OPINION

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Frontiers in alley cropping: Transformative solutions for temperate agriculture

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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: (i) diversification via woody polyculture and (ii) 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.

KEYWORDS
agroforestry, land-use alternatives, multispecies systems, perennialization, permaculture, polyculture, silvoarable, sustainable agriculture, tree crops, tree-based intercropping

1 | INTRODUCTION

Row crop agriculture—primarily maize (*Zea mays*) and soybean (*Glycine max*)—covers over 1.28 billion hectares of land globally (FAO, 2017) (Figure 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 United States (DeLonge, Miles, & Carlisle, 2016). Cover cropping, for

FIGURE 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 alley cropping (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

example, extends soil cover beyond the primary cropping season to reduce erosion, capture excess nutrients, and improve soil quality (Dabney, Delgado, & Reeves, 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, Reicosky, & Hanson, 2007). Organic production aims to minimize the use of synthetic inputs that have adverse ecological effects (Nandwani & 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, Claassen, & Wallander, 2015).

Incremental approaches are unlikely to reverse greenhouse gas emissions and solve the ecological challenges of row crop agriculture (Pittelkow et al., 2014; de Ponti, Rijk, & van Ittersum, 2012; Powlson et al., 2014). For example, while no-till management and cover cropping exhibit lower net global warming potentials (14–63 g CO_2-eq m^{-2} year^{-1}) than conventional crops (114 g CO_2-eq m^{-2} year^{-1}), net emissions remain positive (Robertson, Paul, & Harwood, 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, Justic, & Bierman, 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 (Buttoud, 2013; Jackson, 2002; Malézieux, 2012; Tilman, 1999; 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 (FAO, 2016; Foley et al., 2011; Jordan & Warner, 2010; Robertson & Swinton, 2005).

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 & Hanover, 1987; Leakey, 2014; Wilson & Lovell, 2016). By integrating trees throughout the landscape, agroforestry has great potential as a tool for climate change mitigation and adaptation (Buttoud, 2013; IPCC, 2014; Schoeneberger et al., 2012). 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 (Figure 1b). Interest in temperate AC has grown considerably in recent years with the recognition of its potential benefits (Mosquera-Losada et al., 2012, 2016; Smith, Pearce, & Wolfe, 2013).

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: (i) augmenting AC with woody polyculture and (ii) 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.

2 | 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.)] (Wolz & DeLucia, 2018) (Figure 1b). The potential economic and ecological benefits of temperate AC could be expanded by refocusing AC to (i) combine multiple tree/shrub species into

"woody polyculture" and (ii) include "tree crops" that produce food or fodder (Figures 1c and 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 (Wolz & DeLucia, 2018) (Figure 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 (Bird, Jackson, Kearney, & Roache, 2007; Schultz, Isenhart, Simpkins, & Colletti, 2004). Tropical homegardens take diversity to the extreme, often containing dozens of productive species (Abebe, Sterck, Wiersum, & Bongers, 2013; Méndez, Lok, & Somarriba, 2001; Zaman, Siddiquee, & Katoh, 2010). Furthermore, the use of woody polyculture in agriculture takes inspiration from the structure and function of natural ecosystems (Lefroy, 2009; Malézieux, 2012; Senanayake, 1987), 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 (Wolz & DeLucia, 2018) (Figure 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, Bunce, & Burel, 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
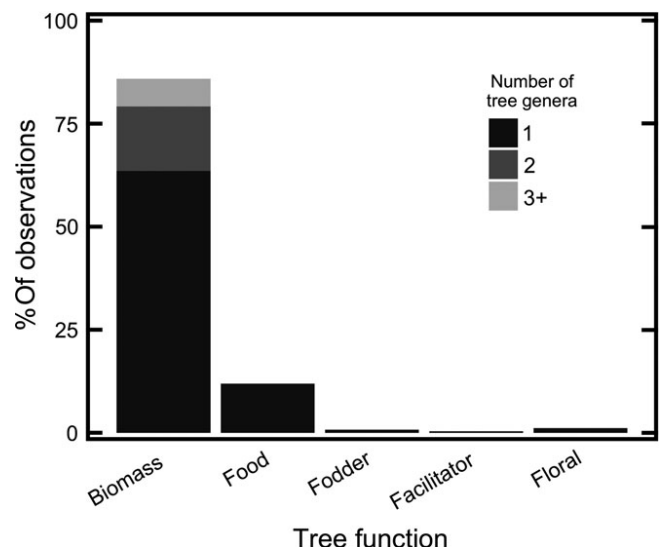

