doi:10.2489/jswc.2022.1028A

FEATURE

Soil and water ecosystem services of agroforestry

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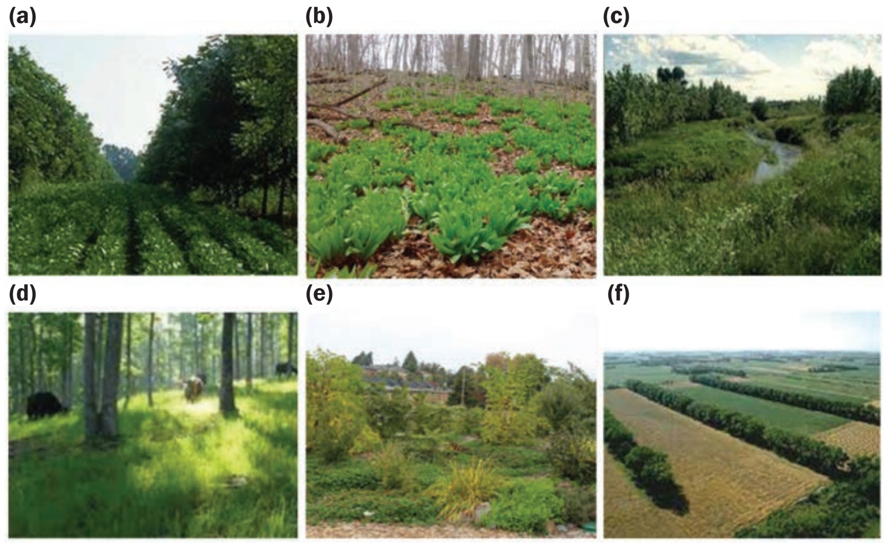
Degraded soil and water affects life by reducing food, clean water, and habitat (Lal 2010; Montgomery 2007; Wall and Six 2015). Sustainable land use practices to ensure soil and water quality are actively promoted by government agencies, but voluntary producer adoption rates are still low. Garibaldi et al. (2021) argue for the restoration of native habitats within working landscapes to at least 20% of land for benefits to food security, nature's contributions to people, and associated ecosystem services (ES).

Agroforestry (AF) is a land use practice that can provide ES by mimicking natural forests. In AF, trees and other perennial plants are integrated into row crop and livestock fields and can conserve and improve soil and water quality and land productivity. The six main AF practices in temperate zones include alley cropping, forest farming, riparian and upland buffers, silvopasture, urban food forests, and windbreaks (figure 1). While AF has been practiced for thousands of years, the scientific quantification of its benefits has advanced only recently. Many recent articles have described beneficial ES created by AF (Jose 2009; Anderson and Udawatta 2019; Udawatta et al. 2017, 2022; Udawatta 2022; Schulte et al. 2017). This paper presents an overview of soil and water services of AF for temperate regions.

Figure 1

(a) Alley cropping, (b) forest farming, (c) riparian buffers, (d) silvopasture, (e) urban food forest, and (f) windbreaks. (Photo credits: a, c, and f courtesy of aftaweb.org, b courtesy of Hannah Hemmelgarn, d courtesy of agebb.missouri.edu, and e courtesy of Catherine J. Bukowski.)



SOIL ECOSYSTEM SERVICES

Agroforestry and Carbon Sequestration. Among soil health indicators, soil carbon (C) is principal as it improves water dynamics and physical, chemical, and biological properties of soil. In the United States, Canada, and the former Soviet Union, windbreaks have been used to combat drought, reduce wind-blown soils, improve soil health, and increase soil C (Brandle et al. 2004; Sanft 2010; Mayrnick et al. 2019). The Prairie State Project in the 1930s planted 223 million trees from Texas to North Dakota (Oklahoma Historical Society 2021), and in the Soviet Union, 5.7 × 10^6 ha (1.4 × 10^7 ac) of windbreaks were planted to combat drought and improve soil and crop yields (Sanft 2010). Broadleaf trees and conifers in windbreaks store 2.5 and 4.4 Mg C ha^{-1} (1.1 and 2.0 tn C ac^{-1}) (Possu et al. 2016), and increases of 16% C beneath tree windbreak plantings in the US Great Plains have recently been reported by Khaleel et al. (2020). In other studies, organic C in the 0 to 15 cm (0 to 5.9 in) layer within the shelterbelt (3.99 kg m^{-2}) was 10% more than in the cultivated fields (3.62 kg m^{-2}), and tree litter contained an additional 1.300 kg C m^{-2} making a 46% increase in C (Sauer et al. 2007; Schoeneberger et al. 2012). In Canada, 3.77 Tg C (4.16 × 10^6 tn C) was sequestered by 610+ million trees of windbreaks (Mayrnick et al. 2019). Other benefits of Canadian windbreaks, including increased crop yields and reduced domestic heating costs, were over C$600 million.

