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Review

Alley cropping: Global patterns of species composition and function

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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 1244 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.

1. 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 (Geertsema et al., 2016; Leakey, 2014; Smith et al., 2012). 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; Lorenz and Lal, 2014; Quinkenstein et al., 2009; Torralba et al., 2016; Tsonkova et al., 2012).

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,b) 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

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or more species, creating many variations of AC around the world (Mosquera-Losada et al., 2009; Nair, 1991; Williams and Gordon, 1992). 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 (McAdam et al., 2009; Nair, 1991). The layering of these functions can vary from simple, two-function systems such as an annual grain rotation between timber tree species (Cardinael et al., 2015; e.g. Thevathasan and Gordon, 2004) 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.

2. 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) (Liu and Zhang, 2011; Mosquera-Losada et al., 2009; Nair, 1991; Williams and Gordon, 1992). 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 S1.

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 S2). The search returned 5291 publications using a search window of 1900 through 2016, and included all major journals with AC-related publications (Fig. S1). All retrieved publications were screened to determine if the criteria were met for inclusion in the inventory, with a total of 1244 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”). The full catalog of reviewed publications and observations is available in the Supplemental Materials.

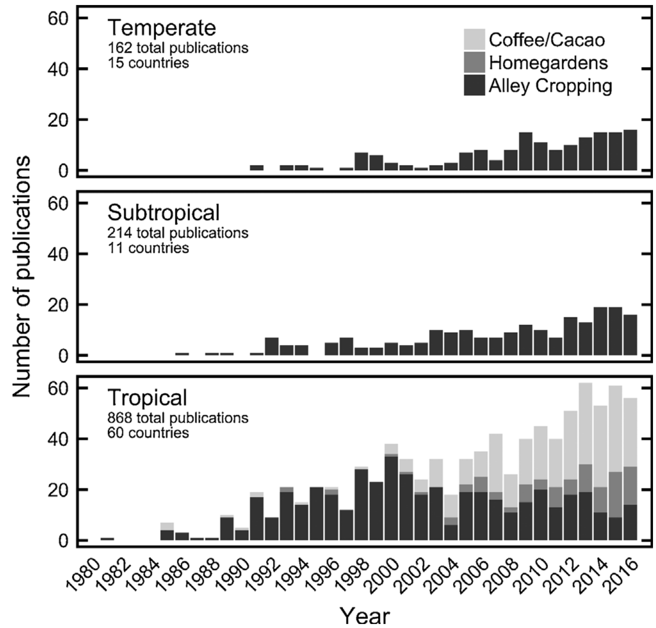

Fig. 1. Historical trend of peer-reviewed publications on AC field experiments.

3. Results and discussion

3.1. When & where

The retrieved publications on AC field experiments spanned 35 years, with the earliest in 1981 (Fig. 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. 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%,

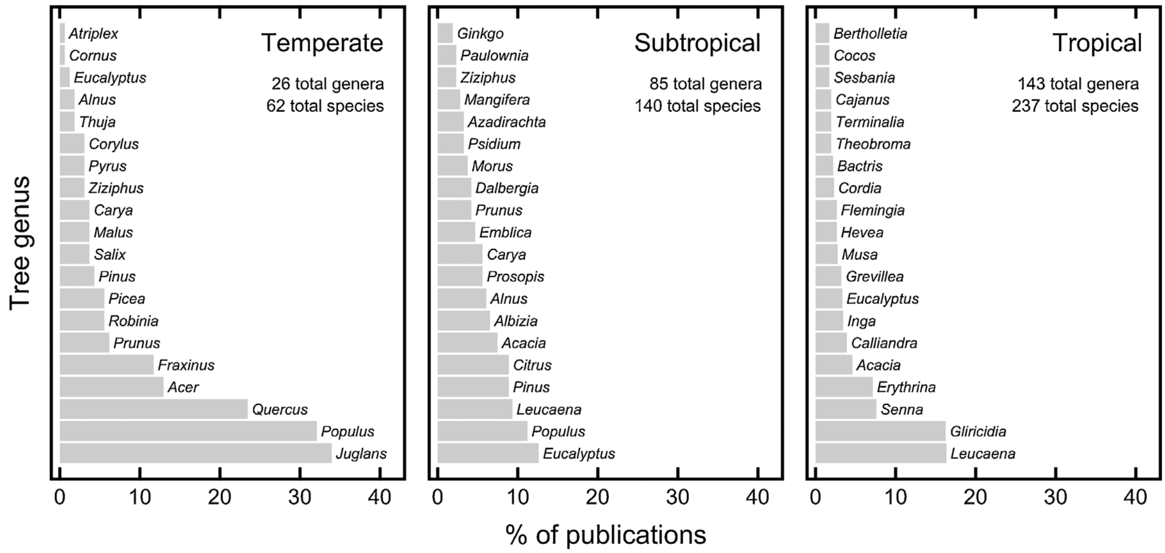

Fig. 2. Frequency of genus occurrence in the tree component of AC field experiments within temperate, subtropical, and tropical climate zones. Since many experiments examined multiple AC systems, often with different tree species, the sum of values within each climate zone is not 100.

respectively (Fig. S1).