FIGURE 3 Proportion of publications on temperate alley cropping field experiments classified by the primary agronomic function and genus-level diversity of the tree component. Data are from a catalog of 162 publications from 15 countries over the last 26 years (Wolz & DeLucia, 2018)

trees in AC in the United States (Stamps, McGraw, Godsey, & Woods, 2009; Zamora, Jose, Nair, & Ramsey, 2007). 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 (Wolz & DeLucia, 2018). Emphasizing tree crops, therefore, constitutes another major frontier in temperate AC.

3 | AC FOR CLIMATE CHANGE MITIGATION

The expanded benefits possible via these frontiers in temperate AC build on agroforestry's potential in climate change mitigation.
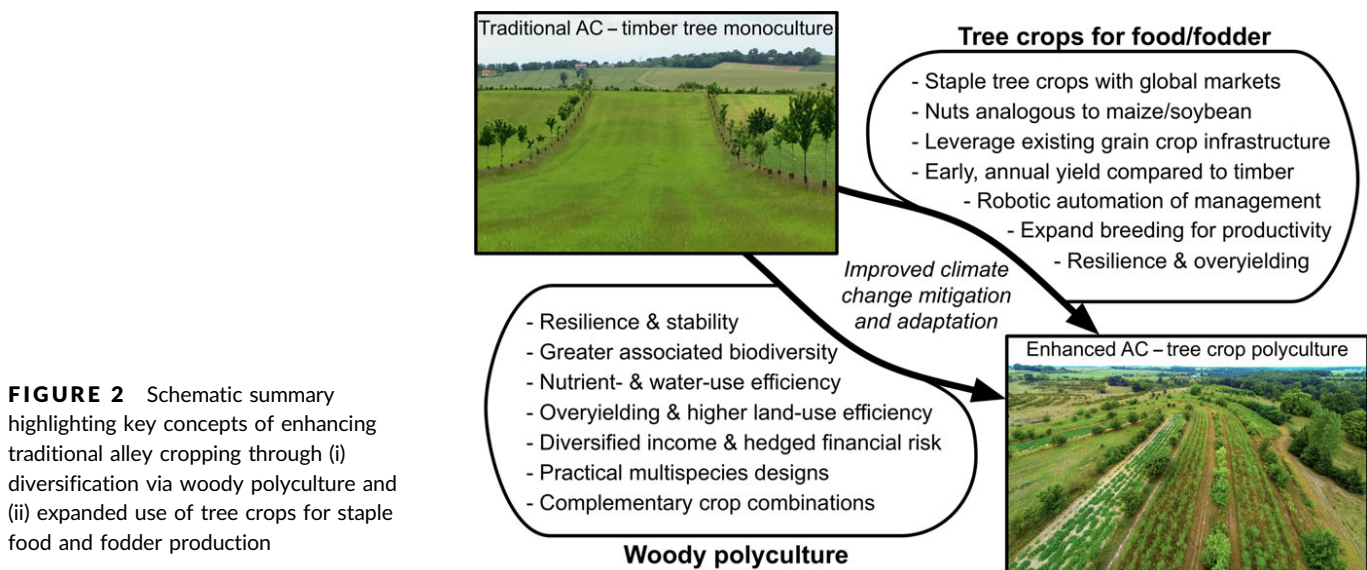

FIGURE 2 Schematic summary highlighting key concepts of enhancing traditional alley cropping through (i) diversification via woody polyculture and (ii) expanded use of tree crops for staple food and fodder production