A meta-analysis collected from 53 studies showed the transition from agriculture to AF significantly increased C by 26%, 40%, and 34% in the 0 to 15, 0 to 30, and 0 to 100 cm (0 to 5.9, 0 to 11.8, and 0 to 39.4 in) zones (De Stefano and Jacobson 2018). In the United States, grazinglands and croplands have an increased potential to sequester C with AF offsetting carbon dioxide (CO_2) emissions (Nair 2012; Udawatta and Jose 2012). In South Carolina, mature riparian buffers sequestered >100 Mg C ha^{-1} (44.6 tn C ac^{-1}) (Giese et al. 2003). Poplar trees (*Populus* spp.) in Iowa sequestered 5, 8, and 2.5 times more C than corn (*Zea mays* L.), soybean (*Glycine max* [L.] Merr.), and pasture, respectively (Tufekeioglu et al. 2003). In a long-term alley-cropping watershed study, Salceda et al. (2022) showed a 12% increase in C sequestration with AF (figure 2). Agroforestry buffers, grass waterways, and row crop areas showed 16.5%, 9%, and 5% greater soil organic C in 2020 versus

Received October 28, 2021.

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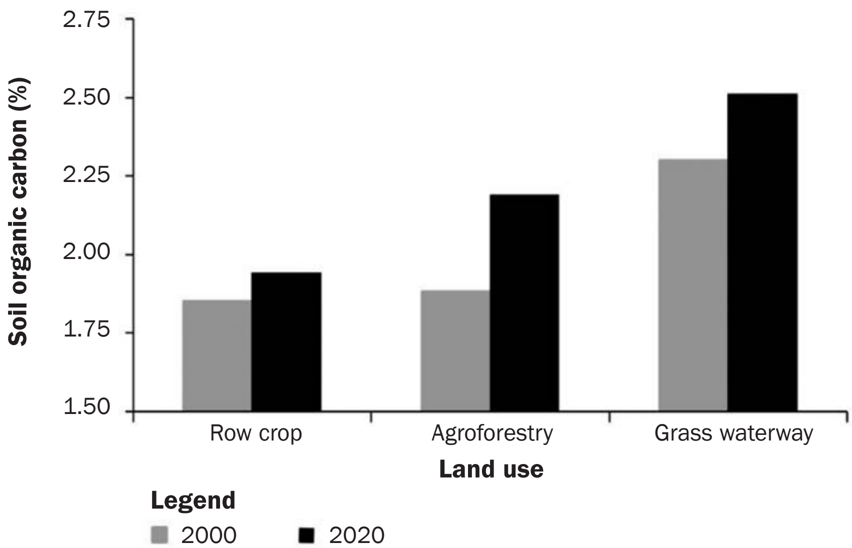
Figure 2
Soil organic carbon (SOC) from 2000 to 2020 for 0 to 10 cm soil depth of row crop, agroforestry, and grass waterway areas; Greenley Research Center, University of Missouri (adapted from Salceda et al. [2022]).



2000. In 20 years, 4.24 and 1.99 Mg C ha^{-1} (1.89 and 0.89 tn C ac^{-1}) was added to the 0 to 10 cm (0 to 4 in) soils of AF and row crop areas. Greater C sequestration in AF versus row crops is created from combined grassland and forest sequestrations, higher percentage of C allocation to below ground portions, structural and functional differences, efficient resource utilization, and stability of C (Sharrow and Ismail 2004; Baah-Acheamfour et al. 2014).

