.6% and 5.5% of annual N inputs to MSR and AC, respectively, over the four study years. Ammonium leaching and N_2O emission were much smaller N losses, constituting 1.5% and 1.6%, respectively, of N inputs in both systems. MSR was consistently a net N exporter across years, with a net export of 304 kg N ha^{-1} over the four study years. While AC was also a net exporter of N over the four study years, the net export was much lower at only 132 kg N ha^{-1}. Overall, conversion of MSR to AC reduced unintended N losses by 83% over four years from 240 to 41 kg N ha^{-1}.

Yield-scaled N losses

Mean yield-scaled NO_3^- leaching during the four study years was 2.8 kg N $MCal^{-1}$ and 2.3 kg N $MCal^{-1}$ for AC and MSR, respectively, with no significant differences between systems (Fig. 4.6a). Mean yield-scaled N_2O flux during the four study years was 0.17 and 0.04 for AC and MSR, respectively, with AC significantly higher than MSR in all years except year five (Fig. 4.6b). The trajectory of yield-scaled N losses in AC was projected to decrease until around year 12 and then plateau once all component tree crops reach mature yields. Yield-scaled NO_3^- leaching and N_2O flux were projected to plateau at approximately 42% and 143% of the measured MSR mean, respectively.

DISCUSSION

Our results demonstrate that transitioning from MSR to AC can rapidly decrease environmental N losses via NO_3^- leaching and soil N_2O emissions, even when mean annual N fertilizer inputs are equivalent (as in 2015-16). Reduction of N losses in AC occurred despite the soil disturbance and low plant biomass of establishment years. Furthermore, leveraging tree crops in AC supports a trajectory of yield-scaled N losses competitive with MSR, producing a multifunctional, land sharing land-use approach. These results improve our knowledge of the N cycle during the transition from MSR to AC. Widespread adoption of AC across the Midwest could rapidly reduce absolute and yield-scaled N losses, reducing hypoxia in surface waters and mitigating global climate change.

Leaching rates in both systems were within the ranges of the working N budgets except for leaching under soybean in 2015, which was unexpectedly high even without fertilization. This may be explained by 2015-16 being the wettest year of the study, with winter precipitation particularly high (Table A.1). Most leaching loss in the Midwest US occurs in winter and spring when vegetation is absent, and much of the loss can occur during a short period of high precipitation (Royer et al. 2006). However, it is also possible that the water table rose above 50 cm during the winter months, which would flood the lysimeters, although such an event would have likely affected MSR and AC similarly. The low ammonium leaching fluxes (Smith et al. 2013) and lack of significant differences between MSR and AC (Allen et al. 2004) observed here are as expected.

One important limitation of assessing N leaching losses using resin lysimeters at 50 cm is that deep roots below 50 cm can scavenge N before it is lost to drain tile. When measuring N leaching rates at a nearby site over 3 years using both resin lysimeters at 50 cm and individual plot drain tile outflow (2 m), Smith *et al*. (2013) found rates measured via tile outlets to be an average of 41% lower than rates measured via resin lysimeters at 50 cm. However, individually tiled plots are costly, and burying lysimeters deeper than 50 cm can cause substantial disturbance to the measured soil profile or the root systems of perennial crops. Furthermore, since over two-thirds of roots in both annual and perennial crops are above 50 cm (Black et al. 2017), any N leached below 50 cm can be considered lost from an agricultural perspective.

Net N_2O emissions measured here were on the low end of the ranges developed in the working N budgets for MSR and AC. In fertilization years, emissions were driven by prominent post-fertilization spikes in both systems. These spikes support previous calls for split fertilizer applications as an approach to reduce N_2O fluxes (Dinnes et al. 2002). The extremely high post-fertilization spikes in 2016 for both maize and AC are especially noticeable. These high peaks, however, are not easily explained by precipitation and soil temperature, which were both higher in 2014-15 than in 2016. This supports previous observations that the relationship between N_2O fluxes and soil moisture/temperature is inconsistent (Amadi et al. 2016, Baah-Acheamfour et al. 2016). Though already low in AC by the fifth year of this study, N_2O emissions are expected to continue to decrease as the trees mature, as was found for afforested pasturelands across climate zones (Allen et al. 2009).

Soil disturbance associated with transitioning between agricultural systems (e.g. planting trees, tillage, drilling seed, low root biomass etc.) has the potential to stimulate an increase in N losses by aerating soil and reducing soil structure. This effect was demonstrated by Smith et al. (2013), where leaching was much higher in the establishment year compared to the subsequent three years after conversion from MSR to three different perennial biofuel crops. While no data was collected here during the initial year of AC (2012), it is likely that the soil disturbance during establishment, with low woody crop biomass and no alley crop, resulted in considerable N leaching and soil N_2O emissions. Nevertheless, any disturbance-driven increase in N losses during the first year, were already diminished by the following year.

Although temperate AC is typically applied using a single tree, emphasizing woody polycultures, such as in the system studied here, could expand its potential (Lovell et al. 2017). Evidence from forests has shown that N retention can increase with diversity (Schwarz et al. 2014, Lang et al. 2014). Leveraging multiple tree species within AC could similarly increase its potential to reduce N losses. Further research is needed to determine the optimal fertilization rates and management practices in mixed species systems that lead to the highest system productivity and lowest yield-scaled N losses (Malézieux et al. 2009).

Row crop agriculture continues to contribute substantially to water quality issues and global climate change through large environmental N losses. Our results demonstrate that AC quickly reduced N losses via NO_3^- leaching and soil N_2O emissions during establishment years, even when mean annual fertilizer N inputs remain the same. These results build on prior work that has demonstrated reduced N losses in mature agroforestry systems by evaluating the underexplored establishment phase. Furthermore, our approach provides a more thorough comparison between AC and MSR via yield-scaled N losses. Future work evaluating the long-term yields and biogeochemical consequences of AC are critical to widespread adoption of this transformative agricultural alternative.

TABLES & FIGURES

Table 4.1 Nitrogen fluxes (May-May) for the second through the fifth years of AC establishment.

	Maize-soybean rotation				Alley cropping			
	Soy	Maize	Soy	Maize				
	2013	2014	2015	2016	2013	2014	2015	2016
	kg N ha^{-1} yr^{-1}							
Inputs								
Fertilizer	0.0	200	0.0	202	0.0	0.0	100	100
Atm. deposition	6.4	10.3	7.8	8.9	6.4	10.3	7.8	8.9
N_2 fixation	148	-[†]	173	-	44.3	44.3	81.6	81.1
Total in	*154*	*210*	*181*	*211*	*50.7*	*54.6*	*189*	*190*
Outputs								
NH_4^+ leaching	1.8	2.0	2.5	5.0	2.1	1.5	1.7	3.5
NO_3^- leaching	21.6	45.6	88.5	68.6	2.7	3.9	15.5	8.2
N_2O efflux	0.4	1.4	0.9	2.0	0.2	0.2	0.7	0.7
Woody biomass	-	-	-	-	0.0	8.0	5.2	10.2
Hay biomass	-	-	-	-	0.0	94	201	238
Fruit/Nut Yield	211	194	272	142	5.4	2.5	4.3	7.4
Total out	*235*	*243*	*364*	*218*	*10.4*	*110*	*228*	*268*
Net N Input	*-81*	*-33*	*-183*	*-7*	*40*	*-55*	*-39*	*-78*
Woody biomass growth								
Aboveground	-	-	-	-	4.3	9.9	10.1	12.6
Belowground	-	-	-	-	9.7	18.9	-4.6	12.1
Total woody biomass growth	-	-	-	-	14.0	28.8	5.5	24.7

[†] Not applicable

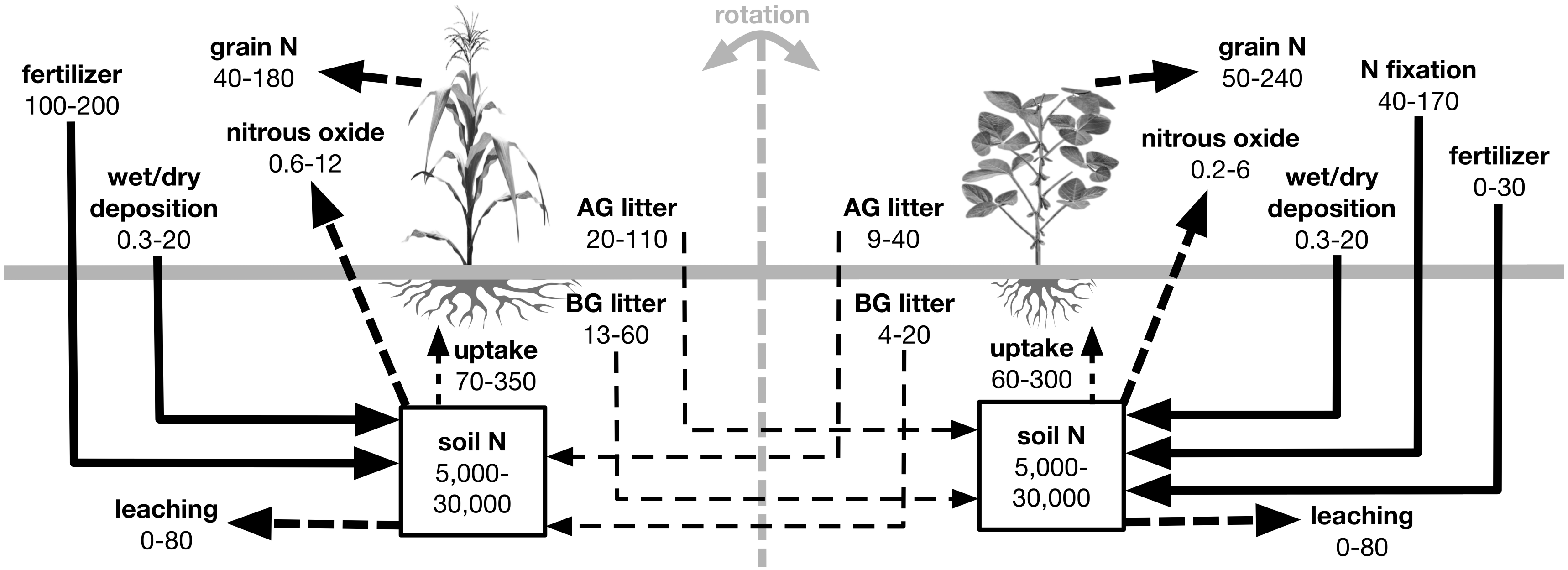

Figure 4.1 Summary of literature values and working N budget for maize-soybean rotation. All arrows represent N fluxes in kg N ha^{-1} yr^{-1}. Solid arrow are N inputs, thick dashed arrows are N losses, and thin dashed arrows indicate internal cycling. All boxes represent N pools in kg N ha^{-1}.

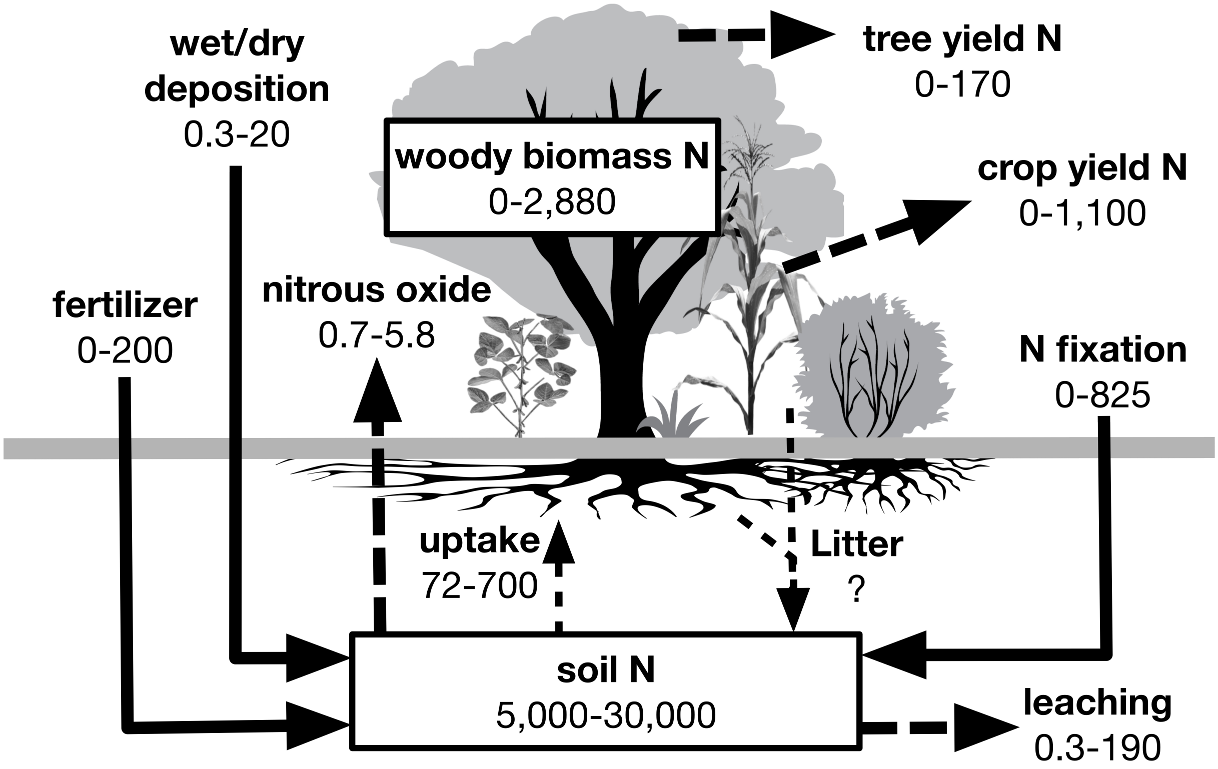

Figure 4.2 Summary of literature values and working N budget for AC. All arrows represent N fluxes in kg N ha^{-1} yr^{-1}. Solid arrow are N inputs, thick dashed arrows are N losses, and thin dashed arrows indicate internal cycling. All boxes represent N pools in kg N ha^{-1}.

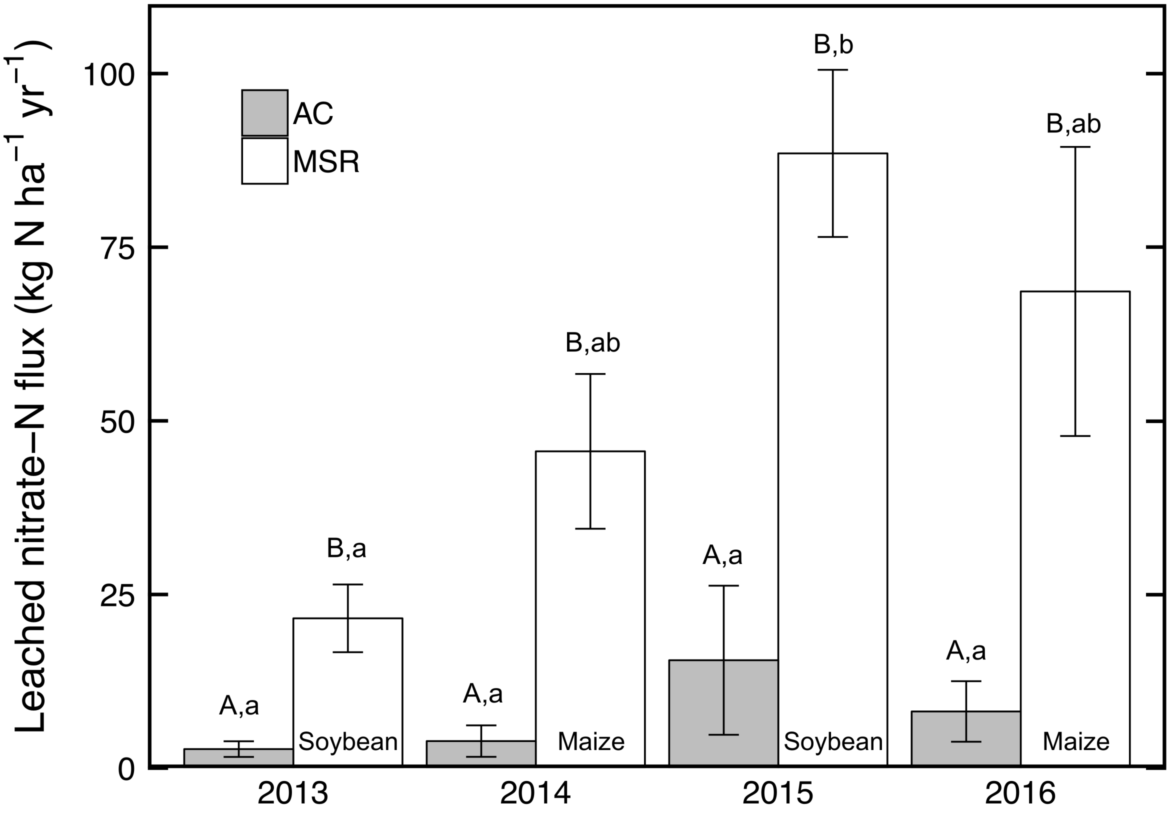

Figure 4.3 Annual nitrate N leaching (May-May) at 50 cm depth using resin lysimeters for AC and MSR (mean ± SE) during 2013-2016. Treatment means within each year with the same capital letter, and means within each treatment across years with the same lowercase letter, are not significantly different. Maize was fertilized with 202 kg N ha^{-1}. AC was fertilized in 2015 and 2016 with 101 kg N ha^{-1}.

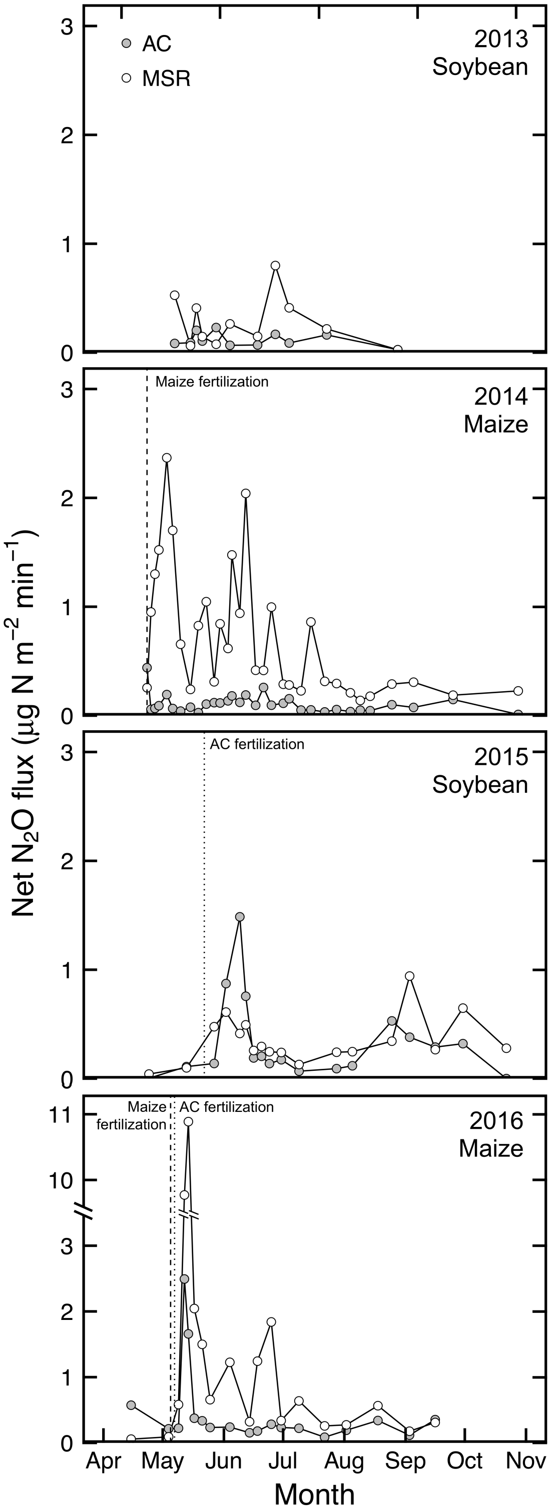

Figure 4.4 Net N_2O fluxes from chamber measurements during 2013-2016 for AC and MSR.

The number of sampling days in 2013-2016 were 11, 32, 18, and 19, respectively.

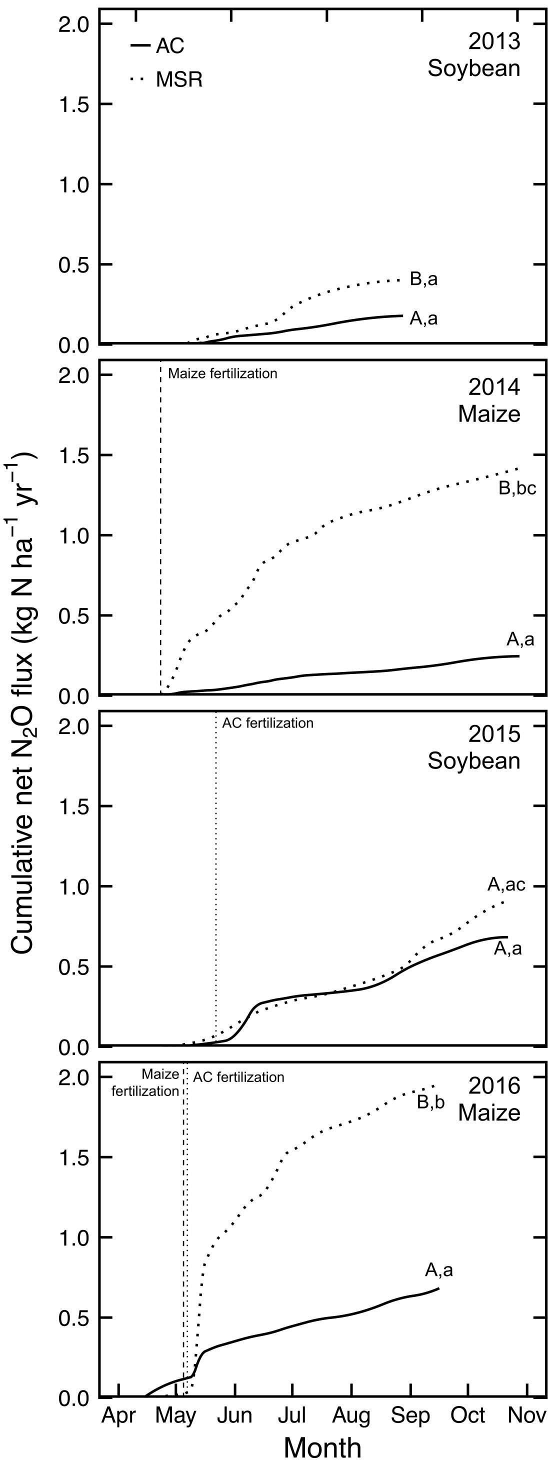

Figure 4.5 Cumulative net N_2O fluxes during 2013-2016 for AC and MSR. Final cumulative fluxes within each year with the same capital letter, and within each treatment across years with the same lowercase letter, are not significantly different.

