Agroforest Syst
DOI 10.1007/s10457-017-0087-4

Temperate agroforestry research: considering multifunctional woody polycultures and the design of long-term field trials

Sarah Taylor Lovell · Christian Dupraz · Michael Gold · Shibu Jose · Ronald Revord · Erik Stanek · Kevin J. Wolz

Received: 3 October 2016 / Accepted: 15 March 2017

Abstract The many benefits of agroforestry are well-documented, from ecological functions such as biodiversity conservation and water quality improvement, to cultural functions including aesthetic value. In North American agroforestry, however, little emphasis has been placed on production capacity of the woody plants themselves, taking into account their ability to transform portions of the landscape from annual monoculture systems to diversified perennial systems capable of producing fruits, nuts, and timber products. In this paper, we introduce the concept of multifunctional woody polycultures (MWPs) and consider the design of long-term experimental trials for supporting research on agroforestry emphasizing tree crops. Critical aspects of long-term agroforestry experiments are summarized, and two existing well-documented research sites are presented as case studies. A new long-term agroforestry trial at the University of Illinois, "Agroforestry for Food," is introduced as an experiment designed to test the performance of increasingly complex woody plant combinations in an alley cropping system with productive tree crops. This trial intends to address important themes of food security, climate change, multifunctionality, and applied solutions. The challenges of establishing, maintaining, and funding long-term agroforestry research trials are discussed.

S. T. Lovell (✉)
Department of Crop Sciences, Institute for Sustainability, Energy, and Environment, Plant Science Lab, University of Illinois at Urbana-Champaign, 1201 S. Dorner Drive, Urbana, IL, USA
e-mail: stlovell@illinois.edu

C. Dupraz
Institut National de la Recherche Agronomique (INRA), UMR System, Montpellier, France
e-mail: christian.dupraz@inra.fr

M. Gold · S. Jose
School of Natural Resources, The Center for Agroforestry, University of Missouri, Columbia, MO, USA
e-mail: goldm@missouri.edu

S. Jose
e-mail: joses@missouri.edu

R. Revord
Department of Crop Sciences, Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana-Champaign, Urbana, IL, USA

E. Stanek
Department of Crop Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA

K. J. Wolz
Program in Ecology, Evolution and Conservation Biology, Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Published online: 23 March 2017

Keywords Agroecology · Multifunctional landscape · Sustainable agriculture · Permaculture · Polyculture

Introduction

Over the years, various researchers have advocated for diversifying or transitioning some land areas to agroforestry with "tree crops" to simultaneously produce food and other environmental benefits (Leakey 2014; Molnar et al. 2013; Smith 1950). Despite compelling arguments for such a transition, particularly on land that is marginal or not well-suited for row crops (e.g., fertile yet highly erodible), we have seen little support for the concept in the United States (U.S.). Land use policy often separates production and conservation, creating a situation in which agroforestry is primarily promoted as a supplier of regulating services, but with very little consideration of commercial production of tree crops such as fruits and nuts. The research funding portfolio is similar, offering very different programs for agriculture versus environmental health, with few resources available for transformative solutions in the "applied research" realm that consider both services.

Indeed, long-term research supporting the integration of food-producing woody crops into agroforestry systems is underdeveloped. Very limited information exists on the productive potential of diverse tree crops established within agroforestry systems. We will refer to this system as Multifunctional Woody Polyculture (MWP), where the term "multifunctional" captures the production potential (as in "multifunctional landscapes" that integrate ecological, cultural, and production functions) (Brandt and Vejre 2004; Lovell and Johnston 2009), "woody" reflects the type of species as trees and shrubs, and "polyculture" references the mixing of different species within the system. The object of this paper is to introduce MWP as a concept relevant to agroforestry, as well as to facilitate the adoption of long-term MWP trials through review of design concepts and discussion of where trials may be implemented. Lessons learned from case studies of selected long-term trials of temperate agroforestry systems are also presented to aid this objective.

Background on multifunctional woody polyculture

Despite broad recognition of the extensive conservation benefits of agroforestry (Jose 2009; Rigueiro-Rodriguez et al. 2009; Schoeneberger 2009; Udawatta and Jose 2012), these systems have not been widely adopted in many regions of the U.S. where annual monoculture crops dominate the landscape (Valdivia et al. 2012). There are several reasons underlying slow adoption of agroforestry. One reason is a lack of emphasis placed on the capacity of the woody plants to produce edible crops themselves (Molnar et al. 2013; Rhodes et al. 2016). Yet, the viability of agroforestry is substantially undervalued when the productive potential of tree crops is not fully explored. The integration of fruit and nut species, especially of those with short juvenile periods, offers the opportunity to improve agroforestry systems' revenue potential and rate of return, enhancing their appeal for prospective adopters. Multifunctional Woody Polyculture systems intend to broaden the extent to which agroforestry's ecological benefits are realized, by expanding the adoption potential through the integration of commercially proven fruit and nut species.

The potential for MWPs to produce a wide range of commercial products and materials has grown recently due to continued germplasm collection and the genetic improvement of edible fruit and nut species that have been historically underutilized in the Midwest U.S. For several important tree and shrub species (e.g., chestnut, hazelnut, black currant, and elderberry), breeding objectives such as increased productivity, disease resistance, and broader environmental adaptability have been achieved. Considering these species, many new selections have recently been transitioned into replicated performance trials in regions throughout the U.S. to identify new varieties or assess the adaptability of varieties to different regions (Anagnostakis 2012; Capik et al. 2013; Dale and Galic 2014; Fulbright et al. 1983; Hummer and Dale 2010; Molnar and Capik 2012; Molnar et al. 2007). This prebreeding work has been formative in developing first generation MWPs, allowing a broader collection of commercially suited fruit and nut species to be considered when conceptualizing plant assemblages.

The improved varieties of tree crops have the potential to boost the overall performance of the system, particularly when integrated into a polyculture. Figure 1 shows how MWPs might compare to

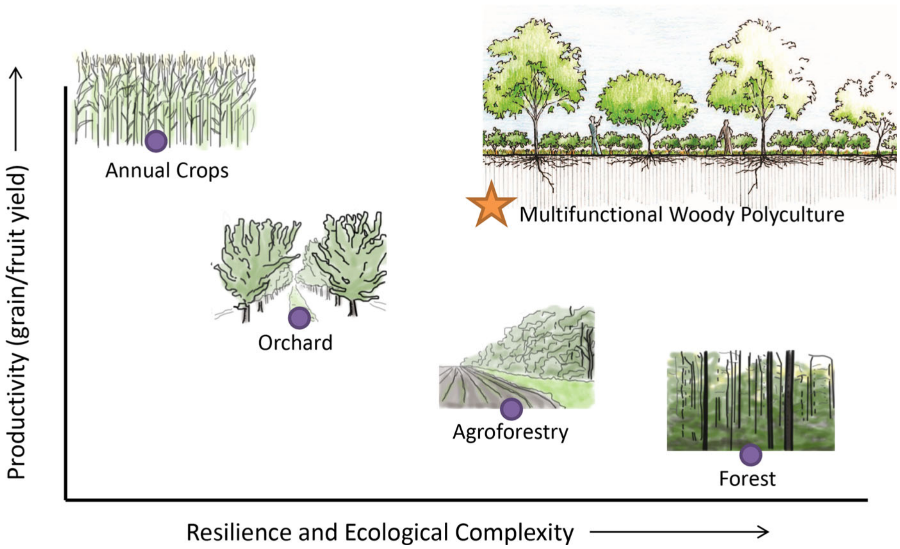

Fig. 1 Tradeoffs in performance along a spectrum of common land use types demonstrating the typical trajectory of decreasing production with increasing resilience and biodiversity

other land use types considering tradeoffs in performance along a continuum of ecological complexity. MWPs integrate multiple species that grow in different layers of the tree canopy, much like the structure of a natural woody plant community. A key goal is to optimize the system for greater productivity, without substantial loss of other ecosystem services.

In addition to recognizing the tradeoffs in allocation of resources, we also appreciate that the concept of polyculture systems with multiple canopy layers is not new, and we can draw from examples in permaculture and tropical homegardens. These systems demonstrate the potential for greater productivity with increasing diversity of plants when species occupy different niches, canopy layers, and below-ground rooting zones (Ferguson and Lovell 2014, 2015; Méndez et al. 2001; Mollison et al. 1981). These relationships, however, have been studied little at the scale of commercial farming in temperate zones.

Long-term research considering multifunctional woody polycultures

The coordinated establishment of both long-term field experiments and on-farm trials is necessary to advance the effort to understand the performance of MWPs. Growers rely on successful examples of functioning systems on farms from which to draw guidance and support (Daloglu et al. 2014; Strong and Jacobson 2005). To date, few long-term projects on MWPs have been established in the U.S. or other temperate regions (Macdaniels and Lieberman 1979; Molnar et al. 2013), particularly considering systems with harvestable products other than timber (Malezieux et al. 2009). Yield estimates from improved tree and shrub cultivars planted orchard-style can provide a baseline for forecasting (Hunt et al. 2005; Molnar and Capik 2012; Thomas et al. 2015; Wright et al. 1990), but we do not have information on the impact of combining different species into a polyculture system with multiple canopy layers. The benefits of mixing species in agroforestry systems will also depend on the specific interactions between crops, providing complementarity of resource capture (Cannell et al. 1996). A clear need exists to better understand the interspecific interactions including new species combinations and site-specific conditions (Jose 2011; Jose et al. 2004). Without the valuable long-term data on the performance of different MWPs under a variety of conditions, growers are unlikely to take on the risk of establishing them due to the relatively high upfront investments and long lag times to realize full financial benefits.