Soil Physical Properties under Agroforestry. Additions of biomass with AF improve soil physical properties including aggregate stability, water holding capacity, infiltration, hydraulic conductivity, and porosity (Udawatta et al. 2008; Sahin et al. 2016; Akdemir et al. 2016; Alagele et al. 2019). Biomass lowers bulk density and may reduce drought stress, wetness, and extreme soil temperatures. A long-term study at the Greenley Research Center has shown large mesoporosity (60 to 1,000 μm diameter [0.002 to 0.04 in]) was 3% higher and saturated hydraulic conductivity was three times higher in AF buffers versus corn–soybean cropland (Seobi et al. 2005; Akdemir et al. 2016). Similar findings have been reported in silvopastures and crops of the US Midwest (Kumar et al. 2008, 2012). Improved soil thermal properties are created with AF buffering soil from extreme temperature conditions (Adhikari et al. 2014). Such improved thermal properties likely reduce the rate soil C mineralizes and prompt microbial abundance and diversity.

Perennial AF roots use water for evapotranspiration before row crops are established in early spring and reduce spring waterlogging (Udawatta et al. 2011a; Sahin et al. 2016; Alagele et al. 2020a). During rains, AF soils store more water than row crop areas because of improved infiltration and porosity, and Anderson et al. (2009) reported greater soil water storage in AF soil than for row crop areas. These increases can provide water during short rainless periods reducing plant stress. During these dry periods, trees hydraulically lift water from deep soil providing water for shallow-rooted plants. Increased hydraulic conductivity and infiltration in AF reduces runoff potential, soil erosion, and other pollution.

Agroforestry Impacts on Soil Chemistry and Biology. Agroforestry-promoted soil chemical services include soil nutrient enrichment and decontamination of pollutants (Anderson and Udawatta 2019). Studies have shown reductions in nutrient loss, increased retention on farms, and addition of plant nutrients with riparian buffers, upland buffers on alley cropping systems, and windbreaks. Two long-term row crop and grazing studies have shown 43%, 48%, and 39% reduction in total nitrogen (N), total phosphorus (P), and soil erosion with AF than control treatments (Udawatta et al. 2011b). Upland buffers like alley cropping and riparian buffers next to a stream effectively retain plant nutrients from runoff (Schultz et al. 2022). Wider buffers are more effective in retaining nutrients, though land is removed from production (Mayer et al. 2007; Liu et al. 2008). However, long-term benefits of improved soil quality with AF may outweigh greater short-term yields (Schulte et al. 2017). Studies in Iowa showed increased economic and environmental (soil and water quality) benefits of strategic placement of perennial vegetation in a row-cropped watershed (Muth 2014; Morris and Arbuckle 2021).

A mixed, diverse vegetation with deep roots can improve soil nutrient status and thus improve soil productivity and reduce water pollution. Safety net, nutrient pumping, hydraulic lift, and hydraulic redistribution from AF's perennial vegetation can promote nutrients and water supply to shallow rooted crops (Ong et al. 2014). For example, nitrate (NO_3^-) loss was reduced by the safety net against nutrient leaching below the rooting zone in an Appalachian silvopasture practice (Boyer and Neel 2010). Those deeper tree roots capture nutrients below crop and grass root zones and reduce leaching losses. In hydraulic lift and redistribution as well as in nutrient pumping, deep roots absorb deeper soil water and nutrients and deliver and redistribute those on drier surface soils for shallow rooted plants.