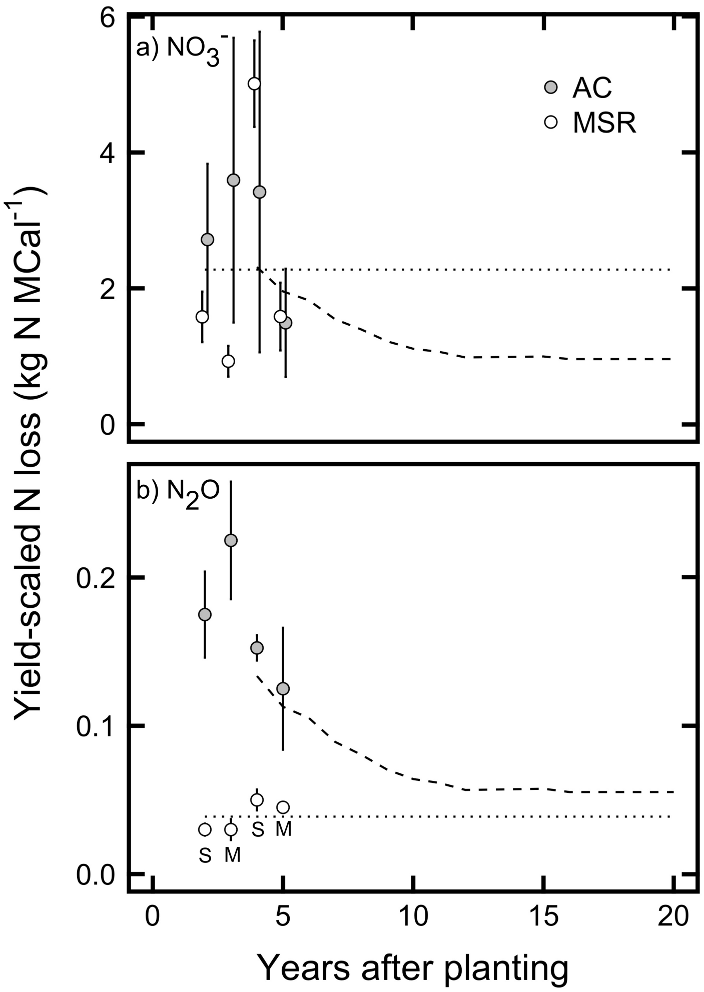

Figure 4.6 Yield-scaled annual N losses for AC and MSR. Points in years 2-5 are data from this study. The dotted line shows the mean MSR value of the four study years. The dashed line shows the theoretical trajectory for AC assuming N losses remain equivalent to the year 4-5 mean and yields follow the trajectory in Figure 3.6. Letters in (b) indicate soybean and maize years.

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CHAPTER 5

TARGET REGIONS FOR PROFITABLE, TREE-BASED ALTERNATIVES TO ROW CROP AGRICULTURE

ABSTRACT

The maize-soybean rotation (MSR) dominates the Midwest US and degrades many ecological functions. Black walnut plantation forestry (PF) and alley cropping (AC) are two alternative land-uses that can enhance productivity and restore ecosystem services. Given the lack of robust market mechanisms to monetize ecosystems services, we tested whether the profitability of PF and AC could drive adoption in the Midwest. Publically available data on black walnut soil suitability, timber prices, crop productivity, and cash rents were combined in a high-resolution spatial analysis to identify target regions where these alternatives can outcompete MSR. We show that PF and AC could be more profitable on 17.0% and 23.4% of cultivated land, respectively, assuming a 5% discount rate. The economic competitiveness of alternatives was not correlated with MSR productivity. Results reveal major opportunities for landowners and investors to increase profitability by investing in PF and AC on both marginal and ideal MSR land.

INTRODUCTION

The maize-soybean rotation (MSR) is the dominant land-use in the Midwest US (Fig. 5.1a). Though extremely productive, MSR degrades many ecological functions (Foley 2005, USEPA 2007, 2012), is sensitive to future climate change (Mistry et al. 2017), and its profitability is volatile (Brandes et al. 2016). Alley cropping (AC), an agroforestry practice that grows crops in alleys between tree rows, is an alternative land-use that can enhance productivity and restore ecosystem services (Thevathasan and Gordon 2004, Jose 2009, Tsonkova et al. 2012). For example, AC can sequester substantial amounts of carbon (Udawatta and Jose 2012) and reduce nitrogen losses via nitrate leaching (Dougherty et al. 2009) and nitrous oxide emissions (Beaudette et al. 2010). While these environmental benefits can certainly increase landowners' interest in agroforestry 1(Winans et al. 2016, Mattia et al. 2016), they have failed to drive adoption due to the lack of robust market mechanisms to monetize their value. Profit remains the central driver for adoption of sustainable agricultural strategies.

Alternative agricultural practices are typically targeted at so-called "marginal" lands, which have low MSR productivity and contribute disproportionally to negative externalities (Richards et al. 2014). However, there are strong economic opportunities for land-use alternatives across existing MSR land (Brandes et al. 2016). Here, we evaluate the economic competitiveness of two specific land-use alternatives containing black walnut (*Juglans nigra*): AC and plantation forestry (PF). PF was included to test whether AC can outcompete its respective tree and crop monocultures. Merging high-resolution site suitability and profitability analyses enabled us to move beyond previous studies of coarse-scale profitability (Yemshanov et al. 2007, Frey et al. 2010) or basic site suitability at high resolution (Reisner et al. 2007, Wang and Shi 2015). Our dynamic black walnut growth model and high-resolution visualizations offer a novel, robust tool for landowners and investors.

Juglans is the most common tree genus in temperate AC, used in 34% of field experiments (Chapter 2). Whether sold as veneer or less valuable sawlogs, black walnut commands higher prices than all other temperate timber species (Fig. B.1). Furthermore, black walnut is an ideal species for AC because of its short growing season, sparse canopy (Moss 1964), large taproot, and deep rooting system (Yen et al. 1978). While allelopathic interference of crop growth from juglone in black walnut AC can occur, management interventions such as root pruning can minimize its impact. The economic competitiveness of PF and AC depends on the productivity of black walnut relative to that of MSR. Land that is marginal to MSR may not necessarily be productive for a given land-use alternative.

Publically available data on black walnut soil suitability, timber prices, crop productivity, cash rents, and land cover were combined to identify target regions where AC and PF can be direct economic competitors of MSR without monetization of any environmental benefits or direct government assistance. Analyses were performed at a 10x10 m resolution and focused on existing MSR land ("cultivated land") in Missouri, Illinois, Indiana, and Ohio, the only four states with sufficient data on black walnut soil suitability. Comparing the long-term, heterogeneous cash flows of AC and PF to MSR requires conversion into an annual equivalent value (*AEV*) by selecting a discount rate (i.e. the time value of money; (Klemperer 1996). An alternative system was deemed economically competitive with MSR from the landowner perspective if its *AEV* met or exceeded the estimated cropland cash rent for a given map unit. To avoid selecting an arbitrary discount rate at which to make comparisons, we determined the threshold discount rate (*TDR*) necessary to make AC or PF economically competitive with MSR.

METHODS

All analyses were performed at 10x10 m resolution using the raster version of the National Soil Survey Geographic Database (gSSURGO) (USDA NRCS 2017). Cultivated land was identified using the 2016 Cropland Data Layer (CDL) created by the USDA National

Agricultural Statistics Service (USDA NASS 2016a), a spatially explicit raster data layer identifying crop locations based on satellite imagery (Fig. 5.1a). All data integration and calculations were performed using the R statistical computing software version 3.4.0 (R Core Team 2017). Prior to analysis, historical economic data were adjusted to 2016 US$ using the consumer price index (U.S. Bureau of Labor Statistics 2017).

Cropland rent

Average cash rental rates of cropland for each county in 2008-2016 were obtained from USDA NASS (2016b). Nine-year mean values were calculated for each county (Fig. B.2) to remove variability caused by market and climate fluctuations. To estimate cash rental rate for each map unit *m* in each county *c*, we followed the method of Brandes et al. (2016) to scale county-level rent by an index of maize-soybean productivity. The productivity index used was the National Commodity Crop Productivity Index, Version 2.0 (*NCCPI*), which is available in gSSURGO and calculates an index of maize-soybean productivity based on a range of soil and climate characteristics (Dobos et al. 2012). Important factors that influence *NCCPI* include soil pH, cation exchange capacity, organic matter, available water capacity, precipitation, and bulk density.

A coefficient *D* was calculated for each county *c* to describe the increase in cash rent per unit increase in *NCCPI*:

$$D_c = \overline{R_c} \,/\, \overline{NCCPI_c} \,, \tag{5.1}$$

where $\overline{R_c}$ is the nine-year mean cash rental rate for county *c*, and $\overline{NCCPI_c}$ is the area-weighted mean *NCCPI* for cultivated land in county *c*. Missing values of $\overline{R_c}$ (in counties with little cultivated land) were estimated using a linear regression model with $\overline{NCCPI_c}$ across all counties

(R^2=0.50) (Fig. B.3). Using this coefficient, cash rental rate $R_{m,c}$ for each map unit m in each county c was calculated as:

$$R_{m,c} = D_c \times NCCPI_m \ , \tag{5.2}$$

where $NCCPI_m$ is the *NCCPI* of map unit m.

Black walnut growth model

To find all publications measuring diameter at breast height (*DBH*) of field-grown black walnut, a literature search was conducted on the Web of Science Core Collections requiring the key phrases of either "black walnut" or "*Juglans nigra*", along with "growth", "diameter" or "DBH". The search returned 274 publications using a search window of 1900 to 2016. All retrieved publications were mined to extract measurements of DBH and the year of measurement. Compiled data was fit using a Korf growth model (Zeide 2002, Šálek et al. 2012), which was taken to represent the growth curve of black walnut on average soil.

To estimate the potential growth rate of black walnut on each soil map unit *m*, the fitted growth model from the literature data was scaled using the Black Walnut Suitability Index (*BWSI*) (Wallace and Young 2008). As for *NCCPI*, *BWSI* exists in gSSURGO and calculates a suitability index for black walnut based on a range of soil properties and environmental conditions. Important factors that influence *BWSI* include flood frequency and duration, water table depth, depth to restrictive soil layer, soil texture, available water capacity, and soil pH. The fitted growth model from the literature data was set to represent a *BWSI* of 0.4, which is the area-weighted mean *BWSI* of all land in the four states studied. The growth curve for each map unit *m* was scaled linearly by $BWSI_m$ and converted into an maximum potential diameter increment $DI_{m,y}$ for each year *y* (Fig. B.4).

To model black walnut growth and profitability on each map unit *m*, the DI_m trajectory was supplied to a black walnut growth and financial model adapted from one created at the University of Missouri Center for Agroforestry (Godsey 2006). The model establishes trees with an initial diameter at breast height ($DBH_{m,1}$) equal to 0.6 cm (the diameter of typical nursery stock) and an initial stand density. Tree *DBH* increases annually as a function of $DI_{m,y}$ and the estimated intraspecific competition in the stand. To estimate intraspecific competition each year, a crown diameter (*CD*) and crown competition factor (*CCF*, the percentage of the ground area occupied by the total cross-sectional crown areas of all trees) are calculated following Čavlović et al. (2010) as:

$$CD_{m,y} = 0.311 + 0.177 \times DBH_{m,y} \tag{5.3}$$

$$CCF_{m,y} = \frac{SD_{m,y-1} \times (\pi \times {CD_{m,y}}^2/4)}{10000} \times 1.27 \times 100 \text{ ,} \tag{5.4}$$

where $SD_{m,y-1}$ is the stand density in year *y-1*. *CCF* is then used to calculate a growth ratio (*GR*) following Schlesinger (1996) as:

$$GR_{m,y} = \min\left(1,\ 1.411 - \left(0.00485 \times CFF_{m,y}\right) - \frac{7.643}{CCF_{m,y}}\right) \tag{5.5}$$

The predicted growth in *DBH* for year *y* on map unit *m* is then calculated as:

$$DBH_{m,y+1} = DBH_{m,y} + DI_{m,y} \times GR_{m,y} \tag{5.6}$$

Tree height (*H*) was estimated following Šálek and Hejcmanová (2011) as:

$$H_{m,y} = -21.2551 + 32.3733 \times \log\left(DBH_{m,y}\right) \tag{5.7}$$

As trees grow and intraspecific competition increases, tree thinning events are triggered in year *y* when GR_y becomes less than 0.8. Each thinning event reduces stand density by removing a fixed proportion of trees, thereby reducing *CCF* in year *y+1*, increasing *GR*, and allowing *DBH* to grow at a faster rate. Thinning events effectively maintain *CCF* between 75 and

125 and *GR* between 0.75 and 1.0. Doyle thousand board-foot (Doyle-MBF) volume of harvested trees was calculated from *DBH* using USDA Forest Service volume tables and a conservative form class of 78 (Mesavage and Girard 1946).

Alley crop yield

Average maize, soybean, and wheat (*Triticum* sp.) yields for each county were obtained from USDA NASS (2016b). These three species are the most common species used in temperate AC experiments (Chapter 2). Ten-year mean values were calculated for each county to remove variability caused by market and climate fluctuations. For maize and soybean, the ten most recent years (2007-2016) were used. Wheat yield data for 2008-2016 were unavailable for most counties, so data from the ten prior years (1998-2007) were used. To estimate monoculture crop yield for each map unit m, a scaling procedure via $\overline{NCCPI_c}$ analogous to the approach for cash rent values was used. Some counties had missing crop yield data. Missing data was estimated using linear regression models of crop yield between species (Fig. B.5), or, if all crop yield data was missing, then using linear regression models of crop yield and $\overline{NCCPI_c}$ (Fig. B.6).

To estimate the trajectory of alley crop yields following tree establishment, data from all temperate and subtropical AC studies that report relative yield of maize, soybean, or wheat were extracted from the database of AC literature created in Chapter 2 (Tables B.1-B.3). Studies that report alley crop yield but did not have a monoculture crop control, and therefore could not estimate relative yield, could not be included. Furthermore, studies that report relative yield without accounting for the uncropped area within tree rows and provided no data on the size of the uncropped area could not be included. For each crop species, a linear regression was fit between relative yield and years since tree planting. The resulting regression models were used to discount the monoculture crop yields on each map unit m and create an estimated yield time series for the duration of the black walnut rotation in AC. The yield time series was then converted into a potential cash rent time series for each crop using linear regression models between average county-level cash rent and yield values (Fig. B.7). The cash rent income for alley crops in AC was calculated as the maximum value of the potential cash rents of the maize-soybean mean, wheat, and pastureland. Pastureland cash rent values were obtained from USDA NASS (2016b) and scaled for each map unit m using the same scaling procedure via $\overline{NCCPI_c}$ as for cropland rent values. Missing county values for pastureland cash rent were estimated using a linear regression model with county cropland cash rent values (Fig. B.8). Pastureland rent was assumed unaffected by the presence of trees (Garrett et al. 2004).

PF and AC economic parameters

Parameters supplied to the black walnut model in addition to the DI_m trajectory were taken primarily from Godsey (2006), Yemshanov et al. (2007), and Schultz and DeLoach (2004) (Table B.4) unless otherwise noted below. Initial stand spacing for PF was 3.7 x 3.7 m, which is typical of black walnut PF across North America. Initial stand spacing for AC was 3.4 x 9.8 m, which was the mean spacing of systems in the literature used to develop the alley crop yield trajectories. In addition to the trees, an herbaceous groundcover was established within PF. Seedling cost of inexpensive, unimproved seedlings was used since evidence suggests negligible growth differences between unimproved and improved seedlings (Ares and Brauer 2004). Trees dying during establishment were not replanted. The effect of fertilization on black walnut growth is likely small for young trees (Nicodemus et al. 2008) and negligible in the long term (Pedlar et al. 2006). Therefore, no fertilization costs were included for PF or AC. No chemical site preparation costs were included in either system since land coming out of row-crops can be assumed weed-free. Within-row weeds were controlled using herbicides in years 1-14, and the herbaceous groundcover in PF was mowed during years 1-5. Removing lateral branches in black walnut is critical to maintain timber quality and value (Schlesinger and Weber 1987). The pruning labor requirement in AC (P Scheercousse, pers. comm.) is higher than for PF since the lower stand density does not encourage as much self-pruning of branches. At each thinning and the final harvest, 70% of black walnut trees were sold as veneer quality logs. Given the strict quality requirements for veneer logs, the remaining 30% of trees were assumed to fail the quality control and were sold as sawlogs. Extension publications documenting historical select-grade veneer stumpage prices for logs greater than ~71 cm in diameter (Fig. B.9a) and sawlog stumpage prices (Fig. B.9b) were mined for data over the last 40 years in each state. The mean value of all years and states for each market was used as the model input. Prices for select-grade veneer logs were used as a more conservative estimate instead of prices for prime-grade logs. Prices for harvested logs with diameters less than 71 cm were discounted using data from the same extension publications (Fig. B.10). The model ran for a maximum of 200 years, at which time any unharvested trees were harvested regardless of size. Although black walnut can also produce a marketable nut, veneer- and nut-focused management regimes are very different (Schlesinger and Funk 1977, Garrett et al. 2011). Consequently, no nut production was included in the current model.

Economic evaluation and sensitivity analysis

The cropland rent ($R_{m,c}$) represents the average annual income received by a landowner from MSR operators for each map unit m in each county c. Black walnut PF or AC become economically competitive with MSR when the profitability of these alternative enterprises meets or exceeds the threshold of $R_{m,c}$. The long-term, heterogeneous cash flow of PF and AC cannot be compared directly to $R_{m,c}$, but first must be converted into a homogeneous cash flow over the same period, or an annual equivalent value (AEV), which is calculated as:

$$AEV = \frac{i \times NPV}{1-(1+i)^{-N}}, \tag{5.8}$$

where i is the discount rate, N is the total number of years, and NPV is the net present value of the heterogeneous cash flow. NPV is calculated as:

$$NPV = \sum_{y=0}^{N} \frac{R_y}{(1+i)^y}, \tag{5.9}$$

where R_y is the net cash flow in year y (Klemperer 1996). For each map unit m in each county c, there exists threshold discount rates $TDR_{PF,m,c}$ and $TDR_{AC,m,c}$ such that $AEV_{PF,m,c}$ and $AEV_{AC,m,c}$ are equal to $R_{m,c}$. A Levenberg-Marquardt non-linear least squares solver was used to solve for the TDR values via the *lsqnonlin* function in the *pracma* package in R.

To assess the impact of different model parameters on *TDR*, a sensitivity analysis was performed by varying parameters from the base level supplied to model for this analysis. A base level of 0.7 was used for *BWSI*. Median values of MSR rent and crop yields were chosen as base levels. Parameters were independently varied by ±60% in increments of 5%. All establishment and maintenance costs were scaled collectively, as were alley crop yields.

RESULTS

Suitability Indices

Both *NCCPI* and *BWSI* exhibited values across their entire range in a complex spatial pattern across the landscape (Figs. 5.1b and 5.1c). Correlation between county-level area-weighted means of *NCCPI* and *BWSI* was extremely low (Spearman correlation, $p < 0.01$, $r^2 = 0.19$) (Fig. B.11), indicating an opportunity for differential success among alternative systems.

Black walnut growth

A total of 12 publications provided useable data on *DBH* of field-grown black walnut. Data spanned from one to 109 years after tree establishment, with *DBH* ranging from 0.5 to 58.3 cm (Fig. 5.2). Significant estimates of each Korf model parameter were obtained, with high precision for the fitted model ($p < 0.02$, $r^2 = 0.78$). The scaled range of possible growth curves closely matched the range in observed data.

The final harvest year of black walnut ranged from 40 in AC and 43 in PF to 200 (the maximum number of years modeled). Map units with *BWSI* < 0.6, corresponding to soils that are “somewhat suited”, “poorly suited” and “unsuited” for black walnut (Wallace and Young 2008), were unable to grow trees to the desired final harvest diameter of 71 cm within 200 years. Map units with *BWSI* in 0.6-0.8, 0.8-0.975, and 0.975-1.0, corresponding to soils that are “moderately suited”, “well suited” and “very well suited” for black walnut had a median rotation length of 93, 59, and 44 years in PF, respectively. Both PF and AC reached the final harvest diameter with around 25 trees ha^{-1}. All PF systems that reached mature diameter earlier than 200 years underwent six thinning events, whereas AC only required four thinning events since its initial stand density was much lower. Example modeled trajectories of black walnut growth are shown in Figs. B.12 and B.13. At maximum *BWSI*, revenue from thinning events contributed around twice as much as revenue from the final harvest to the *AEV* of PF or AC. The relative importance of thinnings increased as *BWSI* decreased since lower growth rates push back the final harvest.

Alley crop yields

Mined literature provided relative yield data for a total of 93 site-crop-year combinations. Data spanned from one to 23 years after tree establishment, and relative yields ranged from 0.14 to 1.05. Maize, soybean, and wheat all exhibited significant declines in relative yield with tree age ($p < 0.01$) (Fig. 5.3). The largest yield declines were observed in maize, then soybean, and finally wheat with little yield reduction over time.