Temperate agroforestry can drive substantial C sequestration in woody biomass and soil (Mosquera-Losada, Freese, & Rigueiro-Rodríguez, 2011; Udawatta & Jose, 2012), as well as reduce non-CO_2 greenhouse gases (Amadi, Van Rees, & Farrell, 2016; Kim, Kirschbaum, & Beedy, 2016). Over the initial 13 years of a long-term AC field experiment in Guelph, Canada, sequestration was estimated at 25 Mg C/ha in soil and 14 Mg C/ha in woody biomass (Thevathasan & 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} year^{-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 (Allen et al., 2004; Udawatta, Krstansky, Henderson, & Garrett, 2002).

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, Dey, & Rahman, 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, Engel, Miller, Lemke, & Wallander, 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, Gillespie, & Pallardy, 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 (van der Putten et al., 2013; Tilman, 2001; Vandermeer, 1989). 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, Sharma, Sharma, Sharma, & Kishore, 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, Quigley, & Scheerens, 2004).

Increasing the number of woody species in temperate AC could further enhance overyielding. Diversity-productivity relationships have already been shown in herbaceous mixtures (Picasso, Brummer, Liebman, Dixon, & Wilsey, 2011; Tilman, 2001), although woody polyculture has received much less attention (Malézieux, Crozat, Dupraz, & Laurans, 2009). A meta-analysis of 14 studies of forestry plantations found significantly higher biomass accumulation in multi-species 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, Chen, & Reich, 2012). Specific mechanisms that drive overyielding in woody polyculture have been difficult to disentangle. Documented mechanisms include mycorrhizal mediation of nutrient competition (Perry, Margolis, Choquette, & Molina, 1989), heterogeneity in shade tolerance (Zhang et al., 2012), species density and evenness (Collet, Ningre, Barbeito, Arnaud, & Piboule, 2014), plasticity in crown structure, and phenological differences among species (Sapijanskas, Paquette, Potvin, & Kunert, 2014).

4 | AC FOR CLIMATE CHANGE ADAPTATION

In addition to climate change mitigation, agroforestry can help adapt agriculture to global change (van Noordwijk et al., 2014; Schoeneberger et al., 2012; Verchot et al., 2007). More volatile and extreme weather patterns predicted with climate change are expected to have direct impacts on agricultural management and productivity (IPCC, 2014; Tomasek, Williams, & Davis, 2017). Agroforestry practices can buffer the effect of weather extremes by protecting crops from wind stress (Böhm, Kanzler, & Freese, 2014), stabilizing air and soil temperatures (Lin, 2007), increasing soil water infiltration and storage (Anderson, Udawatta, Seobi, & Garrett, 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 (Torralba, Fagerholm, Burgess, Moreno, & Plieninger, 2016; Udawatta, Kremer, Adamson, & Anderson, 2008).

Temperate AC also provides many ecological benefits that can further adapt agriculture to global change (Jose, 2009; Thevathasan & Gordon, 2004; Tsonkova, Böhm, Quinkenstein, & Freese, 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, Woods, Linit, & Garrett, 2002), mycorrhizal fungi (Bainard, Klironomos, & Gordon, 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, Williams, & Zamora, 2006). Diversification can also stimulate biodiversity of associated insects, pollinators, birds, mammals, and soil microbes (Malézieux et al., 2009; Perfecto, Mas, Dietsch, & Vandermeer, 2003). Further evidence from forest ecosystems suggests that tree diversity can increase drought resilience (Pretzsch, Schütze, & Uhl, 2013) and nitrogen retention (Lang et al., 2014; Schwarz 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 (Cubbage et al., 2012; Nadrowski, Wirth, & Scherer-Lorenzen, 2010; Scherer-Lorenzen, Körner, & Schulze, 2005).

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, Lottes, & Dawson, 1991). Furthermore, longer harvest intervals make timber returns more susceptible to natural disasters, climate variability, and changes in market preferences compared to tree crops (Hanewinkel, Hummel, & Albrecht, 2011; Taylor & Fortson, 1991).

5 | 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.