The long timespan for obtaining results of any experiment on tree crops highlights the need for development and use of agroforestry models alongside long-term field trials. It is not possible to examine all mixed-species designs using a traditional factorial experiment (Jose 2011; Jose et al. 2004). Designers and researchers therefore should emphasize the development of modeling tools to evaluate how the range of soil conditions, climate scenarios, management schemes, species selections, and system layouts could impact multispecies systems. Modeling the complexity of tree-crop interactions has become recognized as a vital tool towards successful design and research of agroforestry systems (Malezieux et al. 2009; Martin and van Noordwijk 2009), and various models have been developed that are capable of simulating tree-crop interactions, i.e. APSIM (Wang et al. 2002), Hi-sAFe (Talbot 2011), or WaNuLCAS (Martin and van Noordwijk 2009). While models may be used to forecast above- and below-ground interactions of agroforestry systems, the models are limited in their accuracy at predicting such complex systems where a paucity of data exists to validate or even parameterize the model (Jose and Gordon 2008; Malezieux et al. 2009). Mixed-species models capable of producing reliable results will need to be developed alongside long-term experiments and on-farm trials, to cover a range of potential genotype x environment interactions. The data from these sites can then be used to model alternative scenarios and provide recommendations in the coming decades.

The remainder of the paper is organized into four sections. The next section, titled "Experimental design," summarizes the state of knowledge on the design of long-term agroforestry experiments, including appropriate metrics for evaluating performance. Then, in the "Case study" section, we describe two research sites with a well-documented history of agroforestry experimentation—Restinclières Farm Estate in France and the University of Missouri Center for Agroforestry's Horticulture and Agroforestry Research Center. Following the case studies, the "Agroforestry for food" section introduces a new long-term agroforestry experiment established at the University of Illinois in 2015. Lastly, the "Discussion" section explores the important roles to be played by State Agricultural Experiment Stations and on-farm research trials to advance the science and adoption of agroforestry.

Experimental design

Designing the 'target' agroforestry system

The first issue to consider in designing long-term field experiments is to identify the plant community structure and specific species to include. The concept of MWPs differs from traditional tree crops or orchards, in that multiple woody species are grown in the same area, where they can directly interact with each other through interspecific competition. One strategy that has been promoted for designing sustainable agroecosystems is to use a 'natural' ecosystem as a model, observing the structure and function of the natural ecosystem to gain knowledge that could be transferred to managed agroecosystems through plant assemblages (Dawson and Fry 1998; Jose and Gordon 2008; Lefroy et al. 1999; Malezieux 2012). Recommended principles for designing the cropping system based on this approach include: selecting species for complementary functional traits, developing complex trophic levels, and reproducing ecological succession (Malezieux 2012). An example is the idea of recreating the structure of a savanna in an agroforestry system with multiple canopy layers of fruit and nut yielding woody species, and a dense groundcover. An assemblage of plants can be designed with an overstory of nut trees, mid-layer of fruiting small trees and shrubs, and a groundcover of mixed herbaceous plants that could be harvested as hay.

For MWPs, however, attempting to closely mimic natural ecosystems could come at a cost in terms of yield, as competition between species can reduce the performance of the highest yielding species (Lefroy 2009). Furthermore, for many species, the increase in sexual reproduction and fruit development comes at a cost in terms of vegetative growth and/or defense and adaptation mechanisms (Sanchez-Humanes and Espelta 2011; Sanchez-Humanes et al. 2011). Work on this topic is in the pioneering stage, and the potential to make production gains through the appropriate use of ecological niches and commercially viable fruit producing species is relatively unknown. The goal of initial experiments is to provide insights on species interactions and plant selections that move system development towards a commercially viable alternative. Using this approach requires building a list of fruit and nut species prioritized for regional economic potential. Species assemblages can then be chosen from this prioritized list for architectural and functional capacity to fill ecological niches. Varying the number of species, density of planting, and layout can influence the overall performance of the system, and each of these can be adjusted based on landowner or researcher goals.

With the MWP approach, a "target system" is designed with increasing layers of complexity as described herein. The baseline design simply includes suitable woody plants integrated into an agricultural landscape, which is the core definition of agroforestry. The next level of complexity intentionally selects the previously defined tree crops to produce nuts, fruits, timber, or other products. The final level of complexity, largely under-researched, would be a polyculture system in which multiple tree crops are grown together based upon compatibility, maturation, and management requirements. This concept assumes the benefits of each species are filling unique niches from the uppermost canopy to the lowermost rooting zone, thus encouraging a multi-strata system to optimize light capture and efficient use of nutrients and water.

Designing the experiments to study target systems

Once the target system is determined, experiments should be designed to test the yield and ecosystem services provided, considering inter- and intraspecific competition. Agroforestry field experiments aim to "identify and quantify interactions between trees and crops and/or animals" to find competitive (negative) and facilitative (positive) relationships (Dupraz 1998; Jose et al. 2004). Decisions about the experimental design include: specific species/varieties and arrangement of species within treatments, necessary size of plots, number of replications to provide statistical significance, and arrangement of plots in the landscape (Lefroy 2009; Malezieux 2012). The four traditional experimental designs to study interspecific plant competition include: (1) pairwise—single mixture with varying levels of the treatment factor, (2) replacement/substitution series—growing two species in varying proportions while maintaining constant overall stand density, (3) additive series—mixtures in which the density of target species is constant and that of associated species varies, and (4) response surfaces—regression technique designed with any selection of mixtures and densities that allows the estimation of response (Connolly et al. 2001; Vanclay 2006).

Some challenges exist with the traditional experimental designs when used for applied agroforestry systems. For one, the experiments become unreasonably complicated and large when used to study interactions between more than two to three species, particularly since pure monoculture stands of each species are needed for comparison. For another, if the systems or treatments are to be practical applications for a farmer, they should be designed and managed based on agricultural standards (Dupraz 1998), which could be incompatible with some traditional competition experimental designs. Furthermore, the best agroforestry designs will have plot sizes large enough to "split" into subplots to accommodate future treatments such as fertility rates, thinning, or other factors (Dupraz 1998), leading to even larger areas of land to accommodate the trials. Finally, traditional competition experiments focus on biomass production as the primary indicator for performance. The dynamics of optimizing production of fruit or nut products are much more complicated.

As an alternative to traditional experimental designs, an approach of comparing of whole-plot treatments combined with assessments at the individual plant (tree/shrub) to improve statistical power may overcome some of the challenges when an ideal traditional experimental design is not possible. Another alternative is the "farming system" approach, in which a few differently managed systems are compared to controls. Such experiments do not follow a standard factorial design, and replications may or may not be included. Instead of standard statistical approaches, biophysical modeling is used to test the fit of predicted versus measured outputs of the systems to analyze the functioning of the mixtures.

Metrics for comparing treatments

A wide variety of metrics exist to evaluate the performance of multi-species agroforestry systems. Land equivalent ratio (LER = mixed yield A/pure yield A +mixed yield B/pure yield B) is the most common measure for comparing productivity in terms of biomass or other yields (Malezieux et al. 2009). LER is extremely valuable in comparing the productivity of polycultures versus their monoculture components to determine if the interspecific interactions are synergistic or antagonistic (Dupraz and Newman 1997; Mead and Willey 1980). However, challenges do persist in using LER when drawing yield comparisons across species with long or differing juvenile periods. Consideration must also be given to the appropriate management of monoculture controls, i.e. plots must represent optimal productivity in monoculture. Land equivalent ratio can inform economic studies and provide essential information regarding system viability, particularly as it relates to landowner adoption of agricultural practices. Because agroforestry systems require greater initial investment, the economic returns need to be modeled over a time scale appropriate for full system maturity (Benjamin et al. 2000; Smith et al. 2013).

Processes or ecosystem services such as nutrient cycling, natural control mechanisms (diseases, insects, weeds), carbon sequestration, soil and water conservation should be assessed when resources allow (Malezieux et al. 2009). The collection of biophysical data can be both time- and resource-intensive, often requiring expensive equipment for accurate quantification. Once a long-term experimental trial is established, however, efforts should be made to measure as many outputs as reasonably possible. While describing the methods is beyond the scope of this paper, an overview with appropriate references is provided in Table 1.

Case studies

To better understand the design of agroforestry experiments and the broader context of the experimental farm, two case study sites are characterized below. Each of these sites hosts numerous temperate agroforestry experiments, some of which have reached a maturity level in which trees are in full canopy. For each location, an overview of the entire experimental farm is followed by a specific example of a trial designed within it. The individual trial examples were included to demonstrate the perspective and type of research at each of the research farms.