Rental income from alley crops in AC generally utilized the maize-soybean mean for the first 7-11 years, switched to wheat until year 10-44, and then switched to pastureland for the remaining years of the black walnut rotation. At maximum *BWSI*, alley crops contributed approximately one-third as much as the final harvest to the *AEV* of AC. The relative importance of alley crops increased as *BWSI* decreased, becoming effectively the sole contributor to *AEV* at extremely low *BWSI*.

Economic evaluation

Black walnut PF (Fig. B.14) and AC (Fig. 5.4) exhibited competitive *TDR*s in many regions across the four states studied. The higher the *TDR*, the more competitive the alternative system is with MSR. Therefore, the percentage of cultivated land where PF or AC outcompeted MSR (i.e. where AC or PF has a higher *AEV* than MSR) increased with decreasing *TDR* (Fig. 5.5a). Map units with negative *TDR* were automatically classified with MSR being the most competitive system and removed from further analyses. Area-weighted mean values of TDR_{PF} and TDR_{AC} were 5.4% and 6.9%, respectively. Across all map units that had a $TDR_{PF} > 0$ and $TDR_{AC} > 0$, TDR_{AC} was an average of 2.7 percentage points higher than TDR_{PF}, representing the additional economic value generated by the alley crops.

In an example scenario with a selected *TDR* of 5%, PF and AC outcompeted MSR on 17.0% and 23.4% of cultivated land, respectively (Fig. 5.5a). The geographic distribution of this area was visualized as an example of target regions for PF and AC for a given *TDR* (Fig. B.15). The economic competitiveness of PF and AC was not correlated with *NCCPI* (Fig. 5.5b).

Instead, cultivated land at the high and low extremes of *NCCPI* contained the lowest proportion of land where PF or AC was competitive.

Sensitivity analysis

From the baseline set of parameters used in this analysis, *TDR* was most sensitive to changes in *BWSI* (Fig. B.16). A ~4% change in *BWSI* caused an approximately 1 percentage point change in *TDR*. Sensitivity of *TDR* to all other model parameters was less than ±5 percentage points across the parameter ranges of ±60%. Results were similar for AC and PF. The second most influential model parameter was veneer stumpage price, with a ~17% change in price driving a 1 percentage point change in *TDR*. Sensitivity to all model parameters was monotonic except for harvest *DBH* and initial stand density, which had clear maxima.

Illustrative counties

Results from four counties with varying *NCCPI* and *BWSI* were visualized at higher resolution to illustrate contrasting examples (Fig. 5.6). Perry County, MO had low *NCCPI* and high *BWSI*, resulting in some of the highest observed values of TDR_{PF} and TDR_{AC}. However, finer scale analysis revealed that *BWSI* takes an unfavorable shift in the northeast portion of the county, which lies in the flood plain of the Mississippi River. While this area has similarly low *NCCPI*, unsuitable black walnut growth prevented PF or AC from outperforming MSR. This demonstrates how certain landforms can influence the competitiveness of PF and AC counter to the prevailing conditions within a county. Both *BWSI* and *NCCPI* are high across Stark County, IL. Here, local variation in soil type and topography influenced the competitiveness of PF and AC at a much finer scale. Map units with high *BWSI* drove fast tree growth and a strong economic return that outcompeted MSR even where *NCCPI* is high. Coles County, IL offered little opportunity for PF or AC, with high *NCCPI* and low *BWSI* across the county. While a central valley did have a high *BWSI*-low *NCCPI* combination that would have likely resulted in favorable *TDR*s, this area is currently uncultivated. Finally, even though MSR was relatively uncompetitive in DeKalb County, IN, low black walnut growth rates prevented PF or AC from becoming suitable alternatives beyond just two small areas.

DISCUSSION

Our results project strong economic competitiveness of black walnut PF and AC with MSR. High *TDR*s were found on both marginal and ideal MSR soils (Fig. 5.5b), confirming that the marginal land concept is inadequate in identifying target regions for PF or AC. Instead, black walnut growth rate was the central driver of PF and AC competitiveness (Fig. 5.6). These results demonstrate that the soil suitability of alternatives is more important than MSR productivity in determining optimal land-use allocation. A shift away from the current MSR-centric perspective in defining target regions for land-use alternatives is necessary.

Overall, our results likely underestimate the potential of PF and AC since we did not consider the economic value of enhanced non-provisioning ecosystem services, such as carbon sequestration, reduction of greenhouse gas emissions, decreased soil erosion, and soil nutrient retention (Rhodes et al. 2016). Furthermore, while no direct support payments to landowners were included in the analysis, MSR cash rents are still indirectly inflated by government subsidies to farmers. Our analysis also only included existing MSR land, although substantial areas of pastureland would likely be more profitable as black walnut AC with hay or silvopasture. For example, much of central Perry County has high *BWSI* but is currently in pasture or hay rather than row crops (Fig. 5.6). Incorporating geospatial data that identifies environmentally sensitive areas (SooHoo et al. 2017) or the current extent of existing agroforestry practices (Herder et al. 2017) could further hone the identification of target regions for MSR alternatives.

Accounting for climate change would also likely increase the relative profitability of PF and AC over MSR. Substantial climate change impacts are projected over the time frame of black walnut rotations (IPCC 2014). Impacts are expected to reduce end-of-century MSR yields by ~70% (Mistry et al. 2017). In contrast, temperate AC can stabilize crop performance by moderating drought (Nasielski et al. 2015), reducing erosion and improving soil fertility (Udawatta et al. 2008, Torralba et al. 2016), and reducing the impact of pest outbreaks (Stamps et al. 2002). Hardwood tree productivity is also expected to decrease over the next century due to climate change, although predicted changes are much smaller than those for crops, up to just 20% (Jiang et al. 2015).

The black walnut growth projected here corresponds well to results from previous studies (Schultz and DeLoach 2004, Yemshanov et al. 2007). One major weakness of prior studies, however, is that fixed thinning and harvest years were assumed across all scenarios. This permits harvest volume, but not harvest timing, to affect profitability. The wide range of growth rates examined here necessitated the use of growth-triggered management events. Furthermore, the non-monotonic sensitivity of *TDR* to harvest *DBH* and initial stand density (Fig. B.16) reaffirm the potential for improving timber profitability via management optimization. The aim of our analysis, however, was not to examine optimal economic strategies, but rather to compare land-use alternatives under standard management.

The decline in maize relative yields in the reviewed literature corresponds well to theory since maize utilizes a C4 photosynthetic pathway and cannot tolerate the shade created by maturing trees. In contrast, soybean, which utilizes a C3 pathway, performs better as an alley crop (Reynolds et al. 2007). The low yield decline in wheat is driven by its complementary phenology to most tree species (Dufour et al. 2013). The compiled literature data provides a first approximation of AC relative yield trajectories, but further research permitting the development of more complex models based on tree species and biometrics is critical. Biophysical agroforestry models (Malézieux et al. 2009) and systematic experimental designs (Vanclay 2006, Leakey 2014) will be indispensable tools for evaluating tree-crop interactions in future research.

The consistently higher profitability of AC compared to PF was driven by a range of advantages such as reduced intraspecific competition, lower establishment costs, and earlier revenue from thinnings. Nevertheless, both alternatives studied here were relatively simple. There are many known methods of increasing the profitability of PF and AC. For example, interplanting with nitrogen-fixing trees or shrubs increased black walnut *DBH* by 31-351% after 13 years (Schlesinger and Williams 1984). Mixed-species systems can accumulate higher biomass (Piotto 2008) and be more drought resilient (Pretzsch et al. 2013) than single-species systems. Furthermore, leveraging high value fruit or nut trees in AC can reduce the time to financial maturity and diversify farm revenue streams (Lovell et al. 2017).

While several economic metrics can be used to compare land-use alternatives, *AEV* was chosen here because of the robust estimates available of MSR cash rent (2016b), which serve as a direct comparison for *AEV*. The examples presented in Figs. 5.5b and B.15 utilized a *TDR* of 5%. While this rate is rather high for long-term timber investments, it is typical of the minimum returns required by institutional investors and is, therefore, representative of the rate of return required to drive investment into alternative land uses such as PF and AC (Yemshanov et al. 2007).

One important assumption of our approach is that *BWSI* linearly scales the literature-derived black walnut growth trajectory. Since *BWSI* was never robustly validated against field growth data (Wallace and Young 2008), this relationship is uncertain. The range of modeled growth trajectories and literature-derived data gives us confidence in the chosen method (Fig. 5.2). Nevertheless, the sensitivity analysis here and that of others (Niu and Duiker 2006) indicate that improving our understanding of how soil characteristics influence tree growth is critical. The paucity of soil-based growth models for species other than black walnut is the primary hurdle to applying our approach more broadly, although Jiang et al. (2015) have recently pushed the boundaries to include a wide range of North American species.

Widespread environmental issues caused by MSR demands the evaluation of potential alternatives. Black walnut PF and AC displayed strong potential as economically competitive land-use alternatives, with target regions identified across all MSR productivity class. Restricting the evaluation of land-use alternatives to lands marginal to MSR may miss substantial opportunities for highly profitable alternatives on productive MSR land. Our novel, high-resolution approach offers a robust economic tool to enhance profitability of landowners and investors and drive adoption of sustainable agricultural land-uses.

FIGURES

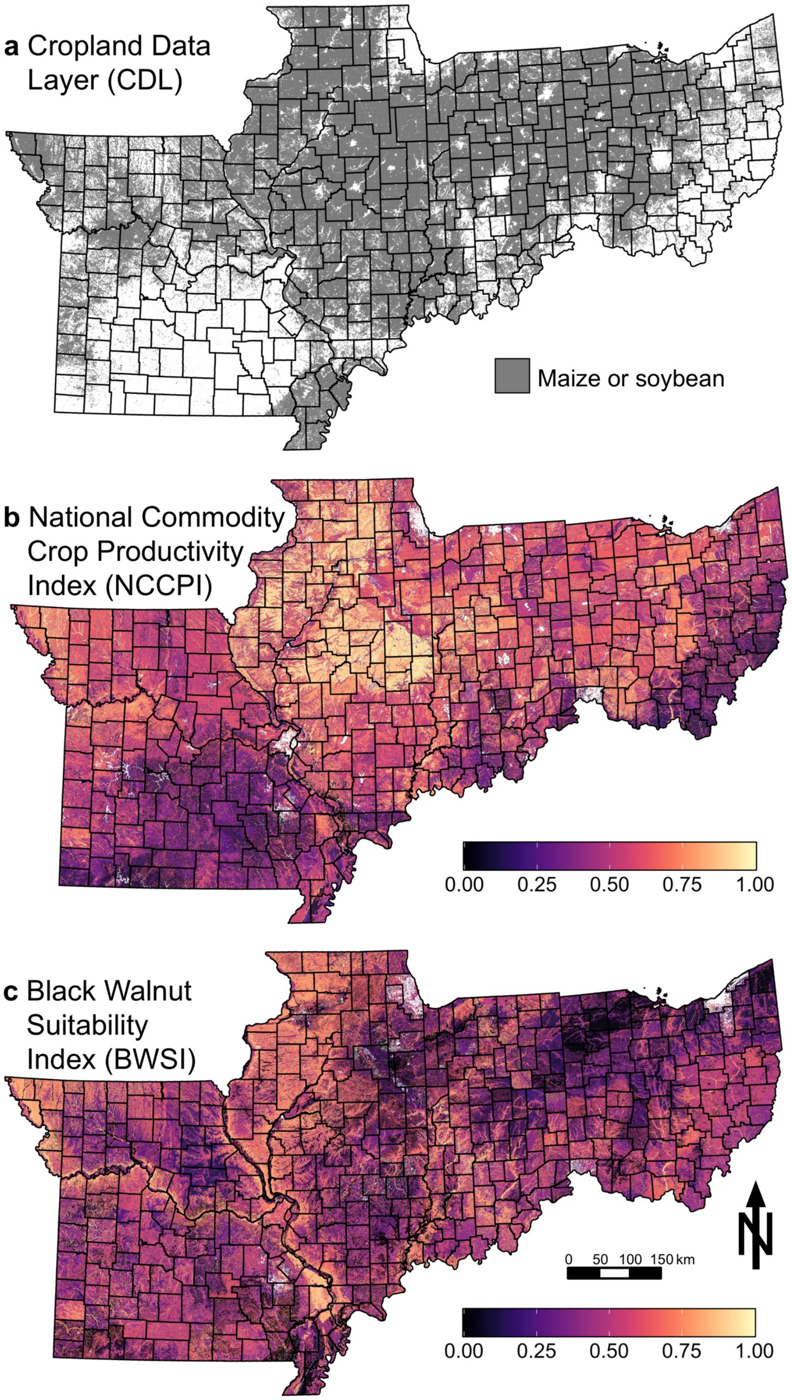

Figure 5.1 Maps of spatial input variables to the model: (a) 2016 Cropland Data Layer (CDL) (USDA NASS 2016a), (b) National Commodity Crop Productivity Index (*NCCPI*) (Dobos et al. 2012), and (c) Black Walnut Suitability Index (*BWSI*) (Wallace and Young 2008).

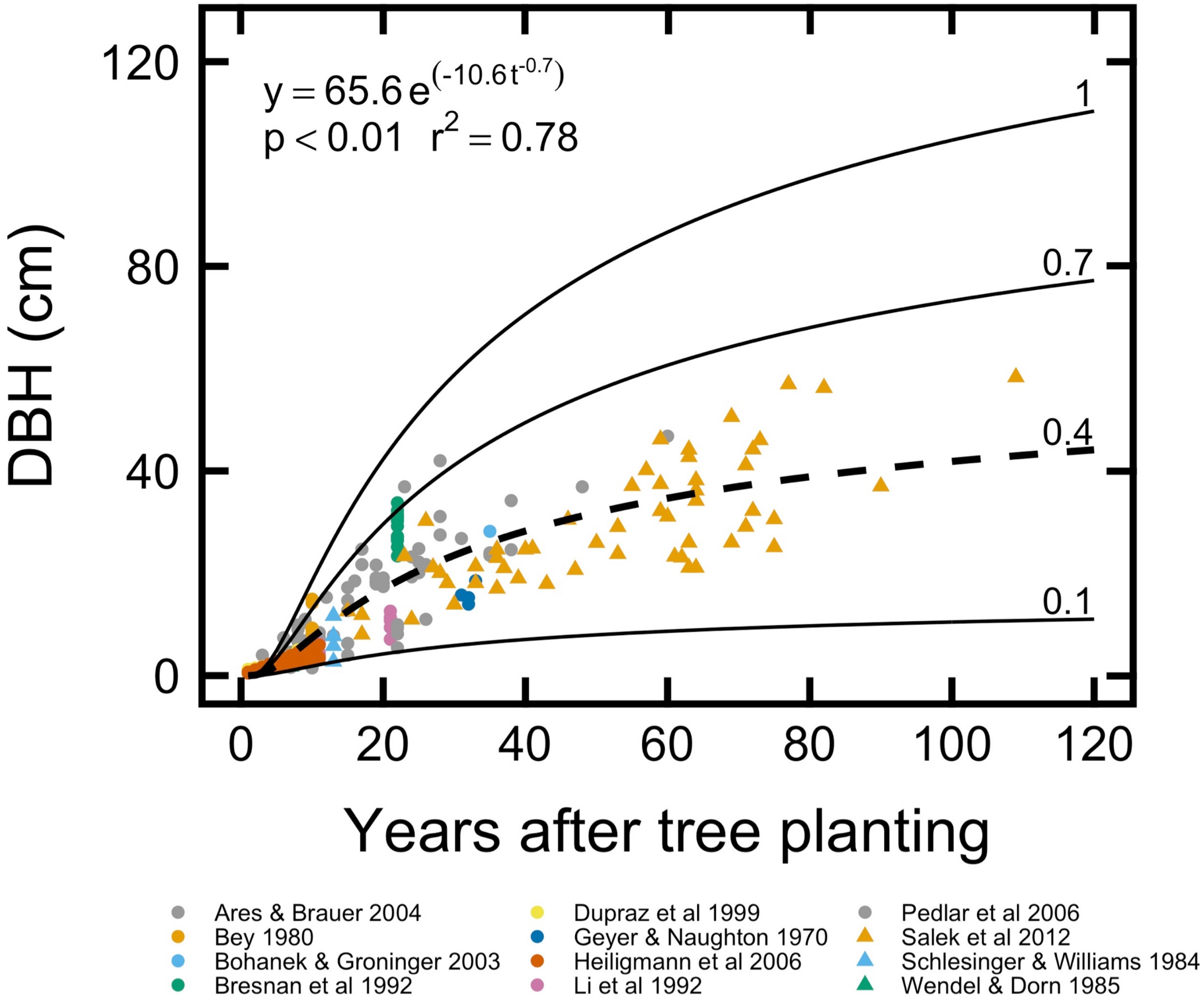

Figure 5.2 Growth of black walnut *DBH* reported in the literature (Geyer and Naughton 1970, Bey 1980, Schlesinger and Williams 1984, Wendel and Dorn 1985, Bresnan et al. 1992, Li et al. 1992, Dupraz et al. 1999, Bohanek and Groninger 2003, Ares and Brauer 2004, Heiligmann and Schneider 2006, Pedlar et al. 2006, Šálek et al. 2012). The dashed line is the Korf fitted curve of the literature data, with the equation shown. This literature fit was taken has representing a *BWSI* of 0.4, which is the area-weighted mean *BWSI* of all land in the four states studied. Black walnut growth in the model was then scaled from the Korf fitted curve by *BWSI*, as demonstrated by the examples (solid lines) labeled by the *BWSI* they represent.

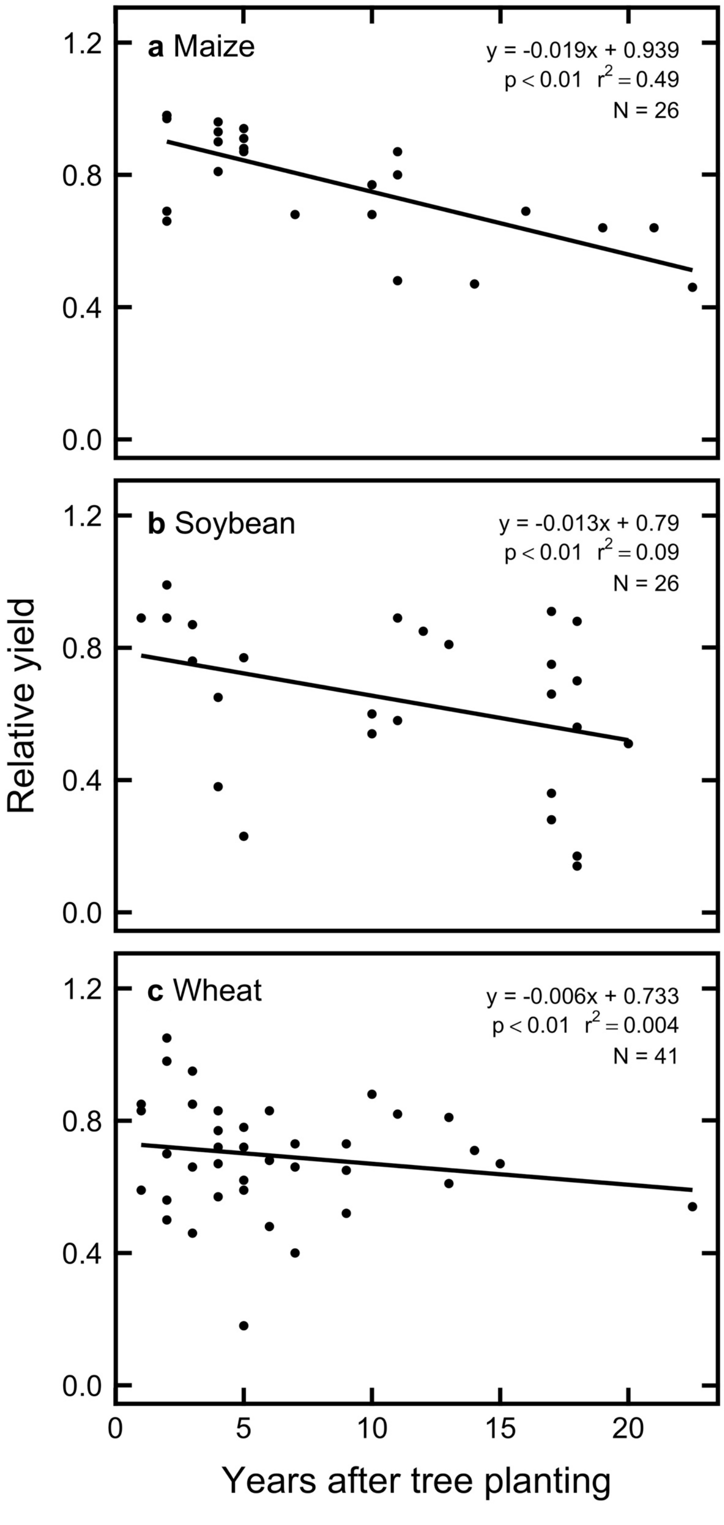

Figure 5.3 Literature values of (**a**) maize, (**b**) soybean, and (**c**) wheat yield in temperate and subtropical AC relative to monoculture controls. Each point represents one site-year.