Decomposition of plant litter and legumes enhances soil water dynamics and nutrient cycling within AF systems. Thevathasan and Gordon (2004) reported 7 kg ha^{-1} y^{-1} (6.25 lb ac^{-1} yr^{-1}) N release from litter fall of poplar in an intercropped system in Canada. In Oregon, red alder (*Alnus rubra* Bong.), a legume, supplied from 32% to 58% of the N needs for corn (Seiter et al. 1995). Integration of legumes further increase potential N supply for crops. Generally, nutrients, such as N, P, and

C, and mycorrhizal fungi (which create beneficial mutual symbiotic associations with plants) are higher under trees, indicating soil fertility benefits of AF (Rivest et al. 2013; Bainard et al. 2011, 2012). Soil microbial communities associated with AF vegetation include arbuscular mycorrhizae fungi (AMF, associations that can benefit crops) and ectomycorrhiza fungi (ENF, common with conifers, birch [*Betula* spp.], beech [*Fagus* spp.], and oak [*Quercus* L.] families and some woody plants). Many crops benefit from mycorrhizal fungi that improve nutrient supply via increasing availability, solubility, transformation, and translocation, and thereby increase land productivity (Bainard et al. 2011).

Nutrients, heavy metals, pesticides, herbicides, antibiotics, personal care products, other chemicals, and highly toxic "forever chemicals" of per- and polyfluoroalkyl substances (PFAS) are found in water and soil (USEPA 2007; Ahrens 2011). Flora and fauna associated with the AF's vegetation help decompose and immobilize the materials in water and soil. Diverse organic compounds in AF soils hold many organic chemicals, including antibiotics, and thus reduce water contamination (Chu et al. 2010). Some of these chemicals are degraded to less harmful chemicals and finally to CO_2 and water (Lin et al. 2010). The soil of AF reduces half-life and increases the rate of degradation of some of these chemicals (Lin et al. 2010, 2011). Agroforestry root exudates also promote chemical degradation by soil fauna (Chu et al. 2010). Plant-soil mechanisms that facilitate soil decontamination include pollution stored in the biomass, biodegradation, rhizodegradation, phytostabilization, phytoextraction, and immobilization (Lin et al. 2010, 2011). Commonly used AF trees, including poplar and willow (*Salix* ssp.), have been shown to be effective in rehabilitating contaminated soils (Rockwood et al. 2004; Chang et al. 2005; Lin et al. 2010; Gomes 2012).

Soil Diversity Benefits. Agroforestry soils are more biologically diverse with greater species richness than monocropped soils. Greater organism diversity improves mineralization, nutrient cycling, nutrient availability, resistance to pests and diseases, regulation of plant growth, soil stability, water dynamics, and primary productivity (Kremer et al. 2015; Banerjee et al. 2016). These benefits are in part attributed to organic compounds produced from diverse fauna and flora and improved soil and microclimatic conditions (Jose 2009; Jose et al. 2004). For instance, greater diversity and abundance of bacteria, fungi, actinomycetes, and protozoa have been observed in AF than in monocrop grass or row crops (Kremer et al. 2015; Banerjee et al. 2016; Beuschela et al. 2019; Lacombe et al. 2009; Alagele et al. 2020b). Enzyme activities in soil were also greater with AF than in monocropping and pastures, and correlated with greater soil C, vegetation density, and soil type (Udawatta et al. 2009; Paudel et al. 2011; Banerjee et al. 2016; Weerasekera et al. 2016). Kremer and Hezel (2013) observed greater abundance of Gram-negative bacteria responsible for N mineralization, plant growth stimulation, and supply of antibiotics. Others have shown greater abundance of saprotrophic, ectomycorrhizal, and arbuscular fungi under tree-based AF than pastures and crop areas (Lacombe et al. 2009; Bainard et al. 2012, 2013; Beuschela et al. 2019).

Individual species richness varies with tree and shrub species due to differences in plant litter, exudates, and biomass (Zak et al. 2003; Banerjee et al. 2016). Microbial communities with AF have been found to be more resilient and robust compared to those of monocrops (Rivest et al. 2013). As these organisms in AF complete their life cycles, significant amounts of C and nutrients are added to the soil to improve soil services and land productivity (Kremer et al. 2015). However, AF biological differences diminish with time due to increasingly uniform distributions of organic exudates, roots, and litter material as the system matures (Bambrick et al. 2010; Bardhan et al. 2013; Weerasekera et al. 2016).