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. S2). 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 Fig. 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.

3.2. 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). 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. 3). 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 (Cannell et al., 1996; Vandermeer, 1989). 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. 3). 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.

3.3. 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. 4). 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

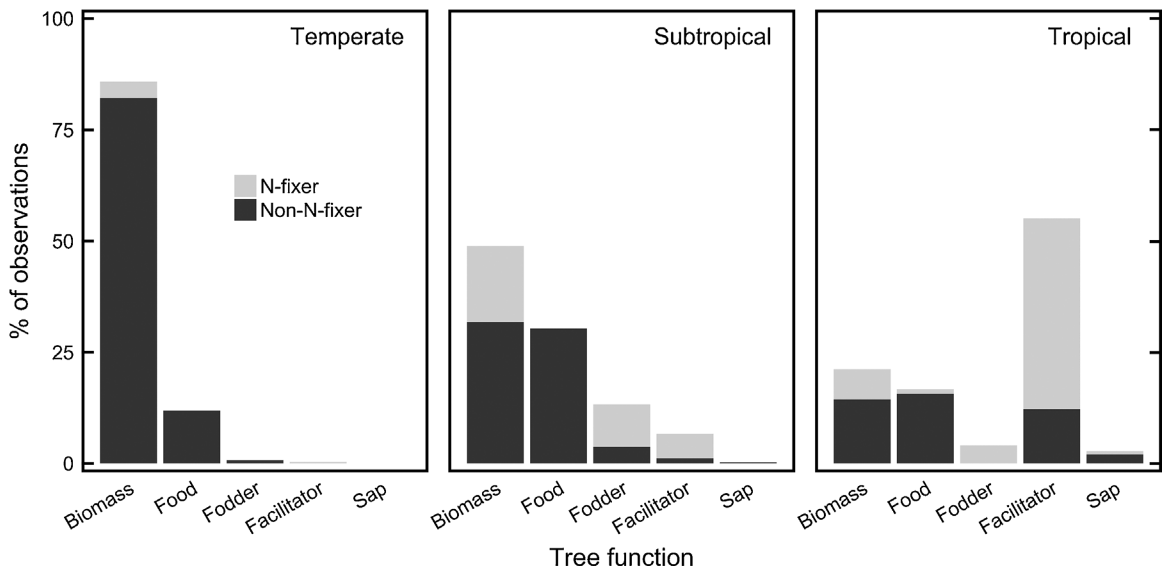

Fig. 3. Frequency of tree function in temperate, subtropical, and tropical climate zones.

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. 5). 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. 5). 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*.

3.4. Frontiers in temperate 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; Nerlich et al., 2013; Smith et al., 2012), this comprehensive inventory of field experiments provides new and robust context for these frontiers.

3.4.1. 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), diversity within the tree component of individual AC systems has been very limited (Fig. 6). 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).

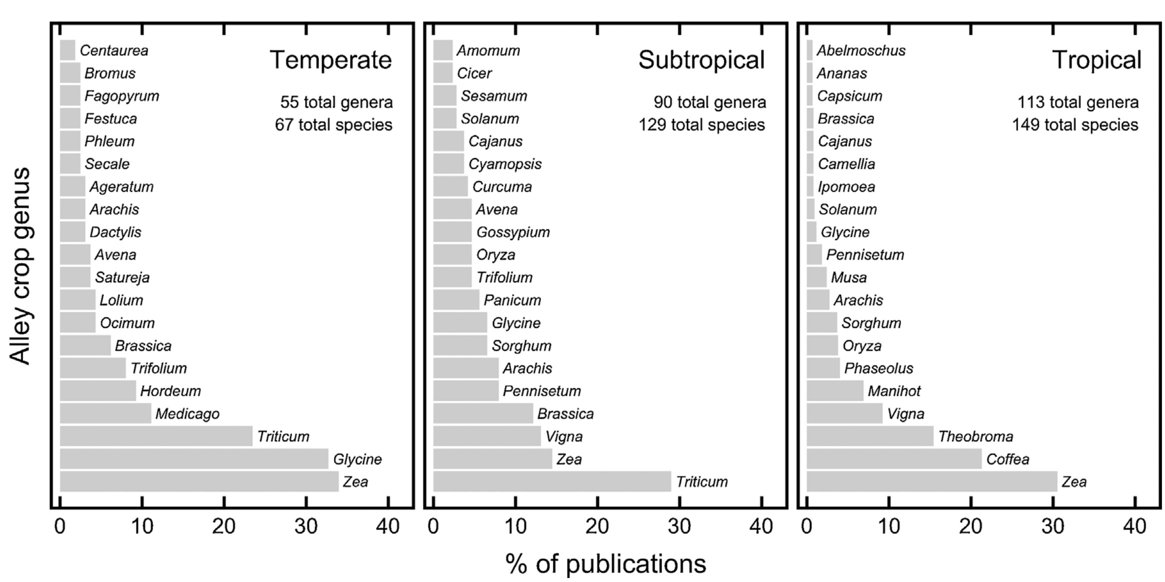

Fig. 4. Frequency of genus occurrence in the alley component of AC field experiments within temperate, subtropical, and tropical climate zones. Since many experiments examined multiple alley cropping systems, often with different crop species, the sum of values within each climate zone is not 100.