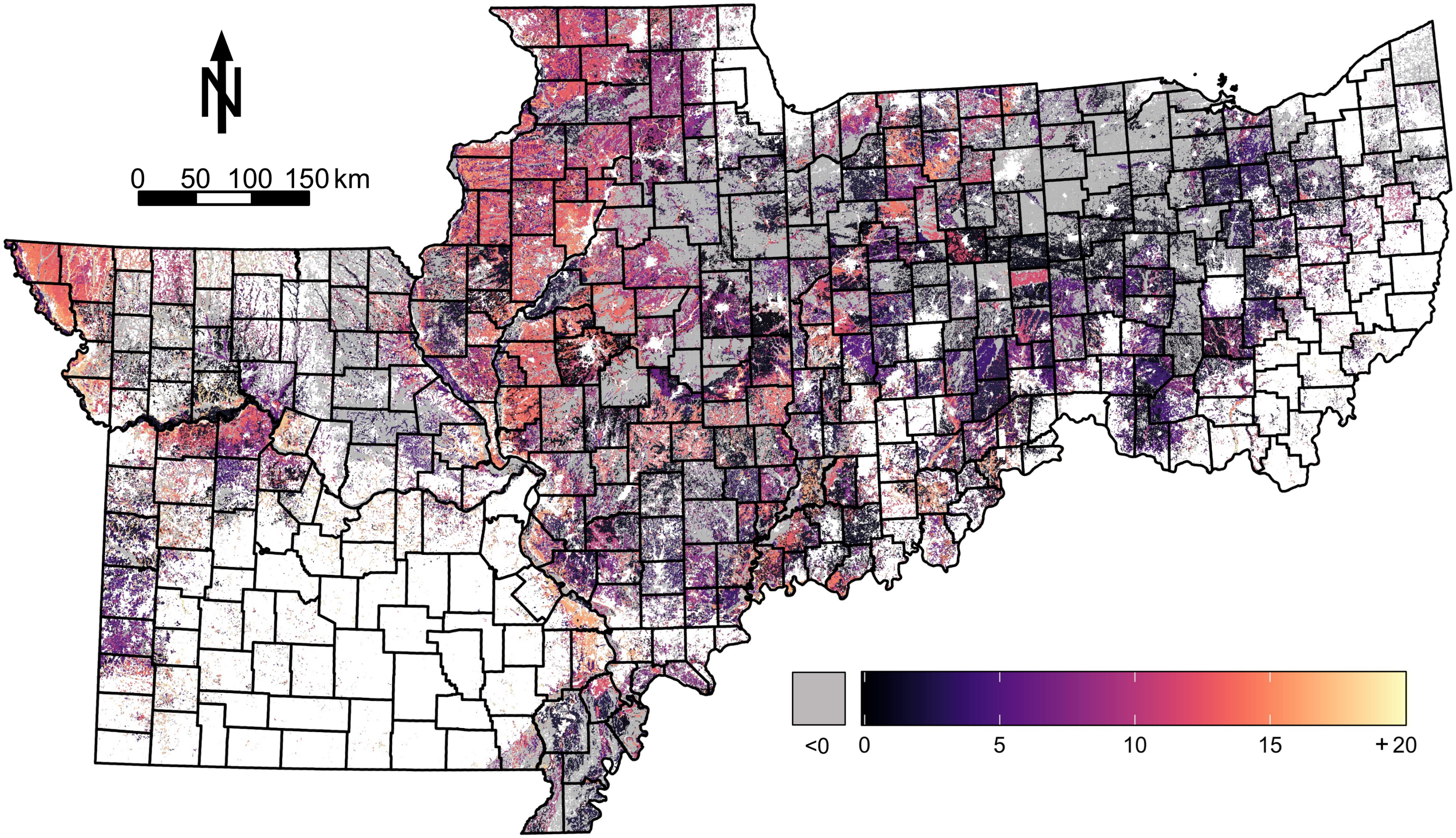

Figure 5.4 Distribution of the threshold discount rate (TDR_{AC}) at which the annual equivalent value (AEV) of AC and MSR are equal. across the four states studied. Gray areas are cultivated land on which either $BWSI = 0$ or $TDR_{AC} < 0$. White areas are non-cultivated land.

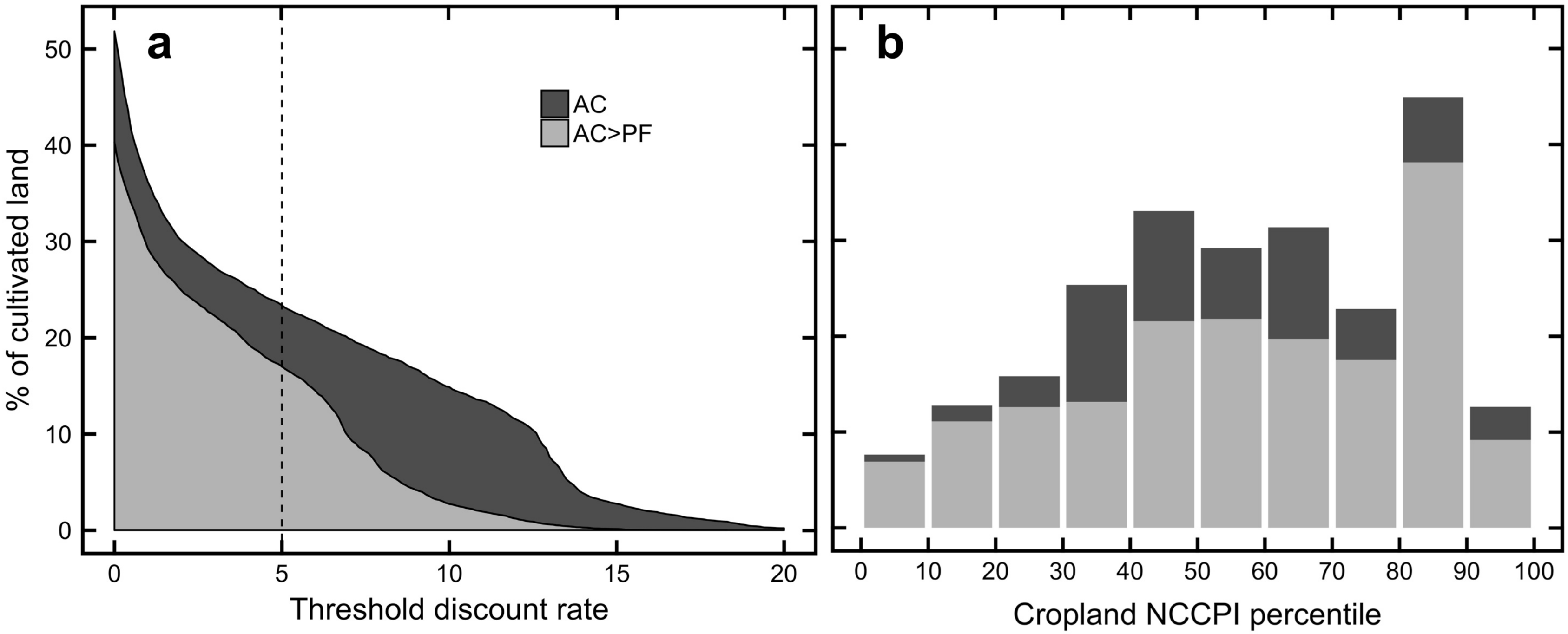

Figure 5.5 (**a**) Percentage of cultivated land as a function of *TDR*, on which black walnut AC and/or PF has a higher *AEV* than MSR. The dashed line indicates a *TDR* of 5%. (**b**) Percentage of cultivated land in each *NCCPI* class on which black walnut AC and/or PF has a higher *AEV* than MSR at a *TDR* of 5%. *NCCPI* classes are defined in terms of percentiles of *NCCPI* (e.g. the 0-10 *NCCPI* percentile includes the 10% of cultivated land with the lowest *NCCPI*). "AC>PF" indicates that AEV_{AC} and AEV_{PF} are both greater than MSR cash rent, but $AEV_{AC} > AEV_{PF}$.

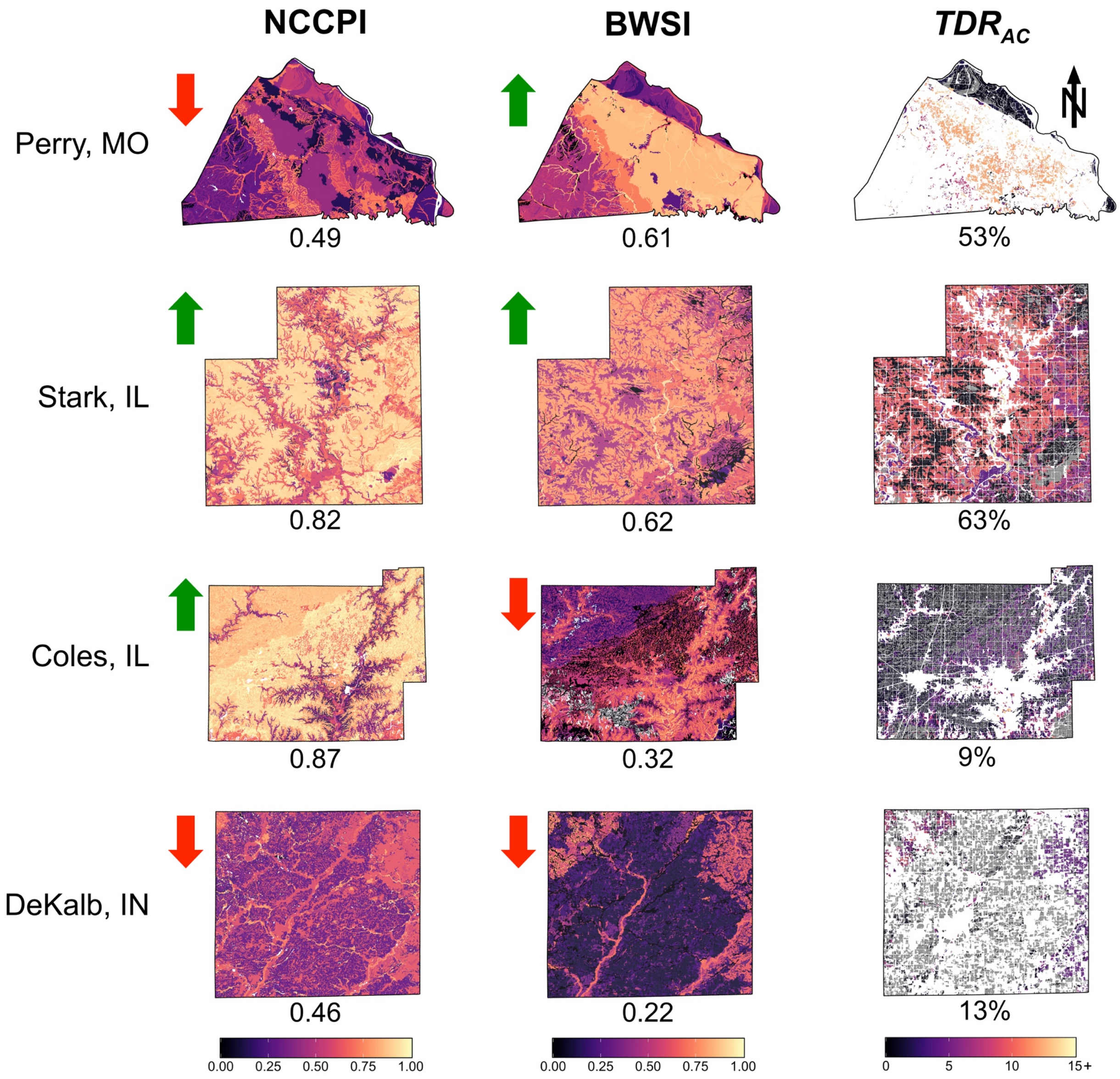

Figure 5.6 Comparison of example counties by their *NCCPI*, *BWSI*, and TDR_{AC}. Counties were selected to provide a range crop and black walnut suitability. Numbers under each *NCCPI* and *BWSI* map indicate the area-weighted mean for cultivated land. Numbers under each TDR_{AC} map indicate the percentage of cultivated land on which $TDR_{AC} \geq 5\%$.

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CHAPTER 6

CONCLUSION

This dissertation explores the frontiers of alley cropping (AC) as a transformative land-use alternative to row crop agriculture in the temperate zone. To capture the many facets of this complex land-use, each chapter approached AC from a different perspective – reviewing the existing research literature, developing a new conceptual framework for application, field experimentation to examine potential benefits, and economic modeling to identify target regions for adoption. Together, these perspectives demonstrate that AC is a highly diverse and complex practice that has many potential ecological and economic benefits.

The literature review of AC field experiments revealed that an immense number of tree and crop species have been used in AC around the world. While this diversity hosts a great breadth of opportunity, just a few tree and crops species dominated the scene in each climate zone. Furthermore, tree and crop functions have remained limited across all regions – trees primarily for timber and crops primarily for food. Though these gaps are certainly limitations of existing work, they should also be considered as opportunities for expanding the potential of AC around the world.

Building on the identified gaps in temperate AC, I examined how adding within-system tree diversity and emphasizing tree crops for food and fodder could improve climate change mitigation and adaptation potential. Since adding diversity and tree crops to AC tends to increase the complexity of the system, I emphasized mechanisms to maintain scalability and drive adoption. This analysis led me to identify four key considerations that could enhance the scalability of temperate AC when increasing diversity and leveraging tree crops: (1) strategic expansion from marginal lands via policy incentives, (2) well-developed tree crops compatible with the maize-soybean supply chain, (3) practical designs optimized for tree-crop interactions and mechanized management, and (4) complementary crop combinations that provide both early returns and long-term yields.

I then put theory to practice in the field by establishing a unique, side-by-side trial of a multispecies, food-producing AC and the maize-soybean rotation typical of the region. This trial served as an important exploration into the establishment and management of an AC system more diverse and complex than almost any found in the literature. In addition, the trial provided an opportunity to study the N cycle of a young, establishing AC. Studies of mature systems dominate the literature; the thorough analysis of the N cycle done here provides a novel perspective on the transition between row crops and AC. Overall, conversion to AC rapidly tightened the leaky row crop N cycle by reducing leaching losses and nitrous oxide fluxes.

Finally, I attempted to elucidate the most frequent question that landowners and farmers have about AC: Is it profitable? To approach this question, I decided to start with the simplest and most common AC system studied in the temperate zone to date: black walnut trees for timber with alleys of annual row crops. The economic model showed that both AC and black walnut plantation forestry are economically competitive with the conventional maize-soybean rotation on a substantial portion of land across the Midwest US. The high-resolution spatial analysis also permitted the identification of target regions where investment in AC should be prioritized. Unexpectedly, the spatial analysis demonstrated that there was no correlation between the competitiveness of AC and row crop productivity, indicating that the marginal land concept is inadequate in determining the full potential of agricultural land-use alternatives.

Although these results are informative, several key uncertainties remain. The field study provided new insight into the establishment phase of AC, but the future trajectory of N fluxes in this system are difficult to predict. As the trees mature and yields increase, management will also intensify, including increased fertilization. These higher N inputs could disproportionately increase N losses beyond the yield benefits, especially since little is known about how competition between the multiple species will affect long-term yields.

This same lack of understanding in the long-term interactions between species directly limited the scope of the economic analysis as well. The economic model was forced to focus on the relatively simple black walnut AC because of a lack of parameterization data for less common species and multispecies systems. Furthermore, the fact that most food-producing tree crops currently drive niche markets with high prices makes their profitability when implemented at scale difficult to predict.

Row crop agriculture continues to degrade many ecological functions across the temperate region. This dissertation affirms that effective AC systems are ready now for implementation as profitable enterprises with significant ecological benefits. Furthermore, there are many opportunities for future research to optimize the productivity and management of these complex systems. Most importantly, long-term operational trials, biophysical models, and innovative systematic experimental designs will be critical to improve our understanding of AC and inform agricultural policy.

APPENDIX A

SUPPLEMENTAL METHODS, TABLES, AND FIGURES FOR NITROGEN BUDGETS AND FIELD EXPERIMENT

SUPPLEMENTAL METHODS

Derivation of Working N Budgets

The range in wet N deposition for both systems was taken from the range in annual totals of wet N deposition (NH_4–N + NO_3–N) over 2005-2014 across all Midwestern sites of the National Atmospheric Deposition Program, and dry deposition was estimated as 70% of wet (McIsaac et al., 2002; USEPA, 2007). The range in the total soil N pool was assumed equal for both systems and derived from the range of soil organic carbon in Midwestern soils (NRCS, 2013) using a soil organic C:total N ratio of 10.0, which was measured in this study.

To construct the MSR N budget, the range of grain yields were taken from the range of county level yields in Midwest states over 2005-2014 (USDA NASS 2016). Retrieved values, reported in bushels per acre, were converted to units of kg ha^{-1} using standard NASS conversions for mass per volume and moisture content. Outliers in county yields were removed. Above- and belowground litter were calculated from yield data using typical harvest indices and root:shoot ratios (Prince et al. 2001). N content of grain, aboveground litter, and belowground litter were taken from Anderson (1988) for maize and Gelfand and Robertson (2015) for soybean. All yield and litter conversion factors used are provided in Table A.5. Plant uptake was estimated as equal to the sum of aboveground litter, belowground litter, and grain yield. The range of fertilizer N input was taken from the range of state-level fertilizer application means in Midwestern states over 2005-2014 (USDA NASS 2016). The range of N fixation in soybean was estimated via empirical relationships (Gelfand and Robertson 2015) using the ranges of N fluxes in litter and grain export. The ranges of inorganic N leaching in maize and soybean were taken as the 5th-95th percentiles in the MANAGE database using only entries for MSR (Christianson and Harmel 2015). The range of N_2O emissions in maize were taken from the 5th-95th percentiles in a comprehensive review by Decock (2014). The range of soybean N_2O emissions was manually mined from the same literature where maize values originated.

A similar approach primarily leveraging existing reviews of various components of the N cycle was used to construct the working N budget of temperate AC. For many N fluxes, reported data from all temperate agroforestry practices were used since insufficient data specifically on AC were available. Fertilization inputs were assumed equal to MSR range since maize is one of the most heavily fertilized crops. Inputs via N fixation were taken as the range of reported aboveground N fixation ranges in literature reviews of N fixation in legume food and fodder crops (Unkovich and Pate 2000, Carlsson and Huss-Danell 2003). These aboveground values (0-550 kg N ha^{-1} yr^{-1}) were increased by 50% to account for fixed N that remains in roots or transferred to soil (Høgh-Jensen et al. 2004). Crop yield N was estimated from the same sources, assuming total harvestable N in aboveground biomass is twice the amount of N fixed (Carlsson and Huss-Danell 2003). Tree yield N was estimated to range from 0 (at establishment) to a maximum value based on the highest protein yield in a temperate nut crop (USDA 2016, FAO 2017) (almond; 0.9 Mg protein ha^{-1}). This range was converted into N content using a Jones factor of 5.18 (Mariotti et al. 2008). Nitrous oxide emissions were estimated using values for all temperate/subtropical agroforestry practices in a review by Kim et al. (2016) (N=3). The range of N leaching in AC was estimated using values from three studies in which annual fluxes were either directly reported or could be reasonably estimated from intermittent data (Udawatta et al. 2002, Allen et al. 2004, Dougherty et al. 2009). To estimate the range of N uptake, the ranges of above- (N=10) and belowground (N=2) biomass carbon sequestration rates in all temperate/subtropical agroforestry practices were first compiled from Kim et al. (Kim et al. 2016). Above- and belowground ranges were summed and then converted to N uptake using an assumed C:N ratio of 50:1. Finally, this range (12-350 kg N ha^{-1} yr^{-1}) was summed with the range of values estimated for MSR to generate an AC total. Insufficient literature data and the highly dynamic temporal nature of AC prevented the determination of a reliable literature-based range of N litter transfer. The pool of aboveground C in standing woody biomass was estimated to range from 0 (at establishment) to the maximum value found for temperate AC in the review of Udawatta and Jose (2012). This value was scaled by the mean root:shoot ratio (0.49) found by the review of Kim et al. (Kim et al. 2016) to estimate the maximum belowground woody biomass in AC. Finally, this range of woody biomass C was scaled by a C:N ratio of 50:1 to determine the range of woody biomass N.

Site Design, Establishment, and Management

Soybean was planted in 80-cm rows in 2013 and 2015 on 17 May and 22 May, respectively. Maize was planted in 75-cm rows in 2014 and 2016 on 23 Apr. and 6 May, respectively. Glyphosate was applied in all years approximately one month after planting. Grain harvest was completed on 28 Oct. 2013, 18 Nov. 2014, 22 Oct. 2015, and 5 Oct. 2016. All MSR plots were conventionally tilled annually.

The AC system contained two types of alternating tree rows. One type of tree row contained standard-sized apple trees spaced 7 m apart, a grapevine planted next to each apple, and hybrid hazelnut shrubs (*Corylus* sp.) and raspberry brambles (*Rubus* sp.) between them within the row. The second type of tree row contained chestnut trees (*Castanea* sp.) spaced 3.5 m apart with black and red currant shrubs (*Ribes* sp.) between them within the row. All woody plants were planted between 12 May and 4 Jun. 2012, and the hay alley crop was planted on 1 Oct. 2012. Except for raspberries, which had a survival rate of 40% and were replanted on 19 May 2013, all species exhibited approximately 90% survival rates in the first year. Apples were grafted on 5 Apr. 2013. Herbicide (29.4% S-metolachlor, 11% atrazine, 2.94% mesotrione) was applied prior to planting on 24 Apr. 2012. In the second year, weeds were managed using a 1.4 m band of preemergent herbicide applied in the tree rows (oryzalin) on 7 May 2013 and the alley crop (prodiamine) on 17 May 2013. From 2014 on, no further herbicides were applied. On 31 Jan. 2013, Dutch white clover was broadcast within the 1.4 m band of bare soil under the tree rows to serve as a living mulch for weed control. From 2013 on, the 0.5 m on either side of the tree rows was mowed monthly using a flail mower. Weeds directly within the tree rows were managed monthly using a string trimmer. To lower soil pH into the range for optimal chestnut growth, ~300 g of granular elemental sulfur was spread around the base of each chestnut tree on 16 Apr. 2015 and 5 May 2016. The hay alleys were mowed monthly in 2013 to prevent weed growth, but no hay was harvested. In 2014-2016, hay was cut, baled, and removed four times each season. Small harvests were removed from the maturing woody crops each year. Beginning in 2014, all species were pruned each winter, except for raspberries, which were cut to the ground after the 2014 and 2016 seasons, and grapes, which were cut to the ground each year.

SUPPLEMENTAL TABLES & FIGURES

Table A.1 Monthly precipitation throughout the study (Illinois State Water Survey).

	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
year						mm						
2013-2014	95	159	90	9	17	91	39	34	41	77	35	100
2014-2015	111	209	221	39	87	126	61	46	36	31	43	92
2015-2016	154	233	107	80	164	31	112	190	23	31	89	83
2016-2017	96	181	113	105	137	48	84	34	64	10	60	148

Table A.2 Mean soil organic C and total N concentrations, bulk density, and mass of C and N by depth at the start of the study in 2012. Values in parentheses are standard errors of the mean.