5.1 | 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 (Brandes et al., 2016; Richards, Stoof, Cary, & Woodbury, 2014). A wide range of drivers can motivate land owners to establish agroforestry practices on marginal lands, with soil health often a top factor (Mattia, Lovell, & Davis, 2016). Valuation of C sequestration benefits in AC shows particular promise as an economic driver of adoption in the temperate zone (Winans, Whalen, Rivest, Cogliastro, & Bradley, 2016). Niu and Duiker (2006) demonstrated that afforestation of marginal lands of the Midwest United States could sequester more than 1,000 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 (Fischer et al., 2017; Lovell et al., 2010). 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, Schulte, & Westphal, 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, Mercer, Cubbage, & Abt, 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.

5.2 | Core 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. Although 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 (Molnar, Kahn, Ford, Funk, & Funk, 2013; Smith, 1929). Dominant tree crops will vary by region based on environmental suitability of tree species (Reisner, de Filippi, Herzog, & Palma, 2007), while also anticipating future climate conditions (Iverson, Prasad, Matthews, & Peters, 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 & Hanna, 2011), and oils (Benitez-Sánchez, León-Camacho, & Aparicio, 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 (Figure 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 fourfold 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 (Figure 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 & 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 & 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 & Gardiner, 2014). Plant material and technology from countries with the highest yields may direct the next generation of breeding and management innovation (Figure 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
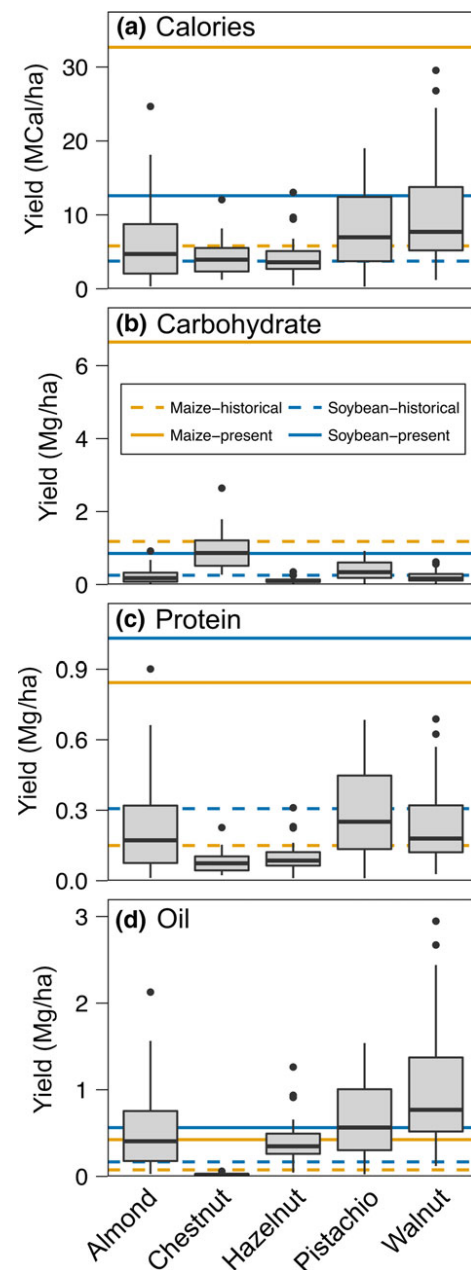

FIGURE 4 Global productivity of the five most grown temperate nut crops (almond—*Prunus* sp. [*n* = 47], chestnut—*Castanea* sp. [*n* = 22], hazelnut—*Corylus* sp. [*n* = 29], pistachio—*Pistacia vera* [*n* = 18], and walnut—*Juglans* sp. [*n* = 50]) compared to that of present and historical US maize and soybean in terms of (a) calories, (b) carbohydrate, (c) protein, and (d) oil. 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)

crops require minimal management (Cubbage et al., 2012; Thevathasan & Gordon, 2004). 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, Amatya, Karkee, Zhang, & Lewis, 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, Henten, Hemming, & Edan, 2014).