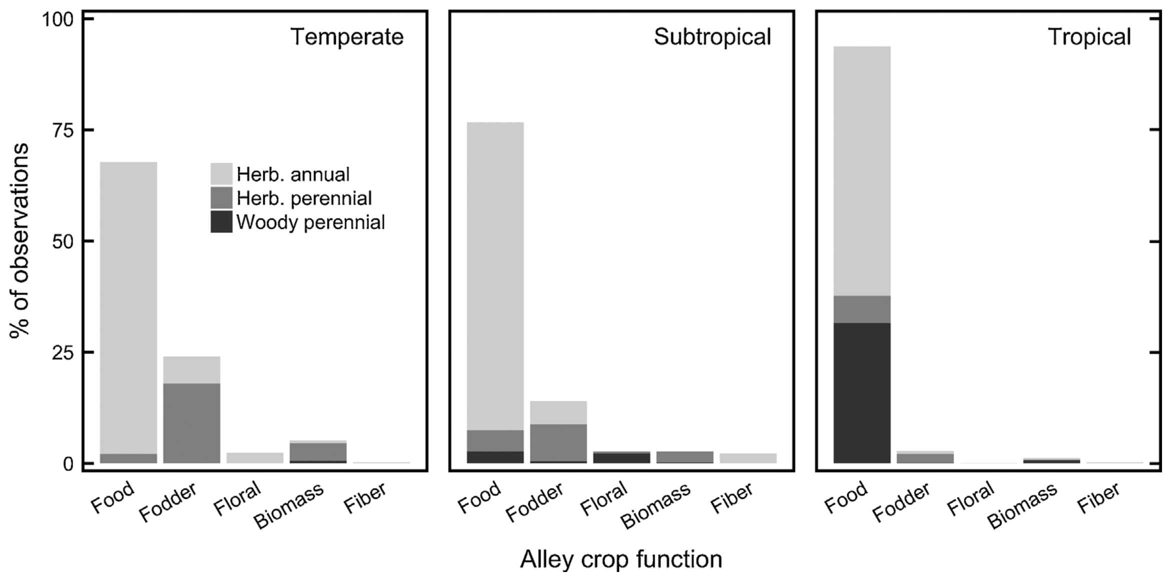

Fig. 5. Frequency of alley crop function in temperate, subtropical, and tropical climate zones.

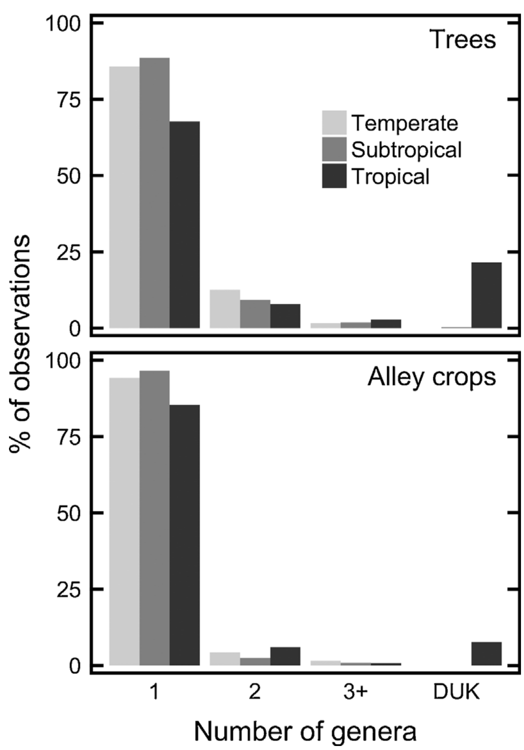

Fig. 6. Number of genera included in the tree and alley crop components within individual AC field experiments in temperate, subtropical, and tropical climate zones. DUK (diverse but unknown) refers to diverse treatments containing an unknown number of genera.

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 (Malézieux et al., 2009; Perfecto et al., 2003).

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. 6). 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.

3.4.2. 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. 3 and 5). 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 1),

Table 1
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	–

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.

3.4.3. 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. 5). 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.

3.4.4. 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 (Cardinael et al., 2015; e.g. Jose et al., 2000a). 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) (Artru et al., 2017; Chirko et al., 1996). In contrast, tropical AC field experiments have more often leveraged trees to facilitate alley crop productivity via nitrogen fixation, shade, and mulch production (Fig. 3).

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).

4. 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.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2017.10.005.

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