Treatment	Depth	Organic C	Total N	Bulk density	Organic C	Total N
	cm	g kg^{-1}		g cm^{-3}	Mg ha^{-1}	
AC	0-10	21.3 (1.0)	2.06 (0.08)	1.28 (0.01)	26.6 (1.2)	2.6 (0.10)
	10-30	16.7 (1.3)	1.71 (0.10)	1.39 (0.02)	46.2 (3.6)	4.7 (0.28)
	30-50	11.3 (1.8)	1.17 (0.12)	1.35 (0.01)	30.2 (4.8)	3.1 (0.33)
	50-100	5.2 (0.7)	0.64 (0.05)	1.40 (0.02)	37.1 (4.8)	4.6 (0.34)
MSR	0-10	21.7 (0.3)	2.08 (0.01)	1.21 (0.03)	27.2 (0.4)	2.6 (0.01)
	10-30	16.8 (0.8)	1.67 (0.05)	1.37 (0.03)	46.4 (2.1)	2.6 (0.13)
	30-50	10.8 (1.5)	1.16 (0.09)	1.33 (0.01)	29.1 (4.0)	3.1 (0.24)
	50-100	5.2 (0.5)	0.65 (0.04)	1.41 (0.01)	37.1 (3.9)	4.6 (0.29)

Table A.3 Total yield, yield N composition, and woody biomass (prunings) removed each year. Values for hay yield and woody biomass are mass of dry matter. Values for fruit/nut yield are mass of raw harvested product. Values in parentheses are standard errors of the mean.

	Yield	Yield				Woody biomass			
	%N	2013	2014	2015	2016	2013	2014	2015	2016
		kg ha^{-1} yr^{-1}							
AC									
Apple	0.8[1]	-	-	-	32.4 (11.9)	-	14.1 (1.6)	6.6 (0.4)	78.4 (41.4)
Hybrid Hazelnut	3.0[2,3]	-	-	25.8 (2.3)	32.9 (2.9)	-	36.2 (3.4)	-	60.7 (5.5)
Raspberry	1.1[4]	35.9 (4.3)	73.9 (1.1)	-	85.6 (1.3)	-	327 (16.9)	-	379 (45.1)
Grape	1.1*	416 (30.9)	20.5 (5.2)	-	-	-	241 (7.3)	28.7 (1.4)	60.2 (6.9)
Hybrid Chestnut	-[†]	-	-	-	-	-	8.1 (2.0)	38.0 (6.7)	123.4 (20.2)
Black Currant	1.1*	16.0 (2.1)	36.3 (8.8)	178 (19.3)	361 (4.4)	-	229 (26.2)	382 (25.3)	369 (17.3)
Red Currant	1.1*	27.7 (4.0)	93.7 (8.0)	132 (11.3)	103 (9.2)	-	33.3 (7.1)	62.8 (4.4)	-
Hay – grass	2.5 (0.3)	-	2730 (129)	5834 (276)	6912 (148)	-	-	-	-
Hay – clover	3.8 (0.2)	-	682 (32)	1458 (69)	1728 (37)	-	-	-	-
MSR									
Maize	1.4 (0.05)	-	13609 (495)	-	9934 (574)	-	-	-	-
Soybean	6.4 (0.04)	3298 (141)	-	4263 (227)	-	-	-	-	-

*Assumed equal to that of raspberry

[†] Not applicable

[1] (Hulme 1958)

[2] (Braun et al. 2009)

[3] (Midilli et al. 2000)

[4] (Rempel et al. 2004)

Table A.4 Estimated growth in above- and belowground woody biomass in AC by species and year. Aboveground biomass was estimated using measured basal stem areas and allometric relationships (Figs. A.2 and A.3). Belowground biomass was estimated from aboveground biomass using root:shoot ratios from destructive harvests in Mar. 2013 and literature values. N content of woody biomass was measured during destructive harvests in Mar. 2013. All values measured in this study unless otherwise noted.

	Woody biomass growth								**Woody root:shoot ratio**	**AG %N**	**BG %N**
	Aboveground				**Belowground**						
	2013	**2014**	**2015**	**2016**	**2013**	**2014**	**2015**	**2016**			
AC	kg ha^{-1} yr^{-1}										
Apple	3.4 (0.6)	19.4 (4.3)	59.7 (15.8)	120 (17)	1.9 (0.5)	13.3 (3.3)	32.3 (12.3)	62.7 (13.6)	0.78[5]	1.1[6]	0.9[6]
Hybrid Hazelnut	31.6 (7.5)	90.2 (22.1)	107 (24)	207 (41)	54.7 (15.1)	139 (44)	61.2 (47.8)	254 (83)	2.00[7]	1.0 (0.1)	1.8 (0.1)
Raspberry	159 (8.3)	426 (31)	283 (24)	344 (41)	293 (15.4)	633 (47)	-404 (34)	339 (41)	1.93[8]	0.9 (0.03)	1.5 (0.1)
Grape	120*	205	39.0	64.8	146	174	-296	35.2	1.36 (0.09)	0.7 (0.05)	1.3 (0.08)
Hybrid Chestnut	10.5 (3.3)	34.9 (8.5)	117 (41)	205 (49)	10.4 (5.4)	44.7 (14.1)	149 (67)	186 (81)	1.66[9]	0.8 (0.06)	1.1 (0.05)
Currant	142 (2.6)	294 (3.4)	416 (28.4)	368 (70.6)	137 (3.2)	238 (4.1)	133 (34)	-36.9 (85)	1.20 (0.09)	1.1 (0.08)	1.7 (0.1)
Total	*467* *(14)*	*1070* *(31)*	*1022* *(78)*	*1309* *(30)*	*643* *(19)*	*1242* *(36)*	*-325* *(25)*	*840* *(19)*			

*Biomass growth standard errors not available for grape

[5] (Liu et al. 2012)

[6] (Neilsen et al. 2001)

[7] (Braun et al. 2011)

[8] (Neocleous and Vasilakakis 2007)

[9] (Wang et al. 2006)

Table A.5 Conversion factors used to convert reported yields (USDA NASS 2016) to grain N export, aboveground litter N flux, and belowground litter N flux in MSR.

Conversion factor	Units	Maize	Soybean
Grain mass / volume	kg/bu	25.4	17.2
Grain moisture content	% moisture	15.5	12.5
Grain N content	% N	1.4	5.8
Harvest index	ratio	0.53	0.42
Root:shoot ratio	ratio	0.18	0.15
Shoot N content	% N	1.0	0.7
Root N content	% N	1.5	1.2

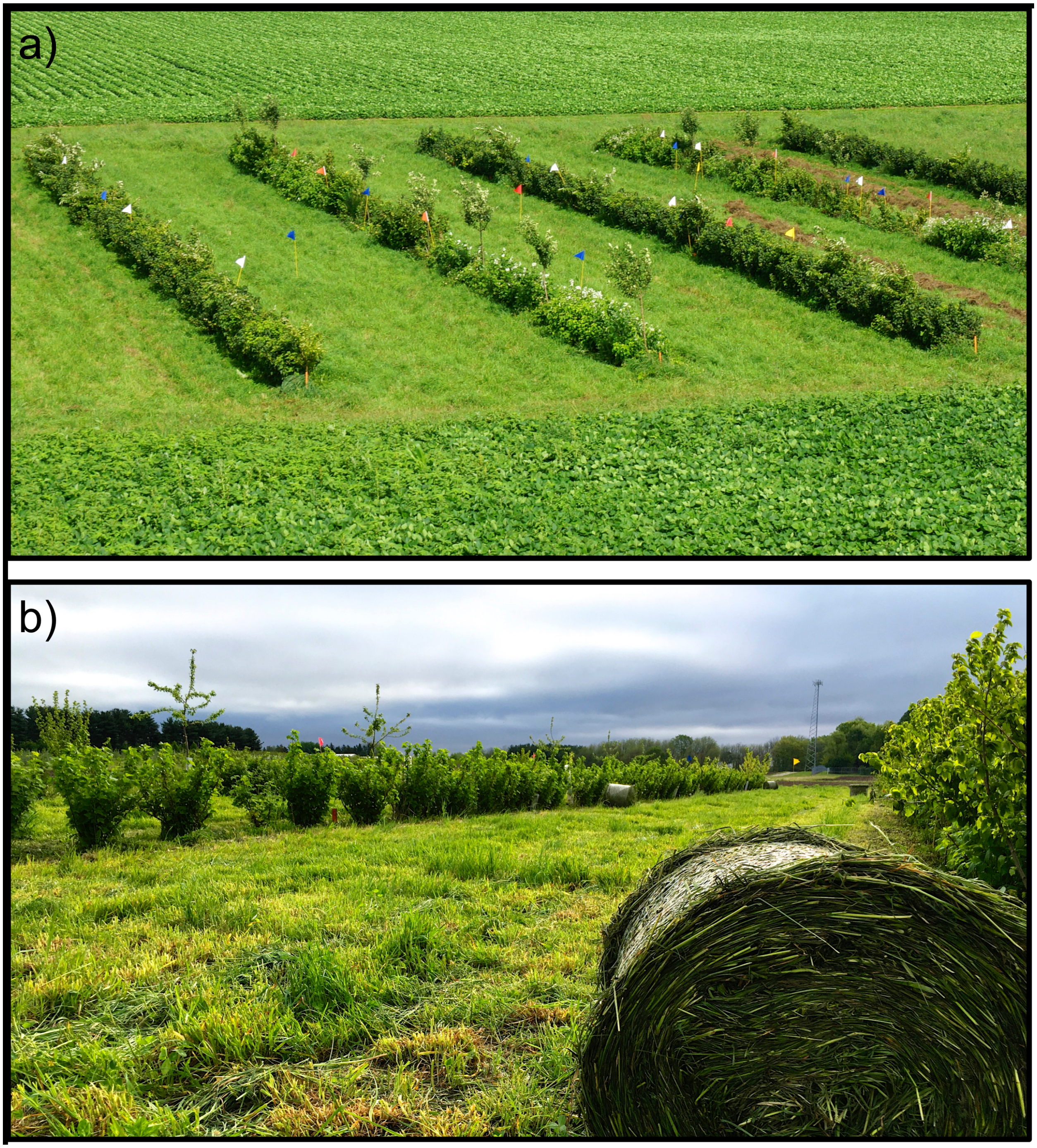

Figure A.1 (a) Aerial view of AC at the study site in 2015, with soybean plots in the foreground and background. (b) Early spring in AC at the study site, just after the first hay cutting and with leaves on tree species still emerging.

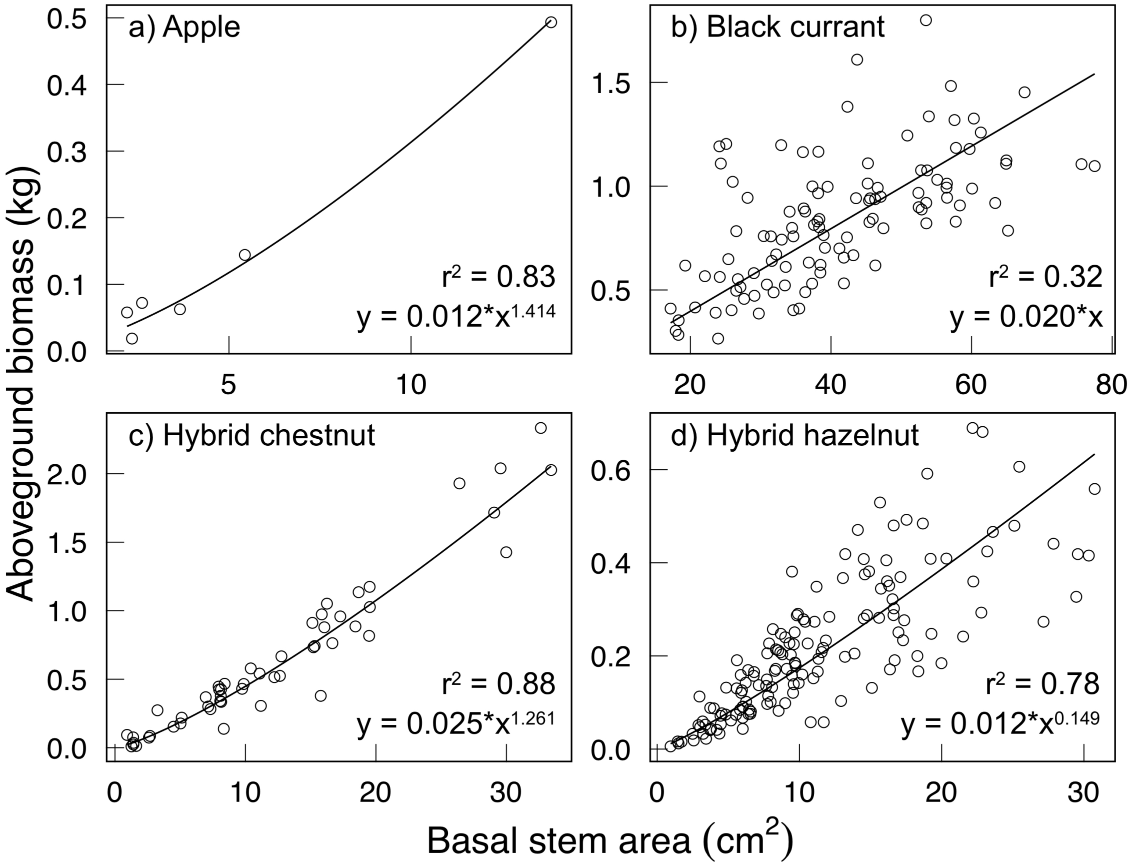

Figure A.2 Allometric relationships for (a) apple, (b) black currant, (c) hybrid chestnut, and (d) hybrid hazelnut used to estimate aboveground biomass. Relationships were constructed using pruning events and destructive harvests.

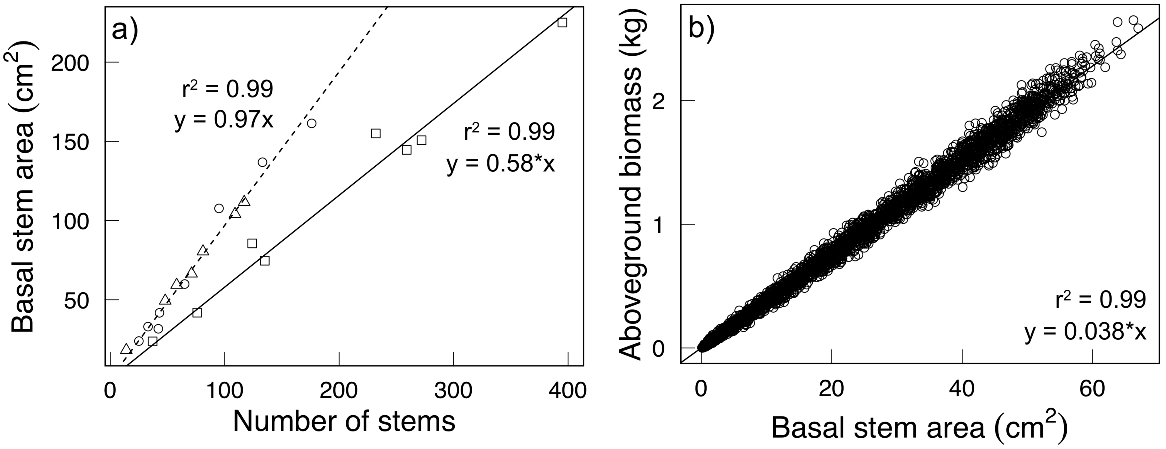

Figure A.3 Allometric relationships for raspberry used to estimate aboveground biomass. Relationships were constructed using pruning events and destructive harvests. (a) Taking caliper measurements on all raspberry stems to directly measure basal stem area was impractical due to the number of stems present. Instead, the number of stems was counted each year, and a relationship with basal stem area developed for each of the three raspberry varieties present. Two varieties (open circles and open triangles) exhibited the same relationship, whereas the third variety (open squares) had a lower slope. (b) The relationship between stem basal area and aboveground biomass was determined by measuring stem caliper and mass on a random sample of 100 stems and then randomly sampling and summing these measurements in groups of 1 to 50 stems (50 times for each group size).

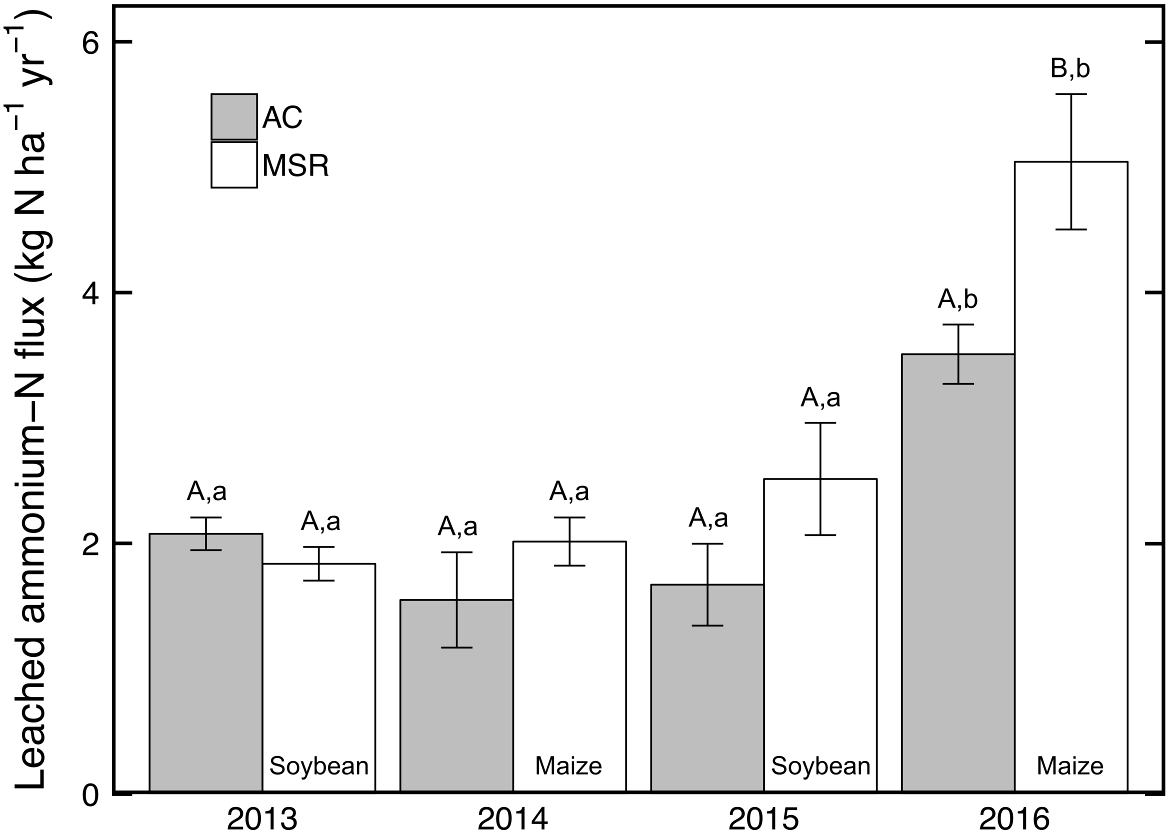

Figure A.4 Annual ammonium N leaching (May-May) at 50 cm soil depth using resin lysimeters for AC and MSR (mean ± SE) during 2013-2016. Treatment means within each year with the same capital letter, and means within each treatment across years with the same lowercase letter, are not significantly different. Maize was fertilized with 202 kg N ha^{-1}. AC was fertilized in 2015 and 2016 with 101 kg N ha^{-1}.

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APPENDIX B

SUPPLEMENTAL TABLES AND FIGURES FOR ECONOMIC MODEL

Table B.1 Compiled literature values of maize relative yield in temperate and subtropical AC compared to monoculture crop controls. Relative yield values are relative to the area of the entire AC system, thereby accounting for the uncropped area within tree rows.

Tree species	Year	Maize relative yield	Country	Citation
Populus deltoides x Populus nigra	10	0.77	Canada	(Reynolds et al. 2007)
Acer saccharinum	10	0.68	Canada	(Reynolds et al. 2007)
Populus deltoides x Populus nigra	11	0.48	Canada	(Reynolds et al. 2007)
Acer saccharinum	11	0.87	Canada	(Reynolds et al. 2007)
Populus euramericana	2	0.69	China	(Dai et al. 2006)
Populus euramericana	2	0.66	China	(Dai et al. 2006)
Alnus rubra	2	0.98	USA	(Seiter et al. 1999)
Robina pseudoacacia	2	0.98	USA	(Seiter et al. 1999)
Alnus rubra	2	0.98	USA	(Seiter et al. 1999)
Robina pseudoacacia	2	0.97	USA	(Seiter et al. 1999)
Alnus rubra	4	0.93	USA	(Seiter et al. 1999)
Robina pseudoacacia	4	0.96	USA	(Seiter et al. 1999)
Alnus rubra	4	0.90	USA	(Seiter et al. 1999)
Robina pseudoacacia	4	0.81	USA	(Seiter et al. 1999)
Alnus rubra	5	0.91	USA	(Seiter et al. 1999)
Robina pseudoacacia	5	0.87	USA	(Seiter et al. 1999)
Alnus rubra	5	0.94	USA	(Seiter et al. 1999)
Robina pseudoacacia	5	0.88	USA	(Seiter et al. 1999)
Paulownia elongata	7	0.68	China	(Newman et al. 1998)
Ziziphus jujuba	22.5	0.46	China	(Yang et al. 2016)
Miscellaneous hardwoods	10	0.77	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	11	0.80	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	14	0.47	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	16	0.69	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	19	0.64	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	21	0.64	Canada	N. Thevathasan, pers. comm.

Table B.2 Compiled literature values of soybean relative yield in temperate and subtropical AC compared to monoculture crop controls. Relative yield values are relative to the area of the entire AC system, thereby accounting for the uncropped area within tree rows.