Counts of soil macrofauna animals like earthworms were also greater with AF than in row crop areas (Pauli et al. 2010; Price and Gordon 1998). The spatial distribution of earthworm casts and counts were related with tree density, species, and litter characteristics (Pauli et al. 2010; Cardinael et al. 2018).

WATER ECOSYSTEM SERVICES

Agroforestry contributes to ES by improving water quality, water availability, and reduction of flooding. Surface litter, stems, and roots reduce flow and increase sedimentation and nutrient retention (Schultz et al. 2009). Litter intercepts rain, which reduces soil splash (Gantzer et al. 1987). Perennial vegetation also intercepts and retains rain, which reduces the rainfall that reaches the ground. Improved infiltration, water storage, and fixed organic C reduce soil and nutrient loss. Borrelli et al. (2021) evaluated 1,697 soil erosion articles from 126 countries and determined that water erosion was the main cause of erosion in 95% of the studies. Erosion rates were 1.2, 0.5, 0.2, and 0.1 mm y^{-1} (0.047, 0.020, 0.008, and 0.004 in yr^{-1}) and for bare, arable, forest, and AF land, respectively.

Vegetative organic matter stores nutrients for long periods. Enhanced nutrient uptake stores nutrients in AF vegetation, releasing it for uptake by other vegetation, thus reducing nutrient loss and decreasing water pollution. In temperate zones, conservation effects by riparian buffers are well documented. Naiman et al. (2005) reported that mature riparian buffers store large amounts of nutrients in biomass (10 Mg P ha^{-1} y^{-1} [4.46 tn P ac^{-1} yr^{-1}]). In Florida, heavily fertilized alley cropping and silvopasture AF reduced NO_3-N by ~23% and P losses by ~50% (Nair and Gartz 2004).

The Lower Mississippi River Basin annually loses 30 kg N $ha^{-1}$and 3 kg P ha^{-1} (26.79 lb N ac^{-1} and 2.68 lb P ac^{-1}) (USDA NRCS 2013). These losses can be reduced by up to 48% with AF (Udawatta et al. 2011b). Pavlidis and Tsihrintzis (2018) wrote a review of more than 2,000 studies that supported findings of these benefits and showed reductions of N and P losses from 20% to 100%, and reduction of pesticide losses by up to 90%. Agroforestry reduces movement of herbicides, antibiotics, and other chemicals in runoff (Chu et al. 2010; Lin et al. 2010, 2011), thus improving water quality.

Agroforestry buffers improve the quality of shallow groundwater by root uptake and enhance conditions for denitrification (Hickey and Doran 2004; Mayer et al. 2005) since the retention time is sufficient for tree roots and bacteria to interact with groundwater. Reductions ranging from 65% to 90% for N and 24% to 81% for P in groundwater have been observed (Mayer et al. 2005; Schoonover et al. 2003). Three times lower NO_3^- concentrations have been reported in wells along a riparian buffer as compared to a grass buffer in Missouri (Wickramaratne 2017) where most removal was observed within the first 20 m (66 ft) of the riparian zone (Peterjohn and Correll 1984; Jacobs and Gilliam 1985).

Climate change–projected rainfall amounts and intensity will further deteriorate water, soil, and land, and damage levees, especially in the Northeast and Midwest United States (Nearing 2001; Nearing et al. 2004; NCA 2014). Riparian buffers, alley cropping, windbreaks, silvopasture, and forest farming can reduce damages and promote faster recovery (Dwyer et al. 1997; Schoeneberger et al. 2012; USDA NAC 2016). Agroforestry perennial vegetation intercepts, transpires, and stores more water than annual crops; creates resistance to overland flow reducing peak flow; and reinforces banks and levees (figure 3), thus reducing levee failure (Udawatta et al. 2022; Venkatraman and Ashwath 2016). Dwyer et al. (1997) reported after the Great Flood of 1993 that riparian buffers longer than 100 m (328 ft) significantly reduced levee breaks. Though sand can be removed from farmlands to repair cropland, levee-breaking rain events are increasingly probable because of climate change (figure 4). After the Great Flood of 1993, the State of Missouri bought ~80,000 ha (197,684 ac) of riverfront farmlands to establish permanent riparian buffers to protect farmlands.