Restinclières Estate Farm in France

Established in 1995, the Domaine de Restinclières, located north of the city of Montpellier, is the oldest and most well-documented agroforestry experimental site in Europe (Fig. 2). The 45 ha of agroforestry trials have produced a variety of encouraging results, including alley cropping (silvo-arable) agroforestry systems exhibiting LER estimates at 1.3 to 1.6. This LER indicates that a 100 ha agroforestry farm produces as much as a traditional farm of 130 to 160 ha in which the trees and crops are grown separately. Several ecosystem services are under investigation at Restinclières including carbon sequestration, water quality, adaptation to climate change, and biodiversity. The program as a whole is intended to be a true integration of social experimentation (combining a landowner and farmers) with agricultural experimentation (combining trees and crops). The experiments include a wide range of intercropped agroforestry plots, compared with conventional forestry and row crop plots to serve as controls. In most cases, these large-scale plots are designed to simulate commercial production, so replication is not possible. Much focus has been placed on intercropping strategies in which annual crops, perennial crops, or forages are planted between rows of timber trees. Figure 2 below shows the overall layout of the site, labeled with the individual trials.

Example trial: hybrid walnut and winter wheat alley cropping

An alley cropping experiment of hybrid walnut and cereal grain was established in 1995 with four treatments: (1) annual crop only, (2) trees only, (3) north–south agroforestry, and (4) east–west agroforestry. In the agroforestry treatments, the tree rows were spaced wide enough to allow four passes of the planter and two passes of the harvester. Trees are pruned up to 4 m to accommodate equipment beneath, above which they are allowed to grow freely.

The experiment has provided important findings, above and below ground. Tree-row orientation resulted in differences in radiation on the alley crop. The north–south tree rows offered much more homogeneous active radiation to the grains, whereas the east–west tree rows had variable shading patterns due to the sun's path throughout the seasons. Temporal complementarity was also demonstrated, as the trees and crops did not directly compete for light during much of the year. The winter wheat has a growing season from late fall into early summer, whereas the walnut trees only begin to bud out in spring/early summer. On average over the past 20 years, the crop yields of the agroforestry sites have only been reduced around 2% compared with monoculture controls. When comparing the size of the walnut trees, the agroforests had significantly larger and more vigorous trees compared to the monoculture forest control, likely due to lower competition from cereals compared to natural vegetation in the forest and to a lower tree density (100 vs 400 walnut trees ha^{-1}).

Table 1 Examples of agroforestry ecosystem services that can be evaluated in field trials and potential methods for their quantification

Ecosystem service	Metric	Methodology
Production	Yields of individual crops per area; land equivalent ratio (LER) comparing polyculture versus monoculture counterparts; return on investment (ROI)	Harvest, weight or count units, record yields, and calculate value based on market prices. LER greater than 1.0 indicates beneficial interaction (Dupraz and Newman 1997; Mead and Willey 1980). ROI comparing cropping systems (Benjamin et al. 2000)
Plant biodiversity	Species richness or total number of taxa; plant diversity indices account for abundance of species	Sample plots randomly or along a transect, determine presence and abundance of taxa and characterize native and invasive species (Barrico et al. 2012; Boutin et al. 2002)
Water use dynamics	Soil water content (SWC) comparing different treatments. Plant water uptake and use efficiency. Mass balance of evapotranspiration (ET)	SWC would provide a relative comparison but not account for all water dynamics. ET is estimated by subtracting SWC, drainage, and surface runoff from precipitation (McIsaac et al. 2010). Plant water uptake is monitored using sap flow sensors (Wanvestraut et al. 2004)
Nutrient use dynamics	Nutrient use efficiency (NUE) as apparent recovery for individual crops; nutrient retention (NR) and leaching (NL) from full treatments	NUE analysis of nutrients from biomass harvested for crops with and without fertilizer (Fixen et al. 2015; Jose et al. 2000) or using stable isotope-labelled fertilizer (Allen et al. 2004a; Jose et al. 2000). NR from analysis of soil at various depths. NL analyzed from resin lysimeters (Lehmann and Schroth 2003) or tension lysimeters (Allen et al. 2004b)
Microclimate control	Atmospheric and soil conditions within treatment area; yields of adjacent crops	Atmospheric conditions can include wind speed, air temperature, and air humidity. Adjacent crop yields, soil moisture, and soil temperature can be sampled along a transect at various distances from a tree row (Baldwin 1998; Kort 1988)
Soil infiltration	Infiltration capacity of in situ soil and bulk density of sampled soil	Estimate relative infiltration rates using a double-ring infiltrometer. Bulk density is typically inversely related to soil infiltration (Bharati et al. 2002; Blake and Hartge 1986; Bouwere 1986; Kumar et al. 2012)
Carbon sequestration	Above ground biomass (AGB) and belowground biomass (BGB) in tree material, soil organic C (SOC)	Estimate AGB based on allometric relationships with diameter at breast height (DBH) and BGB through root-to-shoot ratio. SOC based on CO_2 release through heating (Nair 2011; Udawatta and Jose 2012)
Pollination	Pollinator community through traps and observation of visitation; exclusion studies for direct pollination	Evaluate pollinator community through observation of insects visiting flowers and passively collecting insects in pan traps. Exclusion studies compare pollination with and without access to pollinators (Button and Elle 2014)

The table is not intended to be comprehensive, either in terms of ecosystem services or measurement techniques, but rather to provide examples that do not depend on great investment in specialized equipment

A variety of approaches are used to assess and compare the performance of these systems. Tree biomass is important for both timber yield and for estimating carbon sequestration (Cardinael et al. 2015a). The research team uses both non-destructive and destructive methods to measure tree growth and harvest value (Fig. 3) (Dufour et al. 2013). To monitor activities below ground in a non-destructive manner, several root-cores were assessed to a 4 m depth (Mulia and Dupraz 2006). More recently, deep pits were excavated at each site and equipped with minirhizotrons (Germon et al. 2016) and glass windows inside allowing research to view and photograph the roots as they develop over time. From these pits, they found

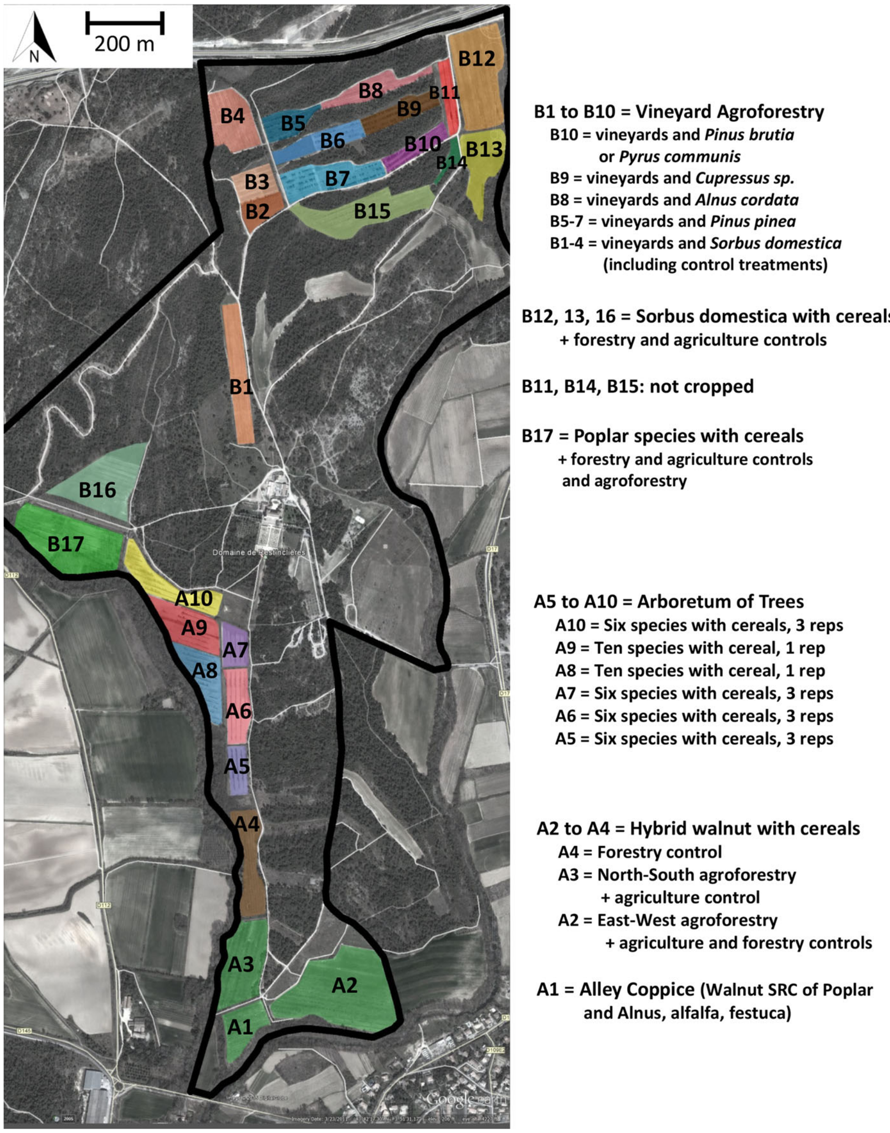

Fig. 2 Map of Domaine de Restinclières agroforestry experimental site near Montpellier, France. Labels indicate the different experimental systems and treatments

that the trees with crops planted between them had significantly deeper and larger rooting systems as a result of interspecific competition causing water stress in the early spring when trees begin to grow, compared with trees grown in monoculture (Cardinael et al. 2015b). Selected trees are harvested through "destructive" methods to provide accurate measures of biomass quantity and quality. Valuable foresight in the phase of designing the experiment has allowed for continuous data collection over the 20-year timespan of the trial. The most important decision was the inclusion of forestry and agriculture control plots that proved invaluable for the assessment of the productivity of agroforestry plots. Several environmental services of agroforestry were documented in the walnut-wheat system including nitrate capture by trees to protect the aquifer (Andrianarisoa et al. 2016) and microclimate modification that could help protect alley crops from a more variable climate (Talbot and Dupraz 2012). A climate change facility, which will be operational in September 2017, will create conditions with reduced rainfall and increased temperature in subplots.