Tree species	**Year**	**Soybean relative yield**	**Country**	**Citation**
Eucalyptus maculata	1	0.89	Brazil	(Franchini et al. 2014)
Eucalyptus maculata	2	0.89	Brazil	(Franchini et al. 2014)
Eucalyptus maculata	3	0.87	Brazil	(Franchini et al. 2014)
Eucalyptus maculata	4	0.65	Brazil	(Franchini et al. 2014)
Juglans nigra	17	0.75	Canada	(Manceur et al. 2009)
Carya illinoensis	17	0.91	Canada	(Manceur et al. 2009)
Populus deltoides x Populus nigra	17	0.28	Canada	(Manceur et al. 2009)
Acer saccharinum	17	0.36	Canada	(Manceur et al. 2009)
Juglans nigra	18	0.88	Canada	(Manceur et al. 2009)
Carya illinoensis	18	0.70	Canada	(Manceur et al. 2009)
Populus deltoides x Populus nigra	18	0.14	Canada	(Manceur et al. 2009)
Acer saccharinum	18	0.17	Canada	(Manceur et al. 2009)
Populus deltoides x Populus nigra	10	0.54	Canada	(Reynolds et al. 2007)
Acer saccharinum	10	0.60	Canada	(Reynolds et al. 2007)
Populus deltoides x Populus nigra	11	0.58	Canada	(Reynolds et al. 2007)
Acer saccharinum	11	0.89	Canada	(Reynolds et al. 2007)
Taxodium ascendens	2	0.99	China	(Huang and Xu 1999)
Taxodium ascendens	3	0.76	China	(Huang and Xu 1999)
Taxodium ascendens	4	0.38	China	(Huang and Xu 1999)
Taxodium ascendens	5	0.23	China	(Huang and Xu 1999)
Malus pumila	5	0.77	China	(Gao et al. 2013)
Miscellaneous hardwoods	12	0.85	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	13	0.81	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	17	0.66	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	18	0.56	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	20	0.51	Canada	N. Thevathasan, pers. comm.

Table B.3 Compiled literature values of wheat relative yield in temperate and subtropical AC compared to monoculture crop controls. Relative yield values are relative to the area of the entire AC system, thereby accounting for the uncropped area within tree rows.

Tree species	Year	Wheat relative yield	Country	Citation
Juglans nigra x Juglans regia	13	0.81	France	(Dufour et al. 2013)
Juglans nigra x Juglans regia	14	0.71	France	(Dufour et al. 2013)
Populus euramericana	2	1.05	China	(Dai et al. 2006)
Populus euramericana	2	0.98	China	(Dai et al. 2006)
Populus sp.	1	0.85	UK	(Burgess et al. 2005)
Populus sp.	2	0.70	UK	(Burgess et al. 2005)
Populus sp.	3	0.66	UK	(Burgess et al. 2005)
Populus sp.	4	0.57	UK	(Burgess et al. 2005)
Populus sp.	5	0.62	UK	(Burgess et al. 2005)
Populus sp.	6	0.68	UK	(Burgess et al. 2005)
Populus sp.	1	0.83	UK	(Burgess et al. 2005)
Populus sp.	2	0.70	UK	(Burgess et al. 2005)
Populus sp.	3	0.85	UK	(Burgess et al. 2005)
Populus sp.	4	0.77	UK	(Burgess et al. 2005)
Populus sp.	5	0.72	UK	(Burgess et al. 2005)
Populus sp.	6	0.68	UK	(Burgess et al. 2005)
Populus sp.	7	0.73	UK	(Burgess et al. 2005)
Populus sp.	4	0.83	UK	(Burgess et al. 2005)
Populus sp.	5	0.78	UK	(Burgess et al. 2005)
Populus sp.	6	0.83	UK	(Burgess et al. 2005)
Populus sp.	7	0.66	UK	(Burgess et al. 2005)
Taxodium ascendens	2	0.98	China	(Huang and Xu 1999)
Taxodium ascendens	3	0.95	China	(Huang and Xu 1999)
Taxodium ascendens	4	0.72	China	(Huang and Xu 1999)
Taxodium ascendens	5	0.18	China	(Huang and Xu 1999)
Paulownia elongata	11	0.82	China	(Chirko et al. 1996)
Jatropha curcas	9	0.52	India	(Mahmoud et al. 2016)
Jatropha curcas	9	0.65	India	(Mahmoud et al. 2016)
Jatropha curcas	9	0.73	India	(Mahmoud et al. 2016)
Ziziphus jujuba	22.5	0.54	China	(Yang et al. 2016)
Juglans regia	1	0.59	China	(Zhang et al. 2015)
Juglans regia	2	0.56	China	(Zhang et al. 2015)

Table B.3 (cont.)

Tree species	Year	Wheat relative yield	Country	Citation
Ziziphus jujuba	3	0.46	China	(Wang et al. 2014)
Ziziphus jujuba	5	0.59	China	(Wang et al. 2014)
Ziziphus jujuba	7	0.40	China	(Wang et al. 2014)
Ziziphus jujuba	2	0.50	China	(Zhang et al. 2013)
Ziziphus jujuba	4	0.67	China	(Zhang et al. 2013)
Ziziphus jujuba	6	0.48	China	(Zhang et al. 2013)
Miscellaneous hardwoods	10	0.88	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	13	0.61	Canada	N. Thevathasan, pers. comm.
Miscellaneous hardwoods	15	0.67	Canada	N. Thevathasan, pers. comm.

Table B.4 Black walnut model parameters. All US$ values are in 2016 US$.

Parameter	Units	Plantation forestry (PF)	Alley cropping (AC)
------------------ Establishment parameters ------------------			
Initial stand density	trees ha^{-1}	746	306
Groundcover establishment	US$ ha^{-1}	62	0
Seedling cost	US$ tree^{-1}	0.50	
Planting cost	US$ tree^{-1}	0.50	
Year 1 mortality	% of trees	5	
------------------ Management parameters ------------------			
Pruning labor efficiency	trees hr^{-1}	500 (1-X†)	100 (1-5), 30 (6-X)
Mowing	US$ ha^{-1} yr^{-1}	74 (1-5†)	0
Cost of labor	US$ hr^{-1}	15	
Chemical weed control	US$ ha^{-1} yr^{-1}	136 (1-14)	
Thinning intensity	% of trees	33	
------------------ Harvest parameters ------------------			
Veneer stumpage price	US$ Doyle-MBF^{-1}	3,315	
Sawlog stumpage price	US$ Doyle-MBF^{-1}	870	
Veneer log proportion	% of trees	70	
Harvest DBH	cm	71	
Maximum saleable log length	m	12.2	

*Numbers in parentheses indicate the years after tree establishment in which the expense is incurred.

†X denotes the year in which tree height equals twice the saleable log length.

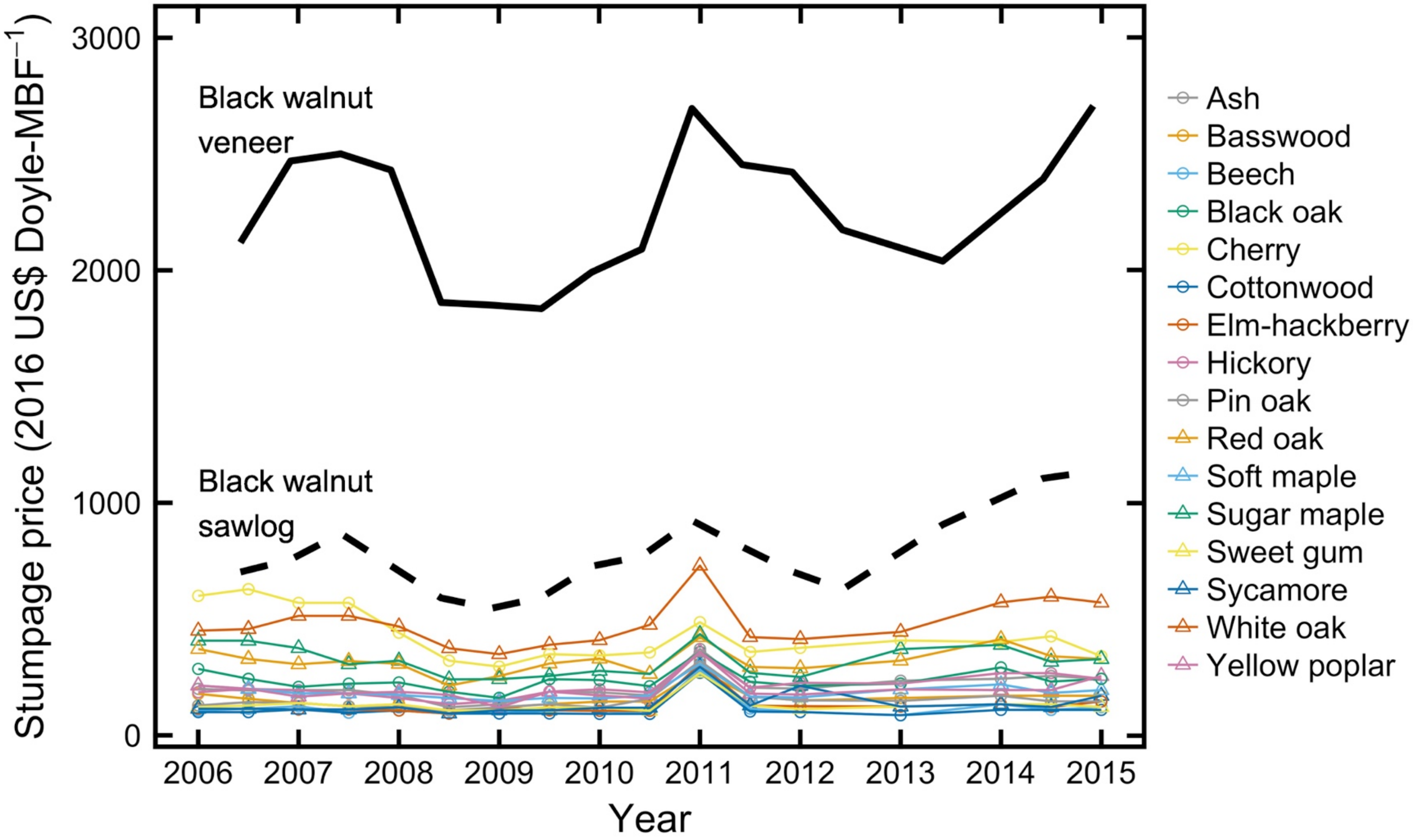

Figure B.1 Reported stumpage prices paid to Illinois landowners for sawlogs of various timber species. The dashed and solid black lines show the sawlog and select-grade veneer stumpage prices, respectively, for black walnut (IL DNR 2017).

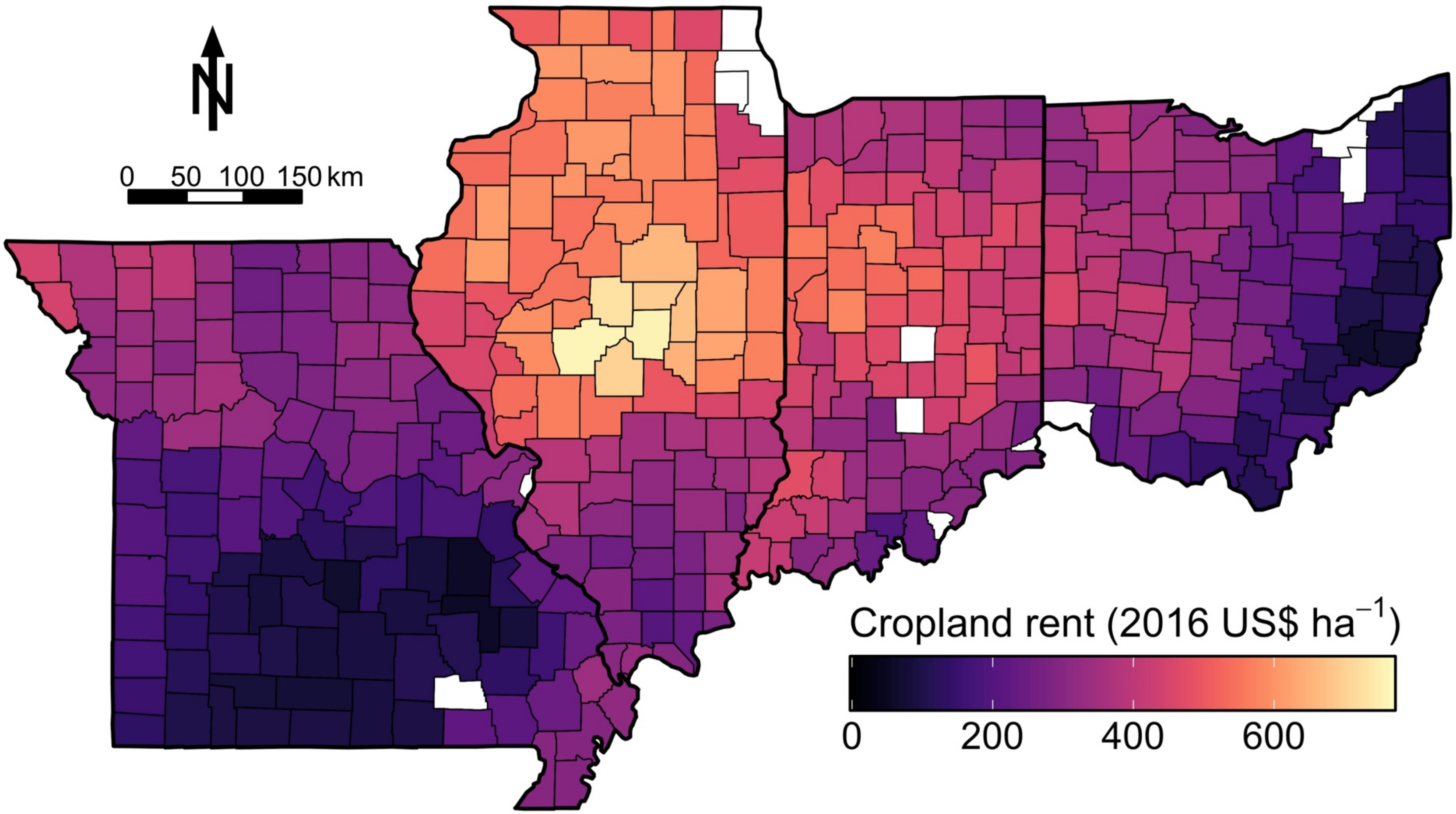

Figure B.2 County-level mean (2008-2016) cropland cash rent received by landowners (USDA NASS 2016). Data was not available for uncolored counties.

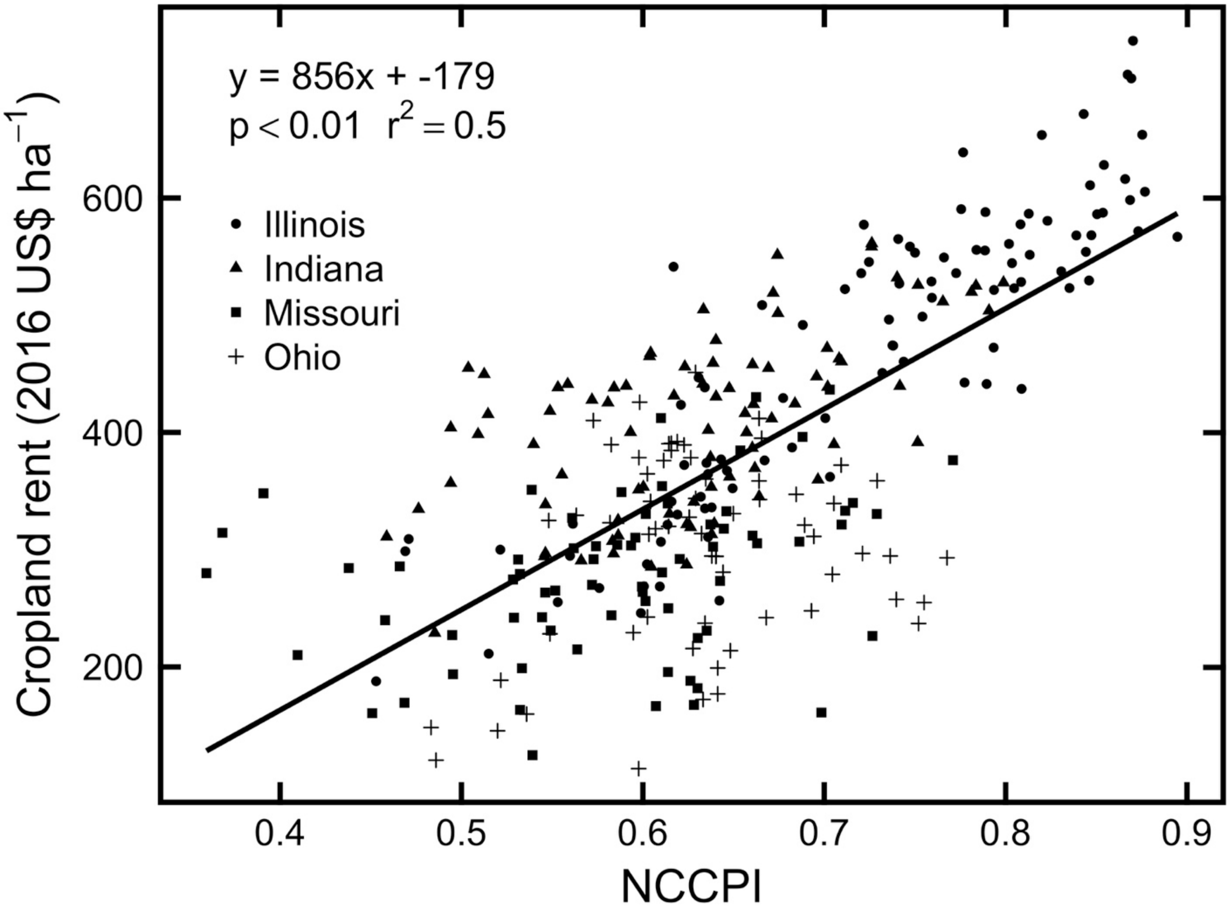

Figure B.3 Relationship between county-level mean (2008-2016) cropland cash rent (USDA NASS 2016) and the area-weighted mean of *NCCPI* on cultivated land (Dobos et al. 2012). Counties with less than 5% cultivated land were not included.

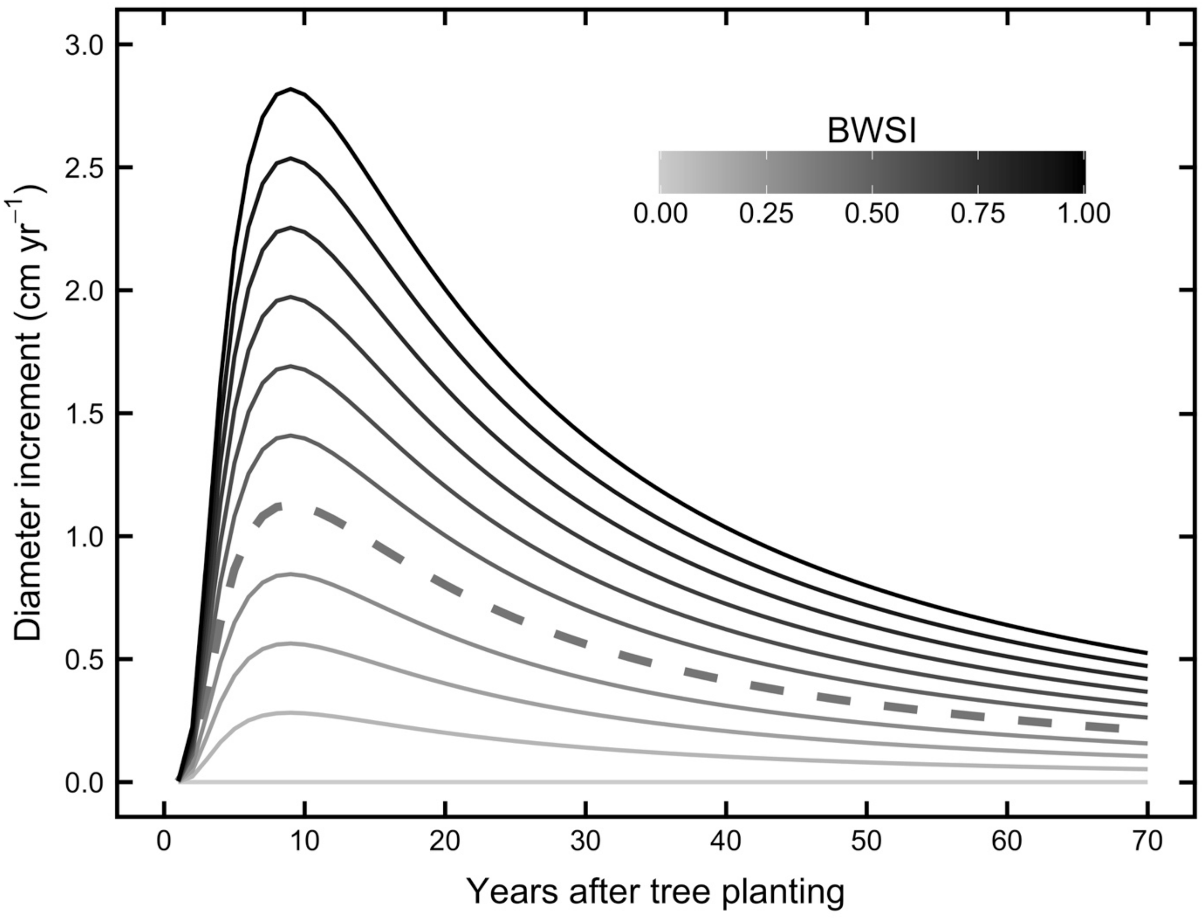

Figure B.4 Trajectory of maximum potential diameter increment supplied to the black walnut growth model for example *BWSI* values ranging from 0 to 1. The dashed line is the curve for a *BWSI* of 0.4, the area-weighted mean *BWSI* for all land area in the four states studied. This curve is the diameter increment (derivative) of the Korf model fit of the literature values of black walnut in Figure 2.