Figure 3
Rooting strength with tree harvesting and regrowth (Source: Sidle 1985).

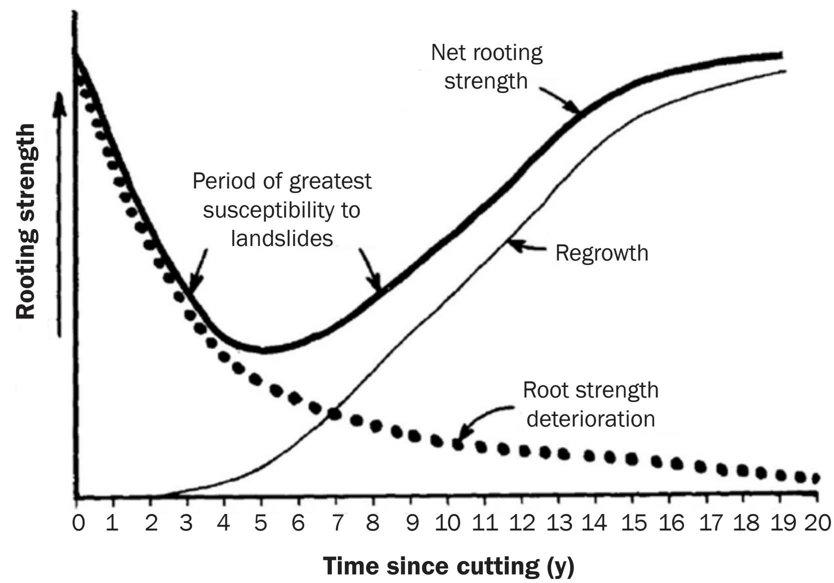
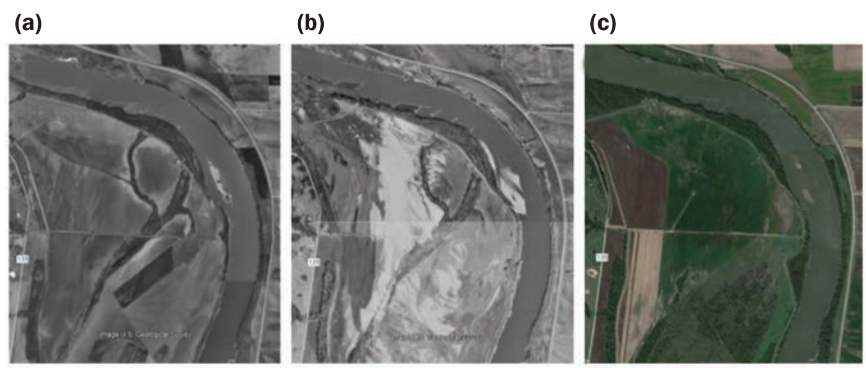


Figure 4
Images of (a) before the Great Flood of 1993 (1992), (b) sand deposition and levee break (1995), and (c) healing riparian vegetation growth (2012) near Cambridge, Missouri (images from Google Earth).



SUMMARY AND CONCLUSION

The term "ecosystem services" implies some human benefits. Integration of AF on agricultural land can mitigate many negative impacts of agriculture. Agroforestry improves soil, water, and land productivity, and reduces flood damage because of its perennial vegetation, limited machinery use, and reduced chemical use. Improved nutrient cycling and legumes in AF increase crop and pasture yields. Trees and perennial vegetation of AF reduce stress conditions by buffering soil microclimate extremes. These benefits extend beyond farm boundaries. For example, wider buffers along streams of watersheds planted in corn and soybean decrease nutrient loads to the Mississippi River and thus improve the health and economy of the Gulf of Mexico and states surrounding the gulf. There is no single factor that contributes to all these services, but many interconnected factors provide these services. Sound AF management can further enhance ES and reduce negative impacts of agriculture. Tree species, age, density, management, and soil-site-climatic characteristics determine these services. Agroforestry is a helpful solution for soil and water ES.

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