The data obtained at the Restinclières Estate have informed French and European regulations on agroforestry. The most important change was the recognition of agroforestry as a standard agriculture management that was therefore included in the

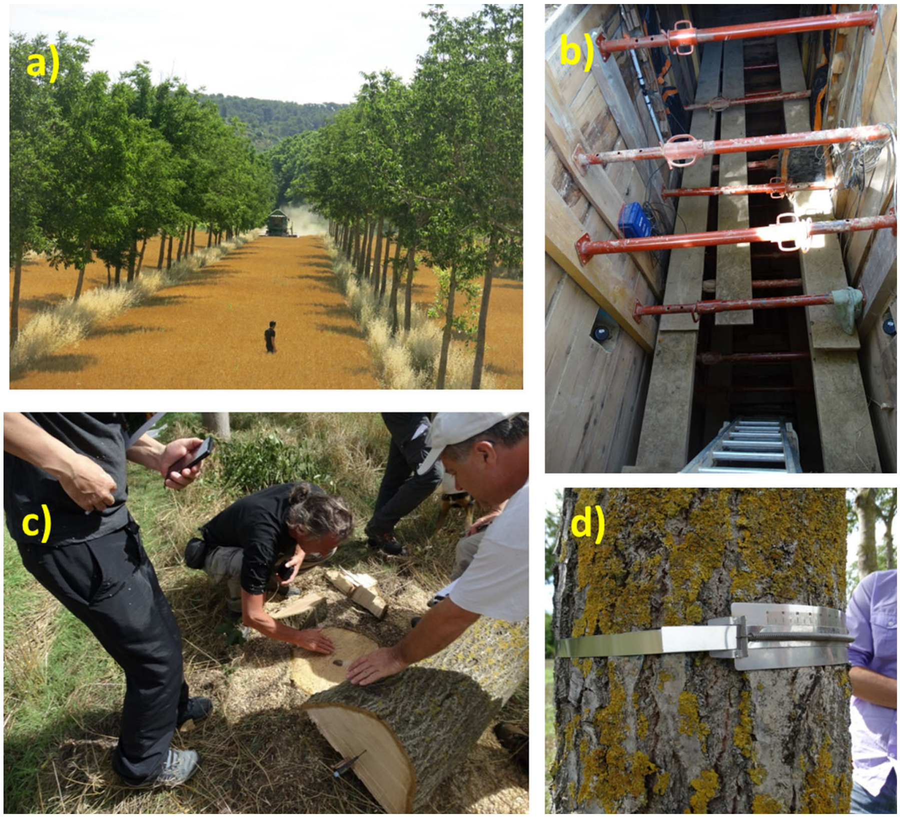

Fig. 3 Images of the alley cropping experiment of hybrid walnut and cereal grain located at Domaine de Restinclières agroforestry experimental site near Montpellier, France. Images depict: **a** the view between rows of timber trees. **b** A pit that was established to view root growth of trees. **c** Destructive harvest of above-ground biomass of timber trees. **d** Non-destructive measure of biomass increments based on continuous recording of diameter at breast height (DBH)

Common Agriculture Payments schemes for the support of agriculture. As of 2006, agroforesters are no longer penalized and get the same grants as all European farmers on the crop grown in their agroforestry plots. The proof that agroforestry could allow farmers to make money was urgently needed, and several thousands of French and European farmers, students in agriculture, policy-makers and farm advisors have been visiting the site during the last 20 years.

Horticulture and Agroforestry Research Center, University of Missouri Center for Agroforestry

Established in 1998, the Center for Agroforestry has been supported primarily through funding provided by the USDA Agricultural Research Services, along with multiple competitive grants and private and public partnerships. Much of the field research for the Center is conducted at the University of Missouri Horticulture and Agroforestry Research Center (HARC), located adjacent to New Franklin, MO and the Missouri River. The original 140-ha research farm was established in 1953 as the Horticulture Research Center focused on large and small fruits, vegetables, and turfgrass. With the addition of more land over time, the HARC farm now totals approximately 270 ha. HARC provides the physical and intellectual space for long-term research to study the science of agroforestry "…combining trees and/or shrubs with other crops and/or livestock". The layout of HARC, including a list of ongoing research, is shown in Fig. 4.

The mission of UMCA, to support working farms, integrates three critical dimensions of sustainability—economic, environmental, and social—through a wide array of research projects. Education and outreach are also emphasized through programs that train and transfer technologies to students, farmers, professionals, scientists, and policy makers. A unique aspect of

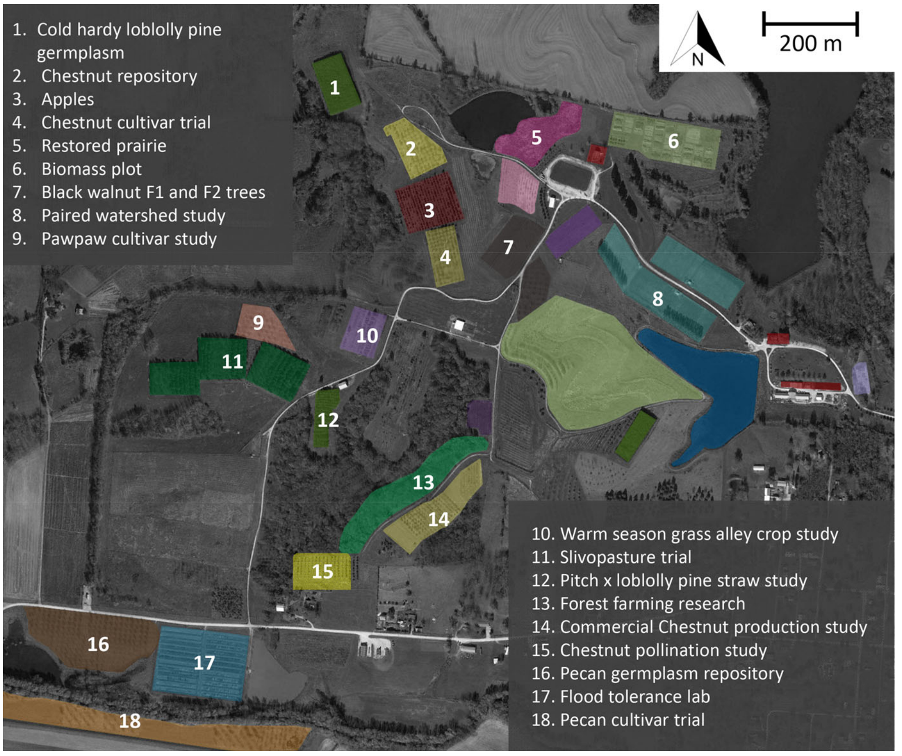

Fig. 4 Map of layout of agroforestry experiments at the Horticulture and Agroforestry Research Center (HARC), University of Missouri Center for Agroforestry

UMCA is the attention given to the potential for agroforestry to improve livelihoods for family farms and the health of rural communities by integrating income-producing specialty crops. UMCA's research portfolio at HARC has primarily focused on improving specialty crops through large germplasm collections of northern pecan (*Carya illinoinensis* (Wangenh.) K. Koch), black walnut (*Juglans nigra*) (Lehmkuhler et al. 2003), Chinese chestnut (*Castanea mollissima*) (Gold et al. 2006), pawpaw (*Asimina triloba*)(Cernusca et al. 2009), and elderberry (*Sambucus Canadensis*) (Thomas et al. 2015) for their production potential on the small farm (University of Missouri Center for Agroforestry 2017). As a truly interdisciplinary effort, a variety of additional studies provide new information on marketing potential, consumer preferences and human health benefits for edible products from agroforestry systems.

Example trial: alley-cropping of warm season grasses with bioenergy potential

Plants of various warm season grasses were established in the Alley-Cropping Shade Laboratory (ACSL) at the Horticulture and Agroforestry Research Center during the 2010 and 2011 growing seasons to explore their potential as productive bioenergy alley crops. The ACSL includes an open field adjoining an alley-cropping practice with three replications of 6.1, 12.2, and 18.3 m wide north–south oriented alleys formed by thinning a 12-year-old mixed hardwood stand (Fig. 5). The varying alley widths allowed researches to test different hypotheses about the effect of tree row shading on the alley grasses. Tillers from plants grown at HARC were used to establish new accessions of several native species with bioenergy potential: gamagrass (*Tripsacum dactyloides* L.), big bluestem (*Andropogon gerardii*), and little bluestem (*Schizachyrium scoparium*). Seedlings from the USDA Plant Materials Center foundation seed collection were used to establish 'Rumsey' Indiangrass (*Sorghastrum nutans*) and switchgrass (*Panicum virgatum*) cultivars.

