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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.

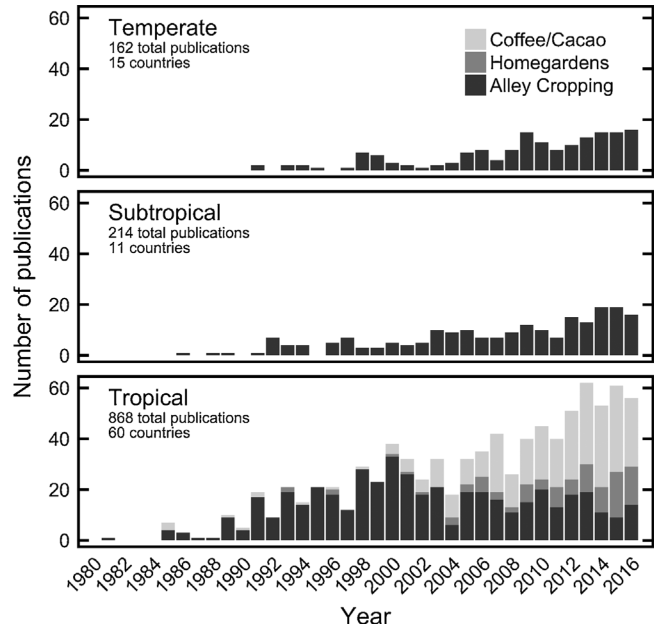

Fig. 1. Historical trend of peer-reviewed publications on AC field experiments.

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.

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%,