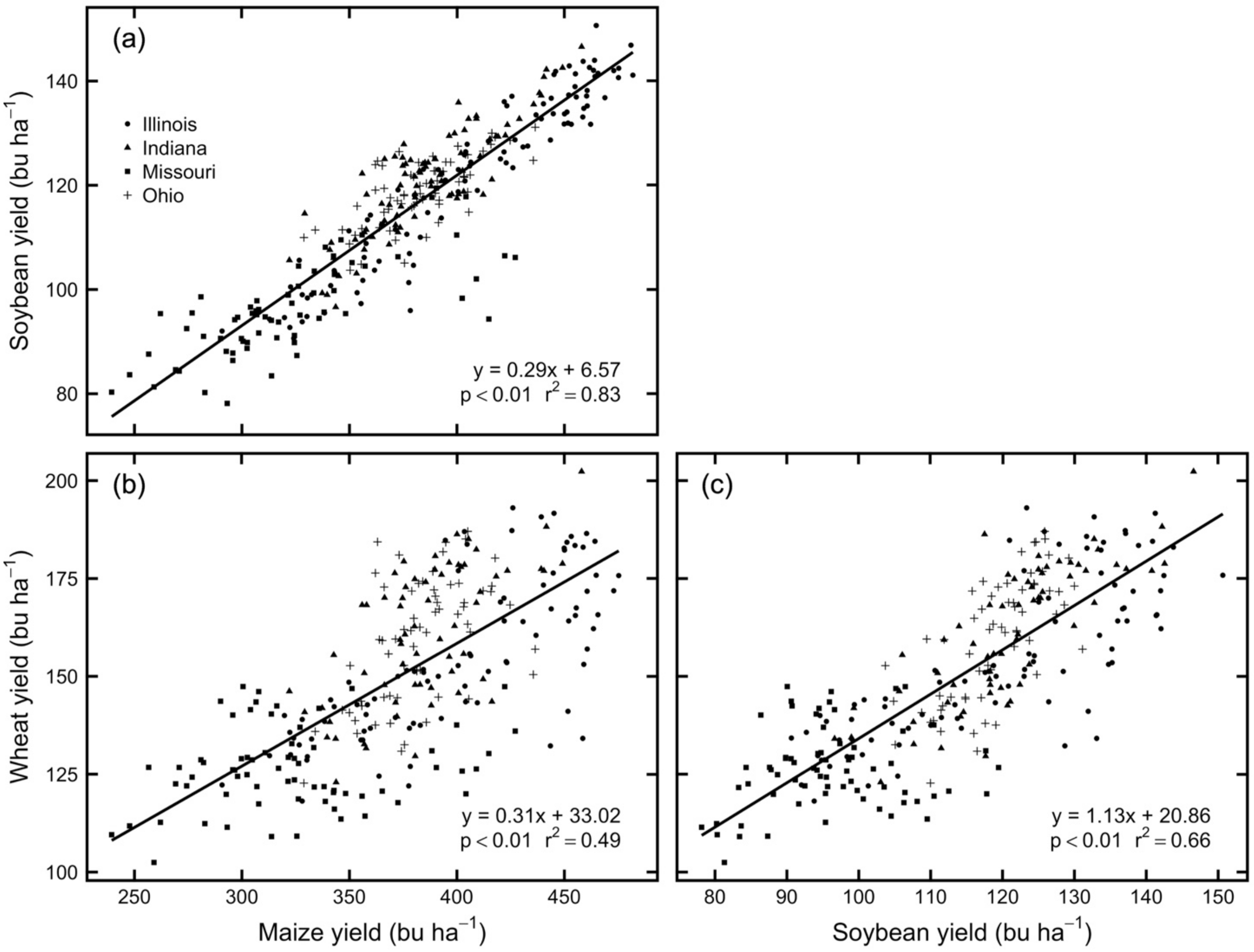

Figure B.5 Relationships between county-level mean (maize and soybean: 2007-2016; wheat: 1998-2007) crop yields (USDA NASS 2016). Counties with less than 5% cultivated land were not included.

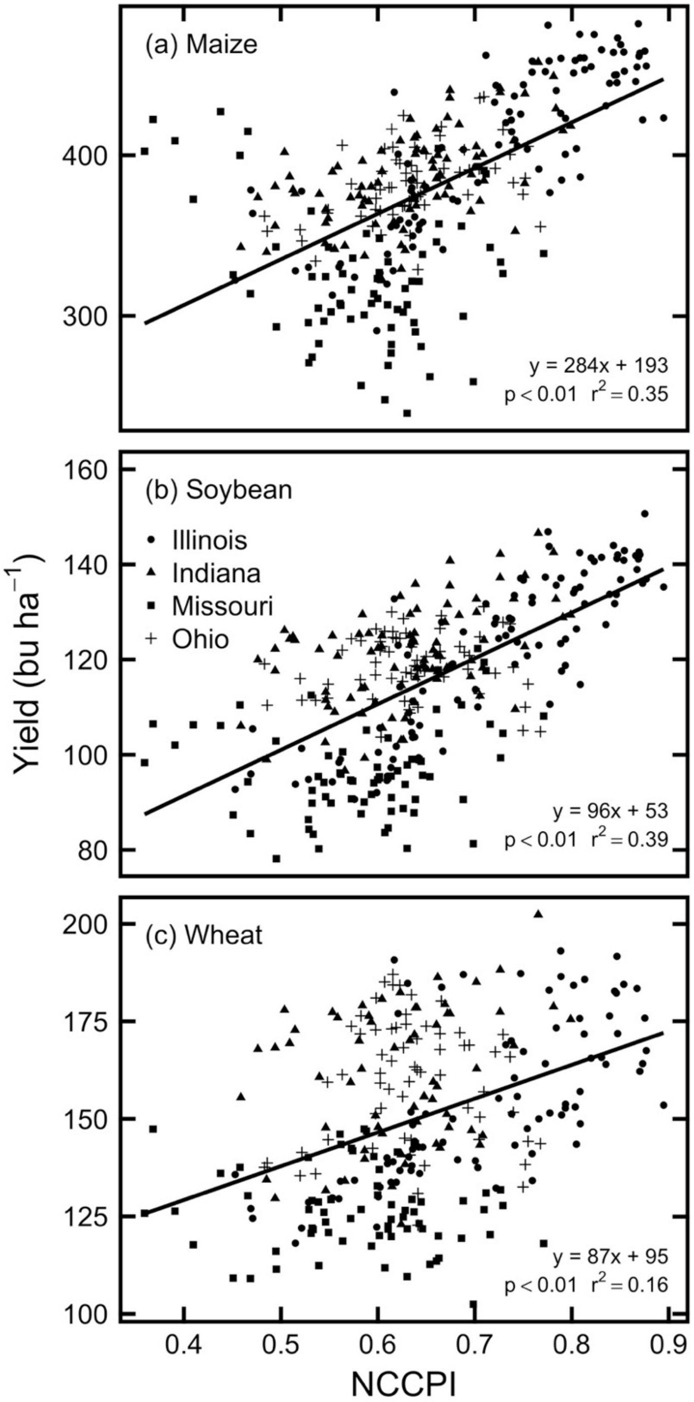

Figure B.6 Relationships between county-level mean (maize and soybean: 2007-2016; wheat: 1998-2007) crop yields (USDA NASS 2016) and the area-weighted mean of *NCCPI* on cultivated land (Dobos et al. 2012). Counties with less than 5% cultivated land were not included.

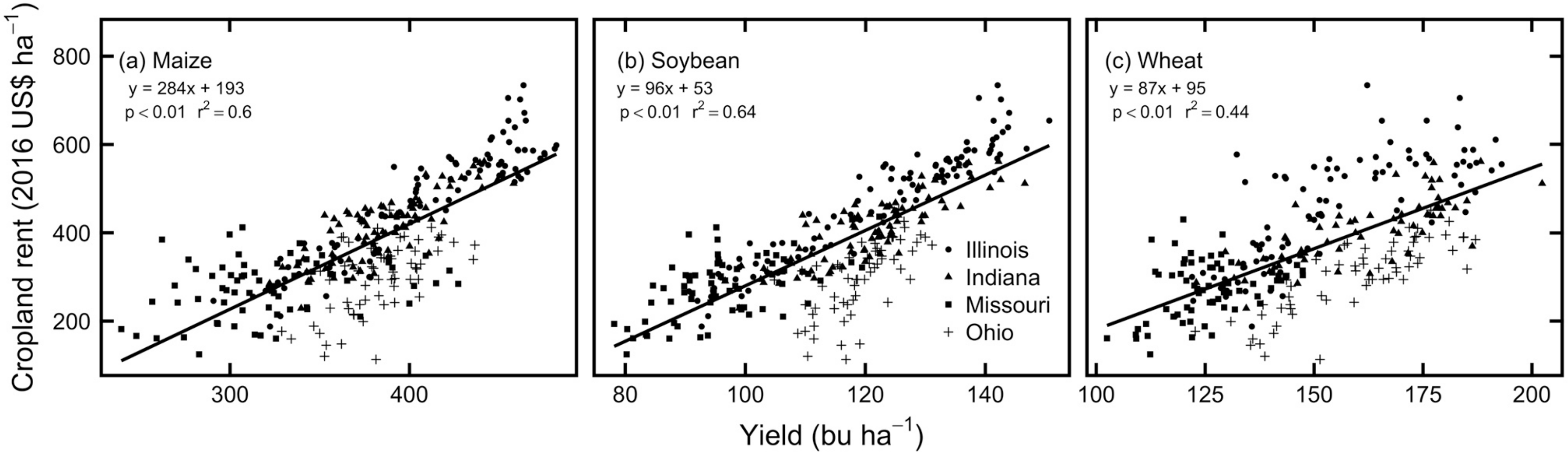

Figure B.7 Relationships between county-level mean (2008-2016) cropland cash rent and county-level mean (maize and soybean: 2007-2016; wheat: 1998-2007) crop yields (USDA NASS 2016). Counties with less than 5% cultivated land were not included.

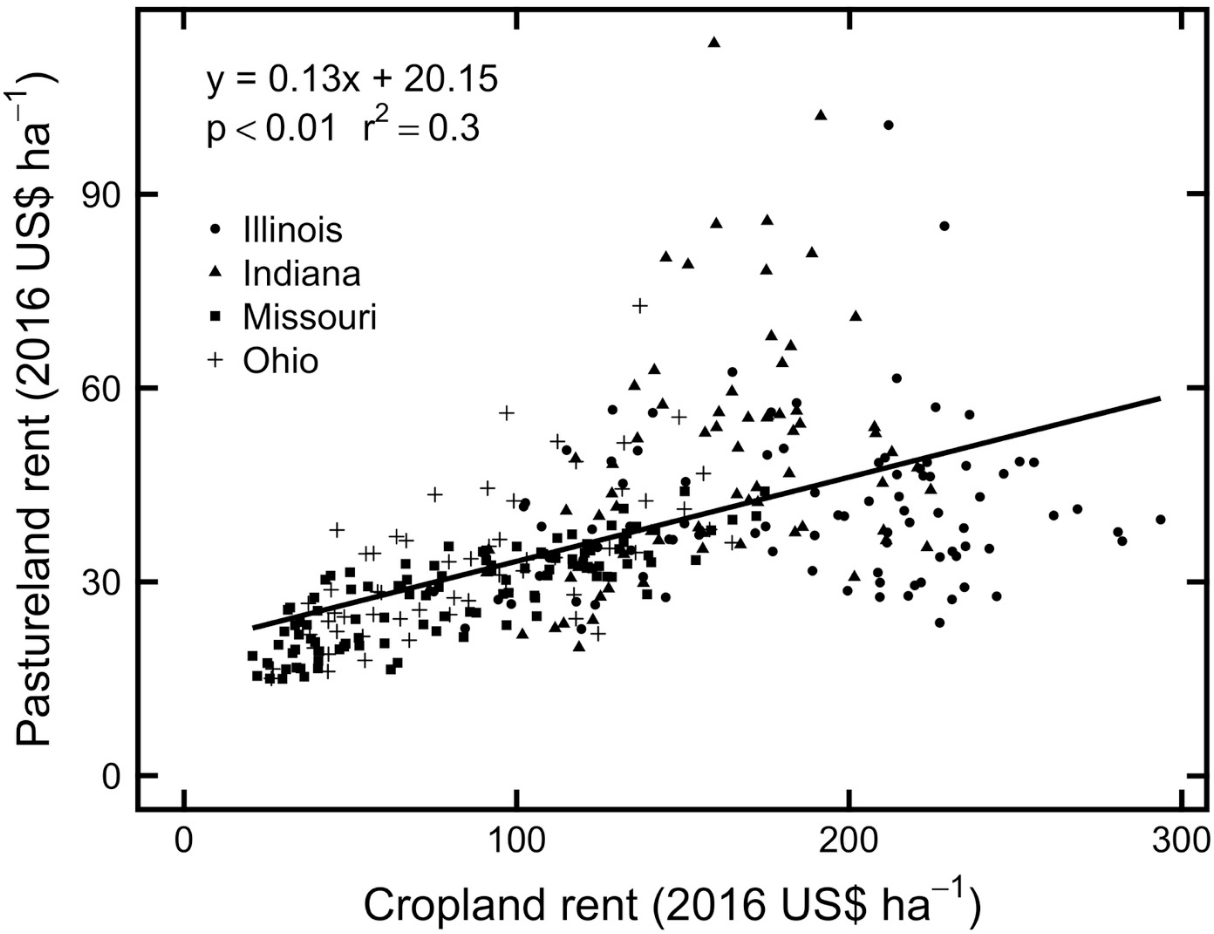

Figure B.8 Relationship between county-level mean (2008-2016) pastureland cash rent and county-level mean (2008-2016) cropland cash rent (USDA NASS 2016).

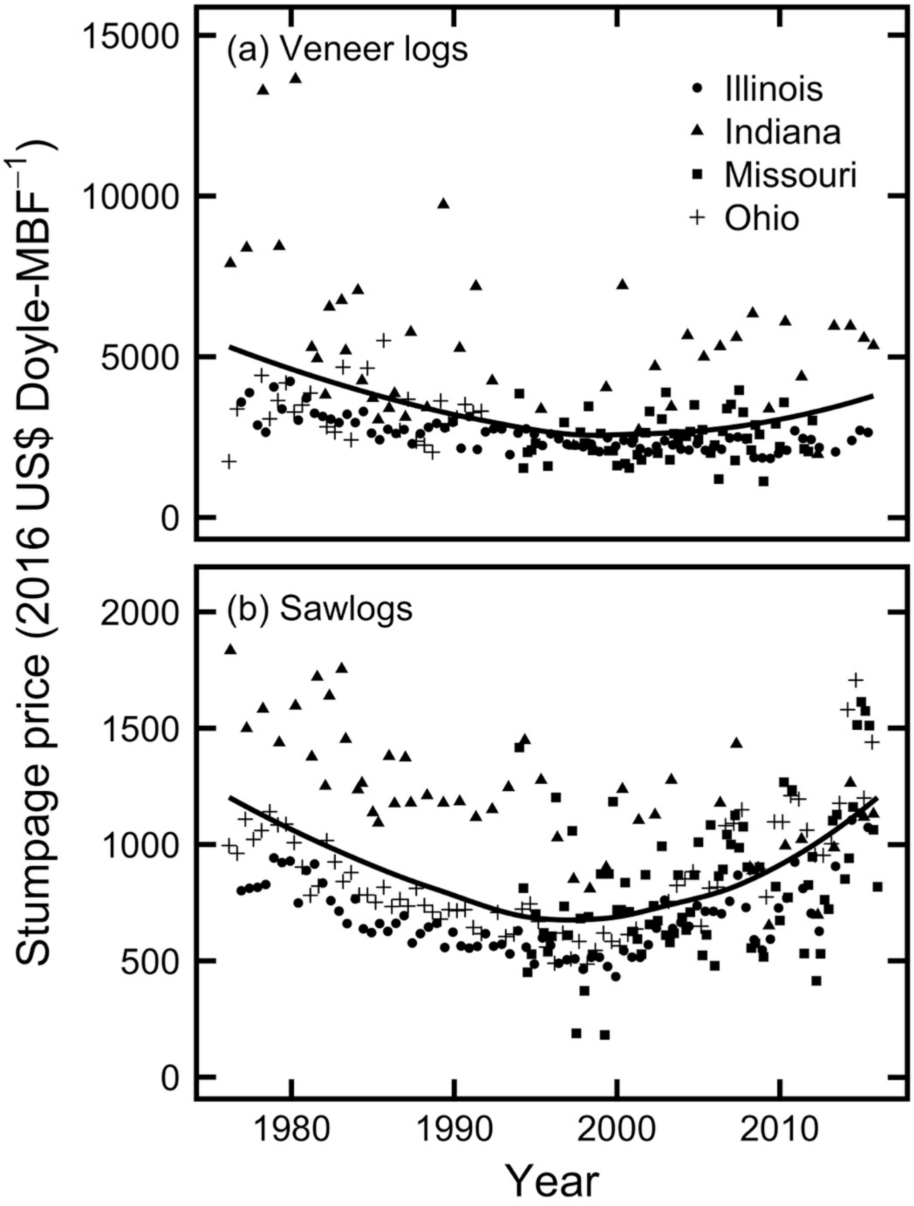

Figure B.9 Reported black walnut stumpage prices paid to landowners for (a) select-grade veneer logs greater than ~71 cm in diameter and (b) sawlogs [Illinois: (IL DNR 2017); Indiana: (IN DNR 2017); Missouri: (MO DOC 2017); Ohio: (OH DOF 2017)]. Solid black line is a loess curve through all data.

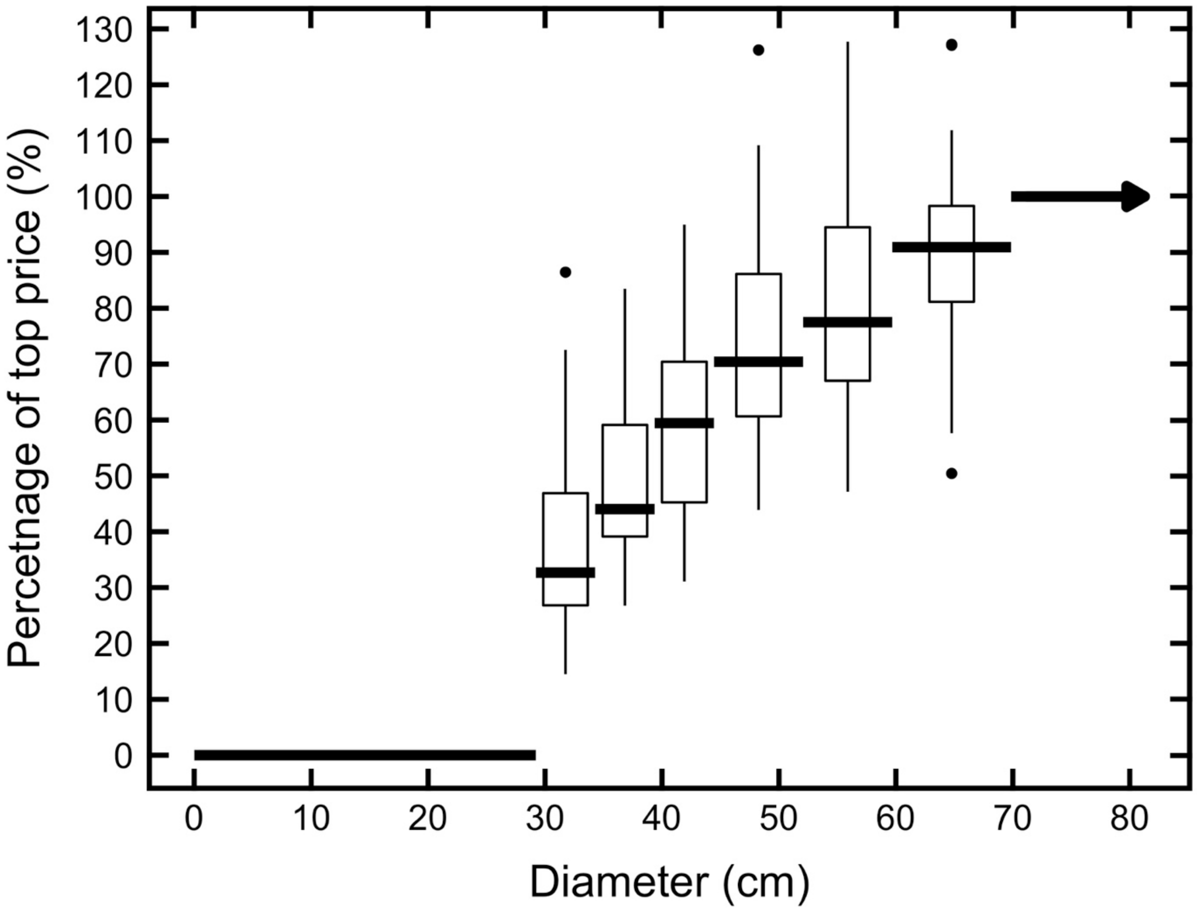

Figure B.10 Percentage reduction in price for black walnut select-grade veneer logs compared to prices for logs greater than ~71 cm in diameter (Figure S9). Boxplots represent data reported by log size class in Indiana (the only state to report black walnut veneer prices by size class) from 1976-2016 (IN DNR 2017). Relative prices for each class compared to the price for logs greater than ~71 cm in diameter were calculated for each year. The median percentage for each size class was used as the value for that size class (horizontal black lines). Logs with a diameter less than ~29 cm were assumed to produce no income but rather cost US$0.20 per tree to remove.