Photosynthetically Active Radiation (PAR) sensors were mounted across each alley above the row of plants and connected to a datalogger to determine daily PAR by position within alleys on cloudless days. Number of tillers was estimated before harvesting

Fig. 5 Alley cropping study of shade tolerance of warm season grasses showing a satellite image of field trial (*left*) and view between plots (*right*)

above-ground forage biomass in fall of each year of the study. The findings were used to determine the impact of varying row widths, and thus PAR availability, on the productivity of the grasses. In 2014, studies were initiated on belowground interactions in the same alley-cropping experiment to examine impacts of established tree-rows on roots of alley crop grasses. Half of the plots were trenched to a minimum of 0.9 m, and polyethylene liners were inserted to prevent root–root interactions of trees and grasses, leaving the other half as a control. Grass biomass production, production physiology, nutrient accumulation, and nutrient use efficiency using ^{15}N labeled fertilizer are being evaluated in this long-term field trial. The constructed belowground barrier allows researchers to identify the impacts of tree root competition on alley crop grasses. Overall, the two alley-cropping experiments at the ACSL provide further understanding of the complexity of interactions that take place above- and below-ground and provide examples of useful experiments that allow agroforestry to progress towards more optimized, productive systems.

Agroforestry for food

The case study sites helped to inspire and guide the design of a new long-term field experiment at the University of Illinois, referred to as "Agroforestry for Food", which examines MWPs at a commercial scale and over the long term. Lessons from Domaine de Restinclières in France were primarily systems level and theory-based, whereas lessons from Horticulture and Agroforestry Research Center at the University of Missouri were primarily species-specific and application-based. Future research sites can benefit from the outcomes of each of these approaches, while also bringing in new elements that have not yet been explored.

Applying the lessons learned

Replication

The Restinclières site challenged the convention that treatments must be replicated to gather valuable data, as replication was not necessary to use the LER approach. The lack of replication has resulted in some limitations, including the ability to extrapolate results to other environments and geographies. For the Agroforestry for Food experiment, the decision was made to use a more standard randomized complete block design with four replications, with blocks placed to reduce variability due to field heterogeneity. A central tradeoff with this design was that subplot or split-plot experiments were not included in an effort to control effects across/within plots and between blocks. The standard homogenous management across treatments renders the site more accessible for data collection and provides an opportunity for collaboration with future researchers. Additional studies may arise from secondary grants to help alleviate potential funding shortages common in long-term agroforestry research.

Importance of water

Results from Restinclières pointed to the critical role of competition for water and characteristics of the water table in determining LER, tree-crop management, and tree root health/die-back, while also facilitating inter-specific competition and alley-crop loss. Drawing from this lesson, the Agroforestry for Food site has prioritized measurements of the water cycle in two ways. First, in experimental design, treatments were blocked primarily according to water availability (i.e. using high-resolution maps of soil electrical conductivity and magnetic susceptibility). Second, the limited available funds have been prioritized for collecting soil moisture and water table data (e.g. lysimeters, soil moisture tubes, etc.).

Plant diversity across treatments

The plots at Restinclières were quite simple using a single tree species, a single alley crop species, and a combination of the two. The primary hypotheses revolved around basic tree-crop interactions and system productivity, an important first step towards system development. However, the development of commercially suitable MWPs will likely require long-term experiments with treatment variability, which extends to mixed-species tree systems. The Agroforestry for Food trial was intentionally designed with multiple mixed-species systems that allowed the testing of specific species interactions, multiple mixtures, and diversity levels.

Alley management

All alleys at Restinclières were managed using full-scale farm equipment so that management was both easy and representative of large-scale application. In the Agroforestry for Food trial, a similar approach was used to ensure that alleys could be managed at a commercial scale, profitable from the start and a good example for farmers.

Species selection

The trials at HARC in Missouri offer specific information on species selection and management. For example, results of specific trials on chestnut pollination, both for variety compatibility and spacing/density requirements, were used directly to inform the selection and arrangement of plants in the Agroforestry for Food project. HARC also conducted extensive research on variety performance for a range of crops include chestnuts, elderberries, and others that were then used in the Agroforestry for Food Project. Long-term germplasm trials were essential to determine which specific tree crop species and cultivars were best suited to the geographic and edaphic conditions. Their work on germplasm procurement and assessment identified gaps on other species that might be targets for future research (e.g., hazelnuts and native small fruits). Since HARC is located to the southwest of the Agroforestry for Food site in central Illinois, the conditions are similar to those expected in future years with climate change (National Oceanic and Atmospheric Administration 2013; Pryor et al. 2014).

Modeling

Both case study sites highlighted the need for modeling to predict outcomes of agroforestry treatments under various conditions and to produce publications prior to system maturity. The Restinclières site demonstrated how the development of Hi-sAFe (a spatially-explicit, process based tree-crop model) can be used to simulate the growth of trees and crops and to predict grain and timber production. While Hi-sAFe has proven useful in Southern France, it is not parameterized for use in other temperate regions or with different tree-crop species. Additionally, the UMCA demonstrated how long-term funding can be a serious concern, and sustained interest by grant organizations must be pursued. The lack of usable models/species data and the need to generate interest through publications has resulted in attempts to begin model parameterization for the Agroforestry for Food trial. The parallel development of field research (model validation) at UIUC and data collection of species-specific parameters (model calibration) is aimed at making it possible to accurately predict biogeochemical and environmental interactions

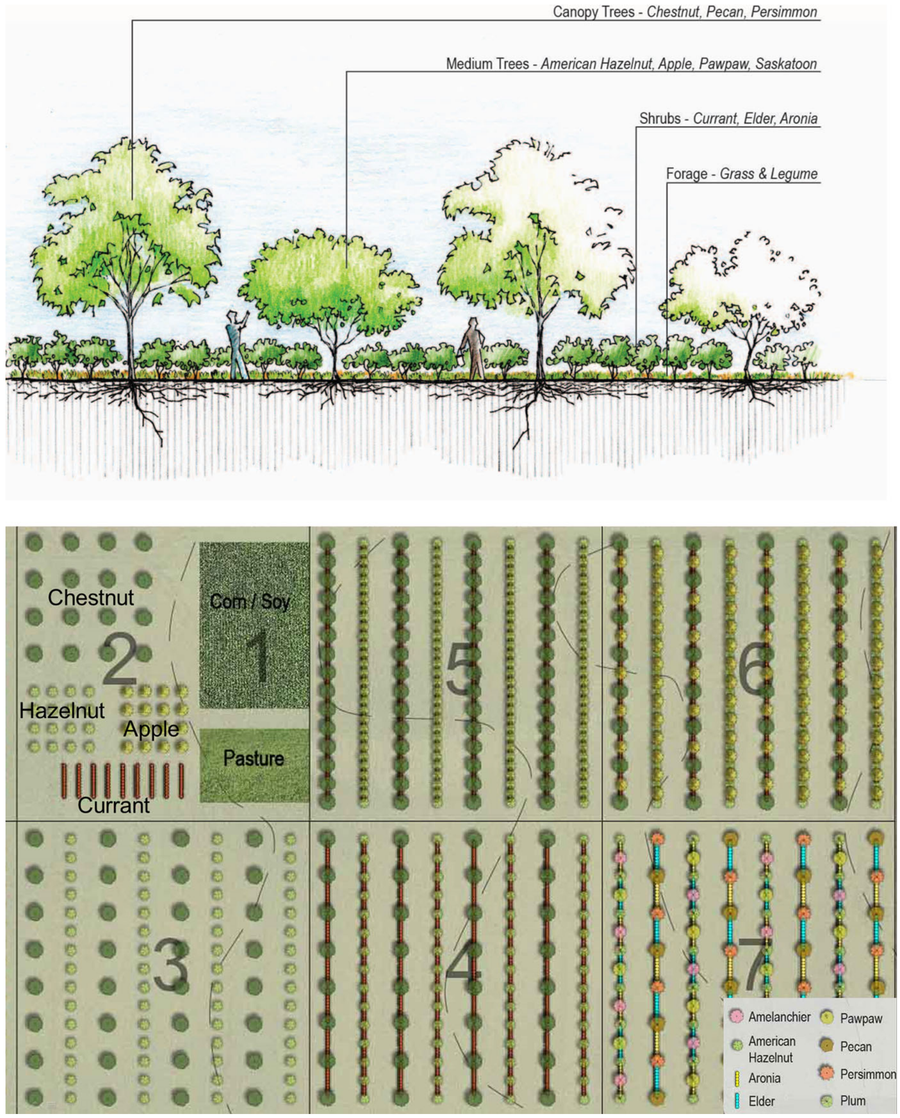

Fig. 6 Long-term research trial to study Multifunctional Woody Polyculture systems, showing the general structure of plant materials (*above*) and field layout of individual treatments, where each treatment is 73 m by 73 m (*below*). Illustrations by Paul Littleton

influencing agroforestry system productivity. From these modeling efforts, we hope to increase the conversation on mixed-species agroforestry systems and show how they can be relevant to the sustainable agriculture community. This outcome would theoretically allow for more interest in our research and opportunities for additional grants and funding opportunities.