5.3 | 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, Glavin, & Jones, 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 (Wolz &

DeLucia, 2018). In tropical regions, diversified AC commonly takes nonlinear forms. By constraining trees to rows, designs are more scalable and easily mechanized (Figure 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 (Figure 5b), between-row diversification (Figure 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 (Figure 5d). For example, planting shade-tolerant shrubs such as currant (*Ribes* sp.) or blackberry (*Rubus* sp.) (Djordjević et al., 2014; Gallagher, Mudge, Pritts, & DeGloria, 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 (Leakey, 2014; Vanclay, 2006). 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).

5.4 | 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,
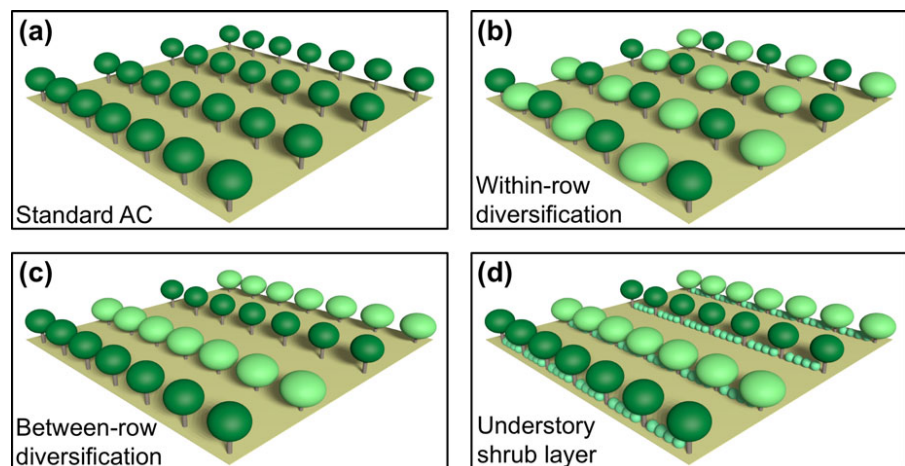
FIGURE 5 Conceptual diagram depicting practical designs for the within-row diversification in alley cropping (AC): (a) traditional temperate AC design with rows of a single tree species, (b) within-row tree diversification, (c) between-row tree diversification, and (d) an understory shrub layer within tree rows
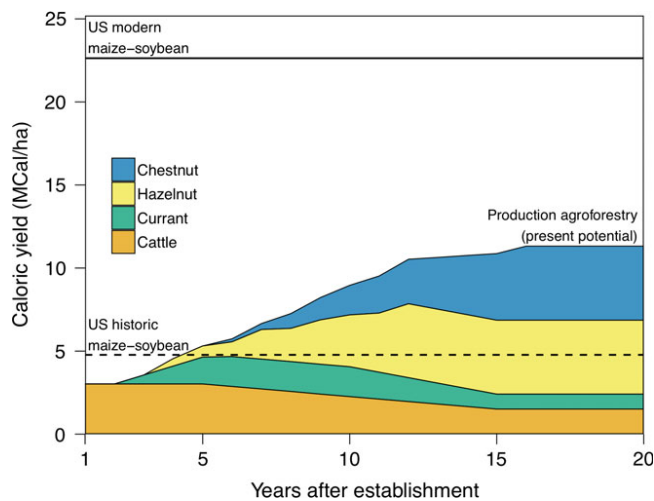
FIGURE 6 Yield projections for a theoretical alley cropping system that combines tree/shrub crops in polyculture. Tree rows contain chestnut or hazelnut with currant in a design similar to Figure 5d. Per-plant mature yields (chestnut: 33 kg, hazelnut: 5.9 kg, currant: 2.3 kg) and yields trajectories are from US extension bulletins. The hay alley crop is assumed to initially support four beef steers/ha (225 kg beef/steer). Currant and hay yields are assumed to decline by 10% each year from years 11 to 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 Figure 4a)

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 5d, this system is projected to reach over half of the modern maize-soybean yield at maturity (Figure 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.

6 | 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.

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