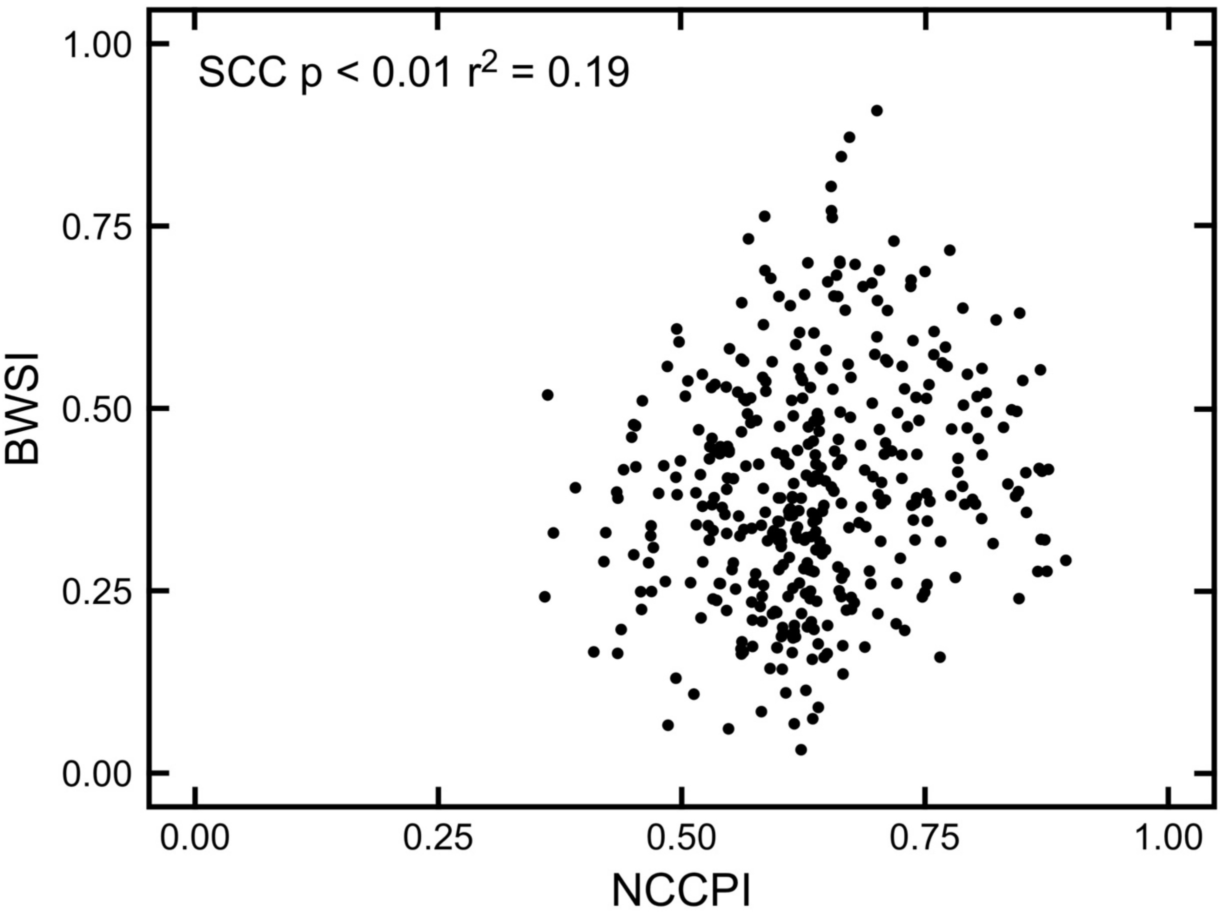

Figure B.11 Correlation between county-level area-weighted means of *BWSI* and *NCCPI* on cultivated land.

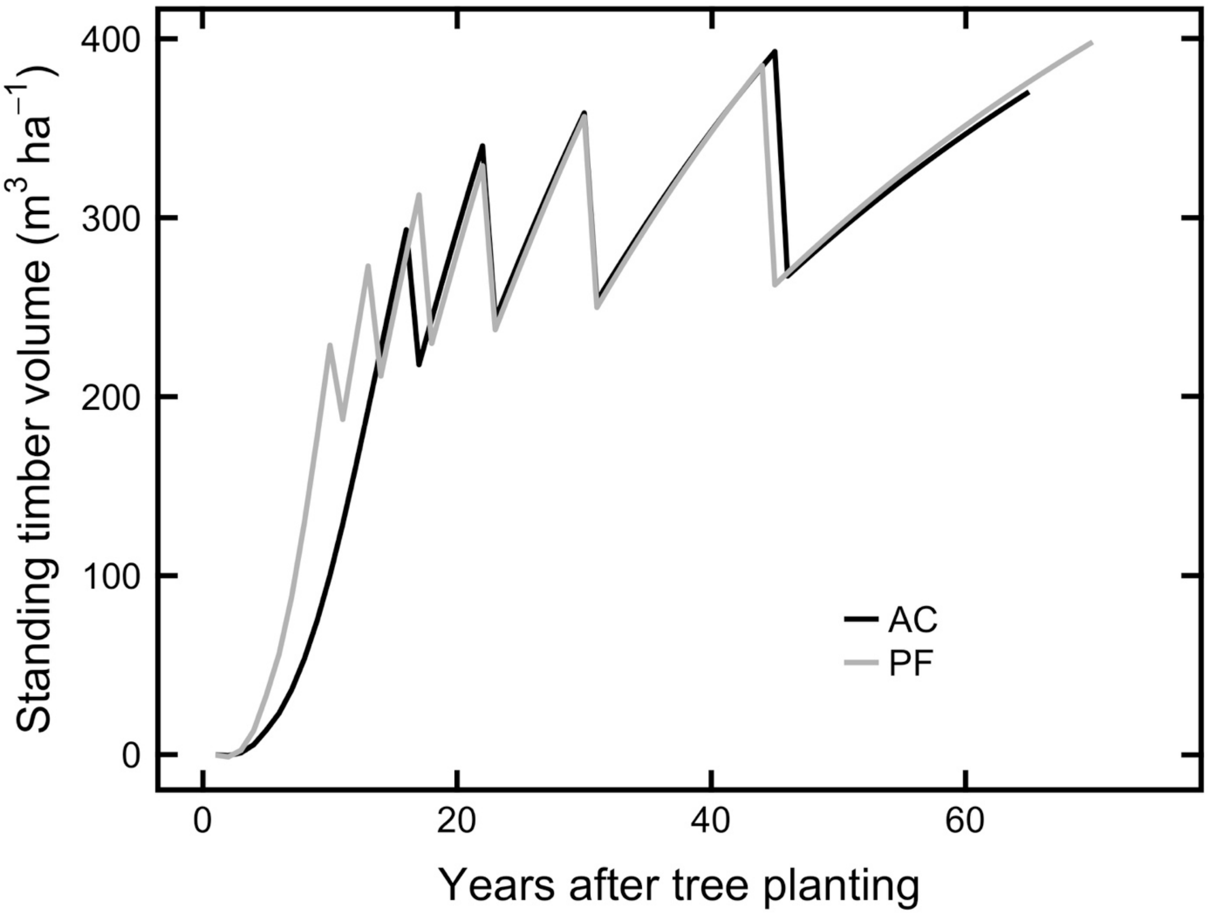

Figure B.12 Example modeled trajectory of black walnut standing timber volume when *BWSI* is 0.8. Sharp decreases in standing timber volume occur at thinning events.

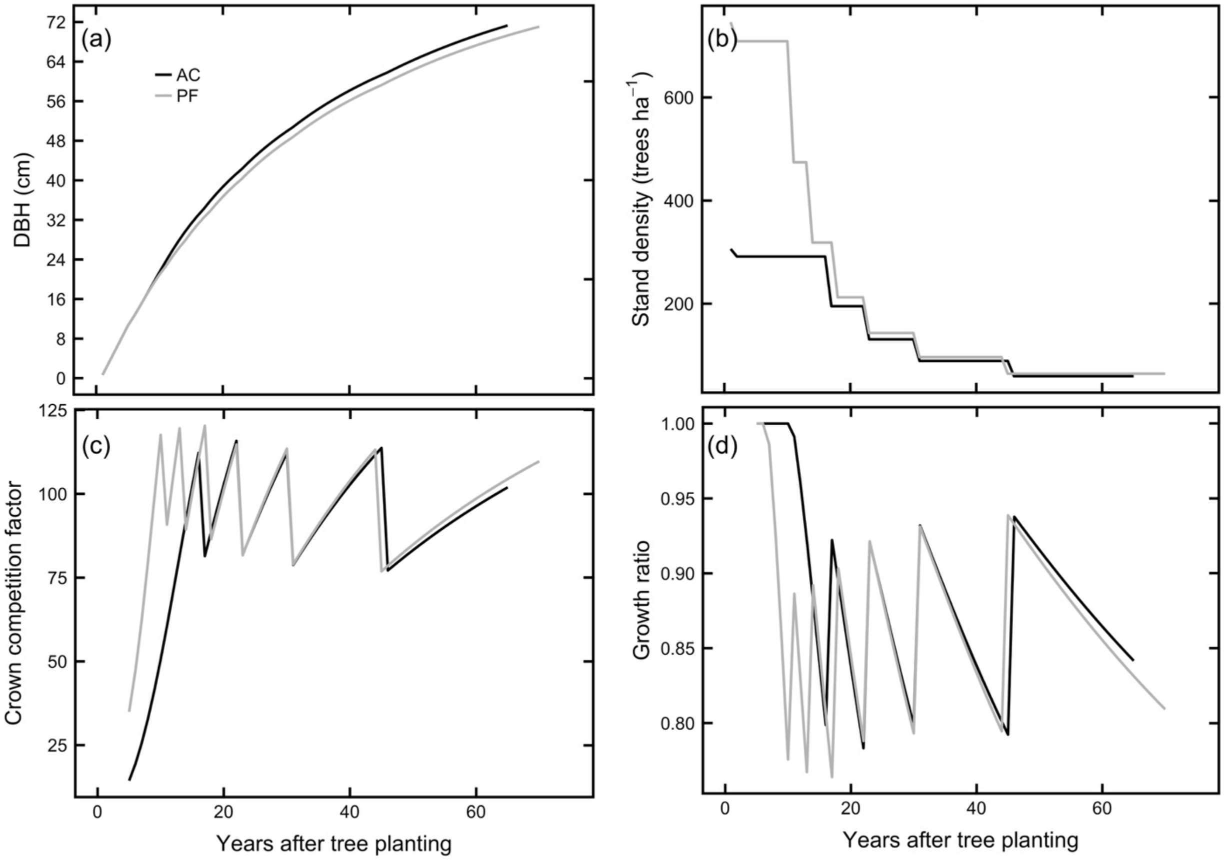

Figure B.13 Example modeled black walnut growth parameters when *BWSI* is 0.8, including (a) *DBH*, (b) stand density (*SD*), (c) crown competition factor (*CCF*), and (d) growth ratio (*GR*). Sharp changes in (b-d) occur at thinning events.

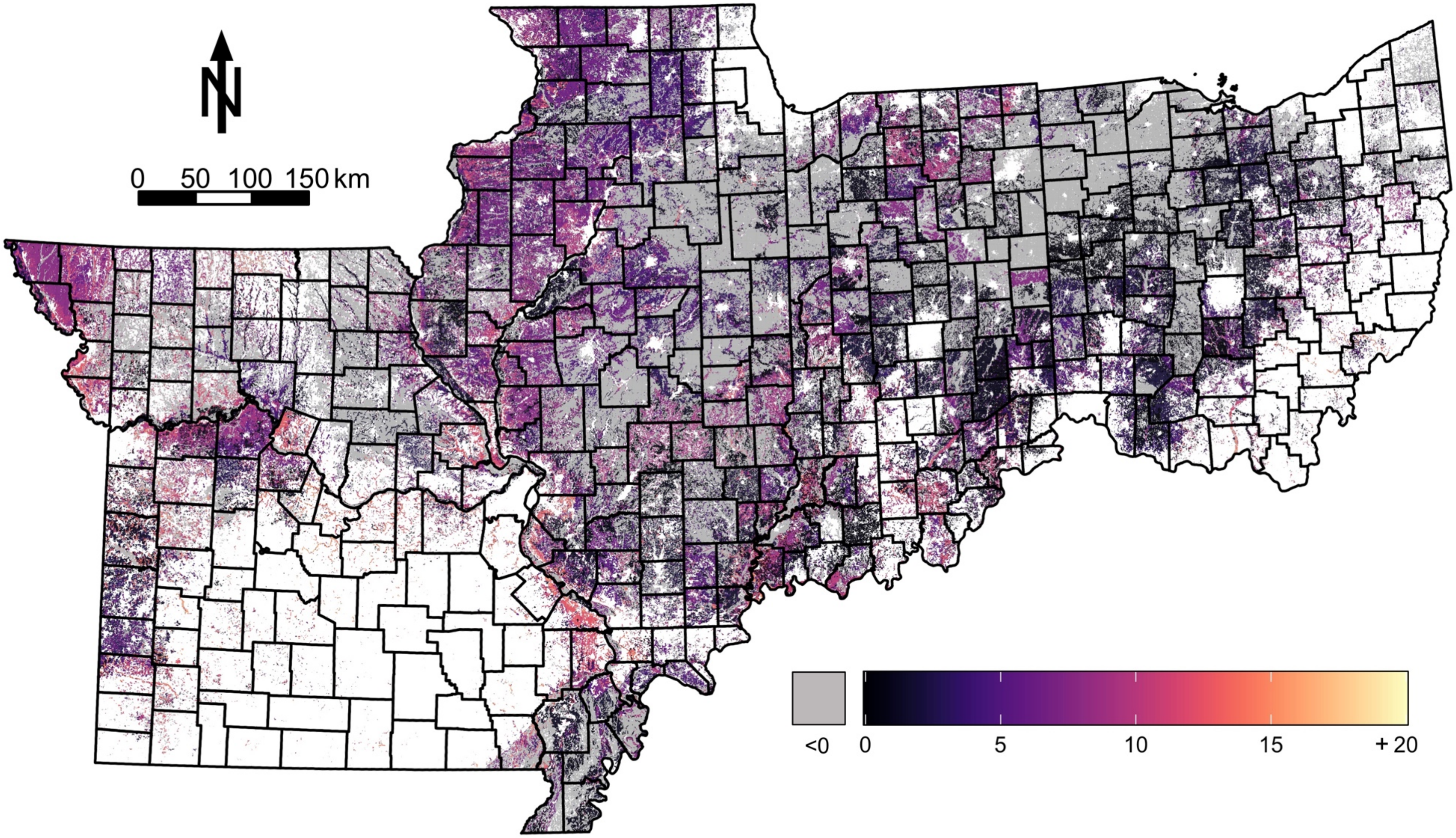

Figure B.14 Distribution of TDR_{PF} across the four states studied. Gray areas are cultivated land on which either $BWSI = 0$ or $TDR_{PF} < 0$. White areas are non-cultivated land.

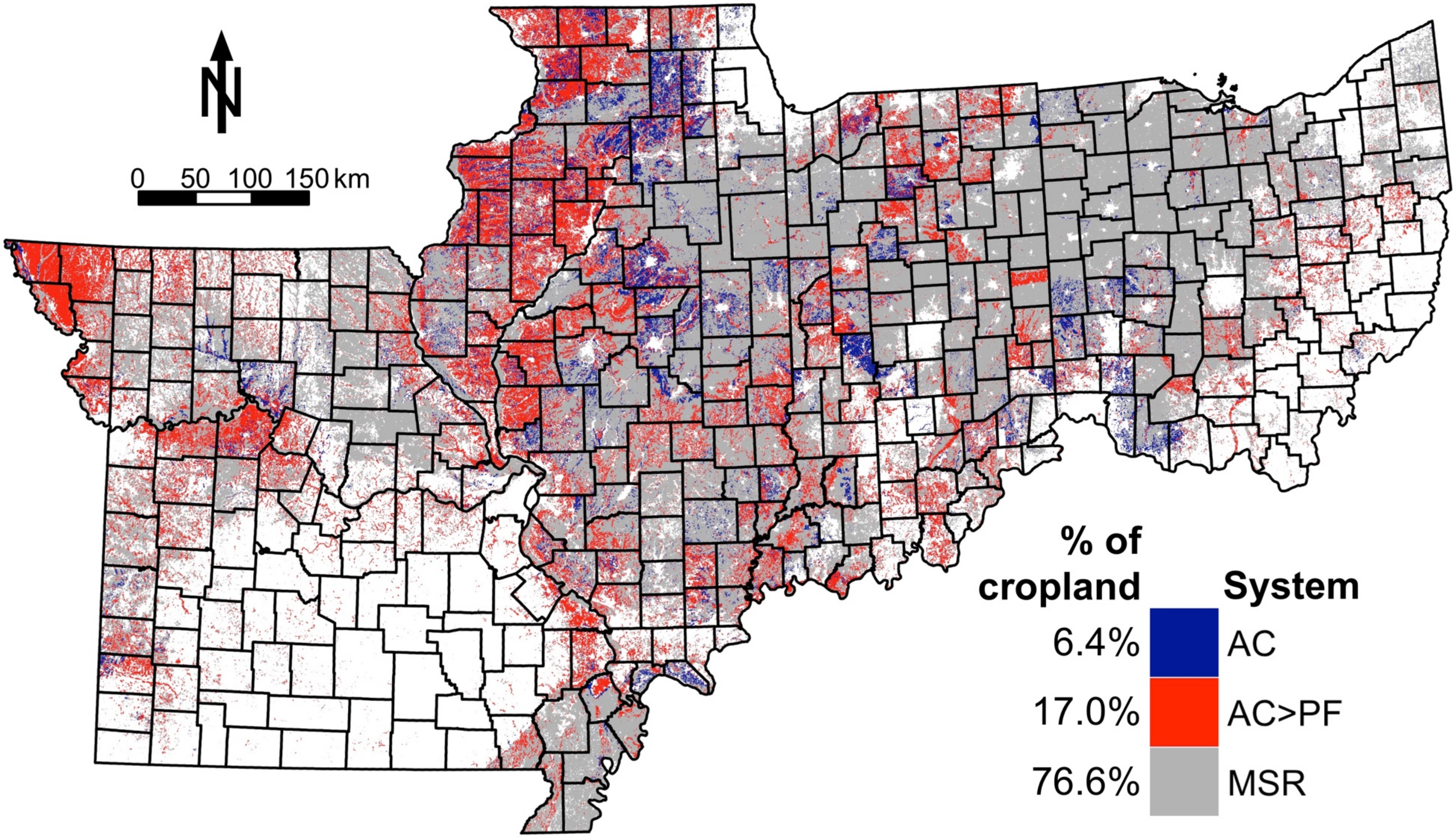

Figure B.15 Distribution of cultivated land on which black walnut AC and/or PF has a higher AEV than MSR at a TDR of 5%. “AC>PF” indicates that TDRAC and TDRPF are both greater than 5%, but TDRAC > TDRPF.

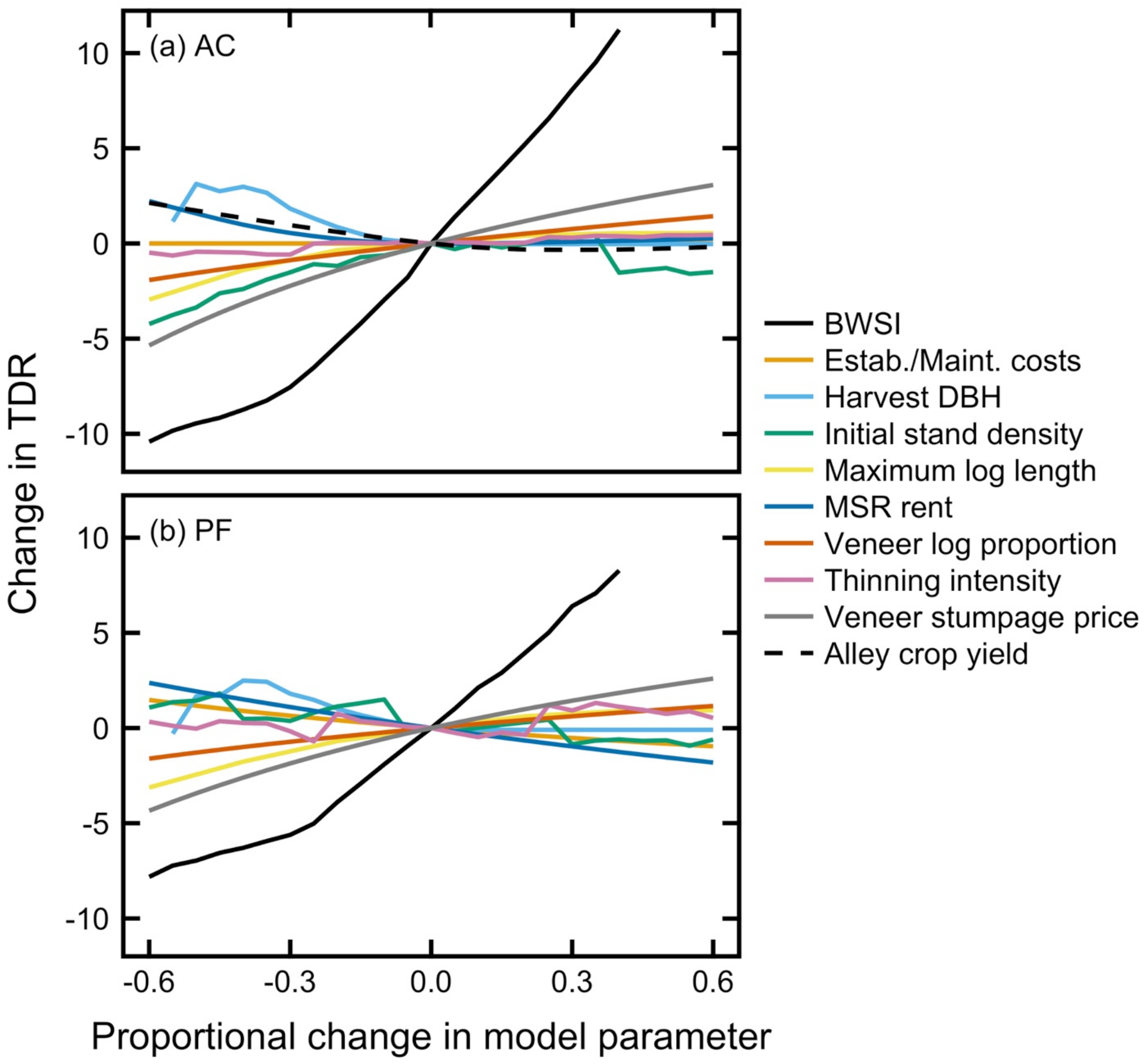

Figure B.16 Sensitivity analysis of *TDR* to model input parameters for (a) PF and (b) AC. Input parameters were varied by ±60% in increments of 5%. Only those parameters which had a non-negligible impact on *TDR* are shown. All establishment and maintenance costs were scaled collectively. Alley crop yields were scaled collectively.

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