Establishing the new trial

The Agroforestry for Food trial was specifically designed to test the performance of MPWs containing tree crops with edible fruits and nuts. The design, developed as a multi-layer structure (Fig. 6), encourages competition and facilitation amongst tree species, while also considering constraints in maintaining the system with agricultural equipment. The design is primarily an additive series, but also a simple treatment comparison of systems that allows for assessing plant arrangements that are practical for maintaining and harvesting treatments with standard equipment. Baseline soil sampling (electrical conductivity, magnetic susceptibility, soil type, and digital elevation) was conducted to determine the blocking pattern for placement of treatments.

Still in the establishment phase, the trial is located on a 12-ha site that includes 28 large plots

(73 × 73 m) in a randomized complete block design with the following treatments:

1. Corn-soybean rotation planted in standard 76 cm rows;
2. Monocultures of Chinese chestnut (*Castanea mollissima*), European hazelnut (*Corylus avellana*), and black currant (*Ribes nigrum*), and grass/legume for hay.
3. Chestnut and hazelnut in separate rows, spaced at 9.1 and 4.6 m within-row, respectively;
4. Same as treatment 3, with black currants added into rows at 0.76 m spacing;
5. Same as treatment 4 at double density of trees;
6. Same as treatment 4 with apples added into rows between chestnuts and hazelnuts; and.
7. High-diversity 'native edibles' with 5–7 species per row, spaced at 9.1 m for large trees, 4.6 m for small trees and 0.76 m for shrubs.

Treatment 7 was designed to be applicable for the Conservation Reserve Program (CRP, a USDA cost-share program). The alleys of each treatment (9.1 m width) were planted with a grass/legume forage mix for high quality hay production. This forage could be used for livestock grazing once trees reached a certain height. While not included in this trial, the alleys could alternatively be managed as row crops in the early years, depending on the preferences of individual growers.

The experiment, designed to mimic the canopy structure of a savanna as discussed earlier, includes crop species selected for their high production potential and baseline market for sale of products. Chinese chestnut, European hazelnut, and black currant were selected as the primary component species of the MWP trial, with an understory of forage for hay. Figure 7 demonstrates conceptually how the combination of crops could contribute to overall production over time. Chestnuts have already been proven in some portions of the Midwest region, with the top varieties averaging yields at full production (ages 10–12 years) of approximately 2200 kg ha^{-1} or 18 kg/tree at 9 × 9 m spacing. The cultivar in our study, 'Qing' has yielded over 45 kg/tree by age 12. With good market prices, chestnut production offers a viable alternative for farmers (University of Missouri Center for Agroforestry 2012). The U.S. hazelnut research communities are in transitional periods taking first generation accessions of improved germplasm from the breeding nurseries to field trials. The 'Yamhill' hazelnut variety was selected for our trials because of complete resistance to eastern filbert blight and high/consistent yields. At 4.6 m in-row spacing, they produce marketable kernel yield of 4 kg/tree or 1078 kg/ha at a between-row spacing of 9 m. Black currant produces a fruit with excellent health properties that can be used in juices, wine, and other products. Black currant trials in northern Wisconsin have shown yields up to 5600 kg ha^{-1} when grown as a monoculture (Fischbach and Dale 2010).

The Agroforestry for Food field trial intends to address several key themes for the future of agroforestry research. Food security is the first theme, since agroforestry including tree crops offers a transformative solution to think beyond grain production as the only primary food product. A second theme is climate change, as agroforestry offers an option for mitigation by reducing GHG emissions compared with other agroecosystems, and for adaptation through greater resilience under variable environmental conditions. Multifunctionality is the third theme, as this system seeks to bring ecological and cultural functions into a production system, offering a new alternative for growers in temperate zones. The forth theme is 'applied solutions' that move beyond basic sciences, to study practical options for growers.

One critical challenge of the project has been the need to answer early research questions and to provide the publishable outputs required by the faculty and graduate students involved in the project. In terms of

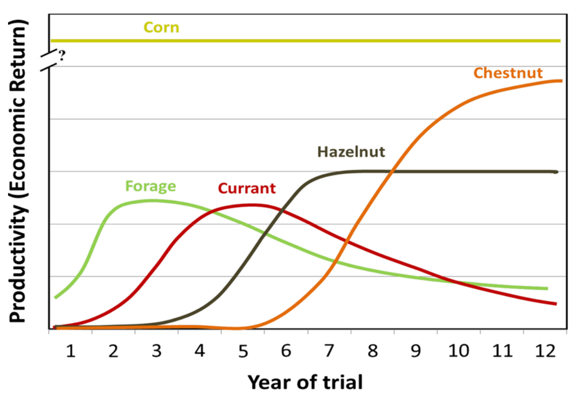

Fig. 7 Conceptual model of productivity of different components of the multi-species treatment in the "Agroforestry for Food" project at the University of Illinois

plant responses, researchers are studying the establishment success of individual species and precocity (age to produce fruit) of shrubs and trees. Intra- and interspecific competition with currants can be studied early, since the plants are spaced on 2.5′ centers. Separate small studies are designed to evaluate the performance of cultivars and shade tolerance of currants using shade cloth. Environmental responses such as water use, water quality, and carbon flux will focus on the impacts of the 'transition phase' in which a long-time tilled field is planted into diverse perennial crops.

Discussion

A strong commitment to long-term research is needed to characterize and quantify the benefits of MWPs. A concerted effort by researchers and growers might be best suited to broadly implement long-term MWP trials, such that the resources of agricultural experiment stations and the innovation of individual growers are both leveraged.

Agricultural experiment stations (AESs) in the U.S. could play an important role in long-term agroforestry experimentation due to their stability in funding and land tenure, potential to control field conditions, availability of staff and equipment, and mission to support research for the benefit of the public. These stations, founded at land grant colleges through the Hatch Act of 1887, retain a goal of advancing agricultural science and improving productivity of agriculture (Pearson and Atucha 2015). J Russell Smith (1950) had proposed a strong role of research stations for tree crop research, and back in 1947, he found that the work on tree crops was very limited. Molnar et al. (2013) proposed that in today's environment, research stations could: (1) identify promising species of perennial crops for regional conditions, (2) develop programs for long-term improvement, and (3) implement the use of tree crops through education and outreach. Broad adoption of these goals could help move MWPs forward as a viable alternative, and the implications could be particularly profound considering the need for agricultural systems adapted to climate variability (Jordan and Warner 2010).

While institutionally-supported long-term experiments offer the opportunity to study systems in a controlled situation, on-farm trials could provide valuable data on performance across a wide range of environments and management conditions. One challenge with on-farm studies is that they must be designed considering the landowner preferences; otherwise, they are unlikely to be retained and managed appropriately. One approach to overcome this issue is to develop a set of options (2–5 treatments) that the landowners can select from. Each treatment would have a prescribed set of species and planting spacing, but the different options could offer a diversity of system combinations and management strategies. Another challenge of studies at this temporal and spatial scale is that replication of treatments at an individual site is not always possible. To deal with the issue of replication, each site with a given treatment could be considered a replication. Recognizing that the variability between replications would be great, a larger number of replications of each treatment would be targeted. Another approach would be to treat the systems more like natural ecosystems, assessing performance based on a wide range of variables, using multivariate analysis across all on-farm study sites. Finally, on-farm research is challenged by the individual management strategies of growers, which calls for an adaptive management approach, whereby management decisions are adjusted in an iterative manner based on unforeseen outcomes along the way.

Initially, on-farm trials could be designated for "marginal lands", to reduce the risk and early economic loss of transitioning away from annual crops. Marginal lands are those areas of the farm that are less productive for conventional crops due to flooding, erosion, or other factors (Richards et al. 2014). The same characteristics that make lands marginal or unsuitable for annual row crops can make them ideal for woody polyculture systems, which can stabilize soil and retain nutrients (Molnar et al. 2013). These areas could then serve as the nodes for diffusion of the technology into the greater agricultural landscape if disruptions to our current agricultural system occur (e.g., climate change or resource limits) and alter the balance of economics. MWPs could also be integrated into farms through federal conservation programs, which also target marginal lands. While some programs, such as Conservation Reserve Program (CRP), do not allow harvesting products for sale (Stubbs 2014), farmers could still include tree crops that would become mature and productive beyond the term of the contract. An even better approach could be to adjust policies to allow some limited harvest of nuts, berries, or other minor products that would not substantially impact the conservation value of the system.

In the future, the UIUC Agroforestry for Food project will be expanding beyond the large-scale experiment at the research station to include on-farm trials. Two of the agroforestry treatments will be promoted with landowners—treatment 4 containing rows of chestnuts and hazelnuts with currants planted between the trees, and treatment 7 with the highly diverse combination of native species that could be used in a conservation planting program. Either or both of those treatments, following their establishment on a farm, could be compared with adjacent plantings of the corn/soybean rotation that are ubiquitous in the region. A goal to attain representation of each of those two treatments on fifteen sites would allow for a strong analytical outcome. To encourage landowners to participate, services of design layout and tree planting would be offered. Investment in the trees themselves would be left to the landowner so that they retain a sense of ownership over the system, increasing the likelihood of continued commitment to the planting.

Conclusions

Transformative solutions to our existing agricultural system are needed, and MWPs offer potential to address complex challenges of expanding population, limited resources, and shifting climate conditions. In addition to the broader environmental and social benefits, these systems may have the potential to improve conditions at the local level—offering greater prosperity for small farmers with diversification of livelihoods. Despite these promising benefits, MWPs remain largely understudied and underutilized.

The study sites across the Midwest United States and Southern France represent examples of research that needs to be reproduced on a larger scale to allow broad adoption of such systems. Research trials are currently too sparse across the temperate region to study MWPs on the scale required for informed consideration by growers. Agricultural Experiment Stations can play a key role in supporting long-term replicated research and improving crop performance, while also educating the public through demonstration plots. On-farm trials can also offer information on the more nuanced results of different designs and management practices administered by landowners and farmers. Networks of researchers, agroforestry landowners, and other stakeholders are developing as the need for knowledge sharing grows. Acquiring the funding to support these efforts will be difficult, but the commitments to agroforestry research at Domaine de Restinclières in France, University of Missouri, and most recently at University of Illinois can provide a springboard to future developments in this area.

The research and development infrastructure of agroforestry is growing. The time has come to invest in the experimentation and education necessary to advance MWPs beyond a mere vision of the future of food production. The state of our current agricultural system demands sustainable alternatives to conventional systems, and researchers working together with growers could provide viable, practical alternatives.

Acknowledgements This material is based upon work that is supported by the Institute for Sustainability, Energy, and Environment at the University of Illinois and National Institute of Food and Agriculture, U.S. Department of Agriculture, Hatch project under ILLU-802-938.

References

Allen SC, Jose S, Nair PKR, Brecke BJ (2004a) Competition for ^{15}N labeled nitrogen in a pecan-cotton alley cropping system in the southern United States. Plant Soil 263:151–164

Allen SC, Jose S, Nair PKR, Brecke BJ, Nkedi-Kizza P (2004b) Safety net role of tree roots: experimental evidence from an alley cropping system. For Ecol Manag 192:395–407

Anagnostakis SL (2012) Chestnut breeding in the United States for disease and insect resistance. Am Phytopathol Soc 96:1392–1403

Andrianarisoa KS, Dufour L, Bienaime S, Zeller B, Dupraz C (2016) The introduction of hybrid walnut trees (Juglans nigra x regia cv. NG23) into cropland reduces soil mineral N content in autumn in southern France. Agrofor Syst 90:193–205. doi:10.1007/s10457-015-9845-3

Baldwin CS (1998) The influence of field windbreaks on vegetable and specialty crops. Agric Ecosyst Environ 22:159–163

Barrico L, Azul AM, Morais MC, Coutinho AP, Freitas H, Castro P (2012) Biodiversity in urban ecosystems: plants and macromycetes as indicators for conservation planning in the city of Coimbra (Portugal). Landsc Urban Plan 106:88–102. doi:10.1016/j.landurbplan.2012.02.011

Benjamin TJ, Hoover WL, Seifert JR, Gillespie AR (2000) Defining competition vectors in a temperate alleycropping system in the midwestern USA: 4. The economic return of ecological knowledge. Agrofor Syst 48:79–93. doi:10.1023/a:1006367303800

Bharati L, Lee KH, Isenhart TM, Schultz RC (2002) Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. Agrofor Syst 56:249–257. doi:10.1023/a:1021344807285

Blake GR, Hartge KH (1986) Bulk Density. In: Klute A (ed) Methods of soil analysis: Part 1—physical and mineralogical methods. Soil Science Society of America, Madison, pp 363–375

Boutin C, Jobin B, Belanger L, Choiniere L (2002) Plant diversity in three types of hedgerows adjacent to cropfields. Biodivers Conserv 11:1–25

Bouwere H (1986) Intake rate: cylinder infiltrometer. In: Klute A (ed) Methods of soil analysis: Part 1—physical and mineralogical methods. Soil Science Society of America, Madison, pp 825–844

Brandt J, Vejre H (2004) Multifunctional landscapes—motives, concepts and perspectives. In: Brandt J, Vejre H (eds) Multifunctional landscapes Volume I: theory, value, and history. WIT Press, Boston

Button L, Elle E (2014) Wild bumble bees reduce pollination deficits in a crop mostly visited by managed honey bees. Agric Ecosyst Environ 197:255–263. doi:10.1016/j.agee.2014.08.004

Cannell MGR, VanNoordwijk M, Ong CK (1996) The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agrofor Syst 34:27–31. doi:10.1007/bf00129630

Capik JM, Muehlbauer M, Novy A, Honig JA, Molnar TJ (2013) Eastern filbert blight-resistant Hazelnuts from Russia, Ukraine, and Poland. Hortscience 48:466–473

Cardinael R et al (2015a) Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon—a case study in a Mediterranean context. Geoderma 259:288–299

Cardinael R, Mao Z, Prieto I, Stokes A, Dupraz C, Kim JH, Jourdan C (2015b) Competition with winter crops induces deeper rooting of walnut trees in a Mediterranean alley cropping agroforestry system. Plant Soil 391:219–235. doi:10.1007/s11104-015-2422-8

Cernusca MM, Hunt KL, Gold M (2009) Pawpaw: production trial and after purchase survey findings. University of Missouri, Columbia

Connolly J, Wayne P, Bazzaz FA (2001) Interspecific competition in plants: how well do current methods answer fundamental questions? Am Nat 157:107–125. doi:10.1086/318631

Dale A, Galic D (2014) Breeding blight resistant American chestnut for Canada. Acta Hortic Int Chestnut Symp 1019:49–54

Daloglu I, Nassauer JI, Riolo RL, Scavia D (2014) Development of a farmer typology of agricultural conservation behavior in the American Corn Belt. Agric Syst 129:93–102. doi:10.1016/j.agsy.2014.05.007

Dawson T, Fry R (1998) Agriculture in nature's image. Trends Ecol Evol 13:50–51. doi:10.1016/s0169-5347(97)01251-2

Dufour L, Metay A, Talbot G, Dupraz C (2013) Assessing light competition for cereal production in temperate agroforestry systems using experimentation and crop modelling. J Agron Crop Sci 199:217–227. doi:10.1111/jac.12008

Dupraz C (1998) Adequate design of control treatments in long term agroforestry experiments with multiple objectives. Agrofor Syst 43:35–48. doi:10.1023/a:1026495002991

Dupraz C, Newman SM (1997) Temperate agroforestry: the European way. In: Gordon AM, Newman SM (eds) Temperate agroforesry systems. CAB International, Wallingford, pp 181–236

Ferguson RS, Lovell ST (2014) Permaculture for agroecology: design, movement, practice, and worldview. Rev Agron Sustain Dev 34:251–274. doi:10.1007/s13593-013-0181-6

Ferguson RS, Lovell ST (2015) Grassroots engagement with transition to sustainability: diversity and modes of participation in the international permaculture movement. Ecol Soc 20:19. doi:10.5751/es-08048-200439

Fischbach J, Dale C (2010) Perfecting black currant production for machine harvest, vol 13. University of Wisconsin, Madison

Fixen P, Brentrup F, Bruulsema T, Garcia F, Norton R, Zingore S (2015) Nutrient/fertilizer use efficiency: measurement, current situation and trends. In: Drechsel P, Heffer P, Magen H, Mikkelsen R, Wichelns D (eds) Managing water and fertilizer for sustainable agricultural intensification. International Fertilizer Industry Association (IFA), Paris

Fulbright DW, Weidlich WH, Haufler KZ, Thomas CS, Paul CP (1983) Chestnut blight and recovering American chestnut trees in Michigan. Can J Bot 61:3164–3171

Germon A, Cardinael R, Prieto I, Mao Z, Kim J, Stokes A, Dupraz C, Laclau JP, Jourdan C (2016) Unexpected phenology and lifespan of shallow and deep fine roots of walnut trees grown in a silvoarable Mediterranean agroforestry system. Plant Soil 401:409–426. doi:10.1007/s11104-015-2753-5

Gold MA, Cernusca MM, Godsey LD (2006) Competitive market analysis: Chestnut producers Horttechnology 16:360–369

Hummer KE, Dale A (2010) Horticulture of Ribes. For Pathol 40:251–263

Hunt KL, Gold MA, Warmund MR (2005) Chinese chestnut cultivar performance in Missouri. In: Abreu CG, Rosa E, Monteiro AA (eds) Proceedings of the third international chestnut congress. Acta Horticulturae, vol 693. International Society Horticultural Science, Leuven 1, pp 145–148

Jordan N, Warner KD (2010) Enhancing the multifunctionality of US agriculture. Bioscience 60:60–66. doi:10.1525/bio.2009.60.1.10

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

Jose S (2011) Managing native and non-native plant species in agroforestry. Agrofor Syst 83:101–105

Jose S, Gordon AM (2008) Ecological knowledge and agroforestry design: an introduction. In: Jose S, Gordon AM (eds) Toward agroforestry design. An ecological approach. Springer, Dordrecht, pp 3–9

Jose S, Gillespie AR, Seifert JR, Mengel DB, Pope PE (2000) Defining competition vectors in a temperate alley cropping system in the midwestern USA—3. Competition for nitrogen and litter decomposition dynamics. Agrofor Sys 48:61–77. doi:10.1023/a:1006241406462

Jose S, Gillespie AR, Pallardy SG (2004) Interspecific interactions in temperate agroforestry. Agrofor Syst 61–2:237–255. doi:10.1023/B:AGFO.0000029002.85273.9b

Kort J (1988) Benefits of windbreaks to field and forage crops. Agr Ecosyst Environ 22–3:165–190. doi:10.1016/0167-8809(88)90017-5

Kumar S, Anderson SH, Udawatta RP, Kremer R (2012) Water infiltration influenced by agroforestry and grass buffers for a grazed pasture system. Agrofor Syst 84:325–335

Leakey RRB (2014) The role of trees in agroecology and sustainable agriculture in the tropics. In: VanAlfen NK (ed) Annual review of phytopathology, vol 52. Annual Reviews Inc., Palo Alto, pp 113–133

Lefroy EC (2009) Agroforestry and the functional mimicry of natural ecosystems. Agroforestry for natural resource management. CSIRO Publishing, Melbourne, pp 23–35

Lefroy EC, Hobbs RJ, O'Connor MH, Pate JS (1999) What can agriculture learn from natural ecosystems? Agrofor Syst 45:423–436

Lehmann J, Schroth G (2003) Nutrient leaching. In: Schroth G, Sinclair FL (eds) Trees, crops and soil fertility. CABI Publishing, Wallingford, pp 151–166

Lehmkuhler JW, Felton EED, Schmidt DA, Bader KJ, Garrett HE, Kerley MS (2003) Tree protection methods during the silvopastoral-system establishment in midwestern USA: cattle performance and tree damage. Agrofor Syst 59:35–42. doi:10.1023/a:1026184902984

Lovell ST, Johnston DM (2009) Creating multifunctional landscapes: how can the field of ecology inform the design of the landscape? Front Ecol Environ 7:212–220. doi:10.1890/070178

Macdaniels LH, Lieberman AS (1979) Tree crops—neglected source of food and forage from marginal lands. Bioscience 29:173–175. doi:10.2307/1307798

Malezieux E (2012) Designing cropping systems from nature. Agron Sustain Dev 32:15–29. doi:10.1007/s13593-011-0027-z

Malezieux E et al (2009) Mixing plant species in cropping systems: concepts, tools and models. Rev Agron Sustain Dev 29:43–62. doi:10.1051/agro:2007057

Martin FS, van Noordwijk M (2009) Trade-offs analysis for possible timber-based agroforestry scenarios using native trees in the Philippines. Agrofor Syst 76:555–567. doi:10.1007/s10457-009-9208-z

McIsaac GF, David MB, Mitchell CA (2010) Miscanthus and switchgrass production in Central Illinois: impacts on hydrology and inorganic nitrogen leaching. J Environ Qual 39:1790–1799. doi:10.2134/jeq2009.0497

Mead DJ, Willey RW (1980) The concept of a 'land equivalent ratio' and advantages in yields from intercropping. Exp Agric 16:217–228

Méndez VE, Lok R, Somarriba E (2001) Interdisciplinary analysis of homegardens in Nicaragua: micro-zonation, plant use and socioeconomic importance. Agrofor Syst 51:85–96

Mollison B, Holmgren D, Barnhart E (1981) Permaculture one: a perennial agriculture for human settlements. International Tree Crop Institute USA, Davis

Molnar TJ, Capik JM (2012) Advances in hazelnut research in North America. Acta Hortic 940:57–65

Molnar TJ, Zaurov DE, Goffreda JC, Mehlenbacher SA (2007) Survey of hazelnut germplasm from Russia and Crimea for response to eastern filbert blight. HortScience 42:51–56

Molnar TJ, Kahn PC, Ford TM, Funk CJ, Funk CR (2013) Tree crops, a permanent agriculture: concepts from the past for a sustainable future. Resources 2:457–488

Mulia R, Dupraz C (2006) Unusual fine root distributions of two deciduous tree species in southern france: what consequences for modelling of tree root dynamics? Plant Soil 281:71–85. doi:10.1007/s11104-005-3770-6

Nair PKR (2011) Methodological challenges in estimating carbon sequestration potential of agroforestry systems. In: Kumar BM, Nair PKR (eds) Carbon sequestration potential of agroforestry systems: oppoortunities and challenges, vol 8., Advances in AgroforestrySpringer, Dordrecht, pp 3–16. doi:10.1007/978-94-007-1630-8_1

National Oceanic and Atmospheric Administration (2013) Regional climate trends and scenarios for the U.S. national climate assessment Vol Part 3. Climate of the Midwest. U.S. Department of Commerce, Washington

Pearson C, Atucha A (2015) Agricultural experiment stations and branch stations in the United States. J Nat Resour Life Sci Educ 44:1–5

Pryor SC et al. (2014) Midwest climate change impacts in the United States: The Third National Climate Assessment. In: Melillo JM, Richmond TC, Yohe GW (eds) Climate change impacts in the United States: the third national climate assessment U.S. Global Change Research Program, Washington

Rhodes TK, Aguilar FX, Jose S, Gold MA (2016) Factors influencing adoption of riparian forest buffers in the Tuttle Creek Reservoir Watershed of Kansas. Agroforestry Systems In press, U.S.A

Richards BK, Stoof CR, Cary IJ, Woodbury PB (2014) Reporting on marginal lands for bioenergy feedstock production: a modest proposal. Bioenergy Res 7:1060–1062

Rigueiro-Rodriguez A, Fernandez-Nunez E, Gonzalez-Hernandez P, McAdam JH, Mosquera-Losada (2009) Agroforestry systems in Europe: productive, ecological and social perspectives. Agroforestry in Europe: current status and future prospects, vol 6. Springer, Dordrecht

Sanchez-Humanes B, Espelta JM (2011) Increased drought reduces acorn production in Quercus ilex coppices: thinning mitigates this effect but only in the short term. Forestry 84:73–82. doi:10.1093/forestry/cpq045

Sanchez-Humanes B, Sork VL, Espelta JM (2011) Trade-offs between vegetative growth and acorn production in Quercus lobata during a mast year: the relevance of crop size and hierarchical level within the canopy. Oecologia 166:101–110. doi:10.1007/s00442-010-1819-6

Schoeneberger MM (2009) Agroforestry: working trees for sequestering carbon on agricultural lands. Agrofor Syst 75:27–37. doi:10.1007/s10457-008-9123-8

Smith JR (1950) Tree crops: a permanent agriculture. Devin-Adair, New York

Smith J, Pearce BD, Wolfe MS (2013) Reconciling productivity with protection of the environment: is temperate agroforestry the answer? Renew Agric Food Syst 28:80–92. doi:10.1017/s1742170511000585

Strong NA, Jacobson MG (2005) Assessing agroforestry adoption potential utilising market segmentation: a case study in Pennsylvania. Small Scale For Econ Manag Policy 4:215–228

Stubbs M (2014) Conservation Reserve Program (CRP): status and issues. USDA, Washington

Talbot G (2011) L'intégration spatiale et temporelle du partage des ressources dans un système agroforestier noyers-céréales: une clef pour en comprendre la productivité?

Talbot G, Dupraz C (2012) Simple models for light competition within agroforestry discontinuous tree stands: are leaf clumpiness and light interception by woody parts relevant factors? Agrofor Syst 84:101–116. doi:10.1007/s10457-011-9418-z

Thomas AL, Byers PL, Avery JD Jr, Kaps M, Gu S (2015) Horticultural performance of eight American elderberry genotypes at three Missouri locations. In: Thomas AL (ed) Acta Horticulturae, vol 1061. International Society for Horticultural Science (ISHS), Leuven, pp 237–244

Udawatta RP, Jose S (2012) Agroforestry strategies to sequester carbon in temperate North America. Agrofor Syst 86:225–242. doi:10.1007/s10457-012-9561-1

University of Missouri Center for Agroforestry (2012) Growing Chinese chestnuts in Missouri. University of Missouri, Columbia

University of Missouri Center for Agroforestry (2017) Specialty crops. University of Missouri, Columbia. http://www.centerforagroforestry.org/profit/#specialty. Accessed 26 Jan 2017

Valdivia C, Barbieri C, Gold MA (2012) Between forestry and farming: policy and environmental implications of the barriers to agroforestry adoption. Can J Agric Econ 60:155–175. doi:10.1111/j.1744-7976.2012.01248.x

Vanclay JK (2006) Experiment designs to evaluate inter- and intra-specific interactions in mixed plantings of forest trees. For Ecol Manag 233:366–374. doi:10.1016/j.foreco.2006.05.034

Wang E et al (2002) Development of a generic crop model template in the cropping system model APSIM. Eur J Agron 18:121–140. doi:10.1016/s1161-0301(02)00100-4

Wanvestraut RH, Jose S, Nair PKR, Brecke BJ (2004) Competition for water in a pecan (Carya illinoensis K. Koch)—cotton (*Gossypium hirsutum* L.) alley cropping system in the southern United States. Agrofor Syst 60:167–179. doi:10.1023/B:AGFO.0000013292.29487.7a

Wright GC, Storey JB, Harris MK, Sprinz PT (1990) Pre-harvest pecan yield estimation. Hortscience 25:698–700