Soil and water ecosystem services of agroforestry

Ranjith P. Udawatta and Clark J. Gantzer

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.

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

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.)

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 (CO₂) 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 (Tufekcioglu 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

Ranjith P. Udawatta is a research professor at The Center for Agroforestry, School of Natural Resources, University of Missouri, Columbia, Missouri, and **Clark J. Gantzer** is an emeritus professor of soil conservation of the School of Natural Resources, University of Missouri, Columbia, Missouri.

Received October 28, 2021.

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 (NO₃⁻) 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 yr⁻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 CO₂ 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* spp.), 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 NO₃-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 suffi-

cient 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.

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

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).

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.

REFERENCES

- Adhikari, P., R.P. Udawatta, S.H. Anderson, and C.J. Gantzer. 2014. Soil thermal properties under prairies, conservation buffers, and corn/soybean land use systems. *Soil Science Society of America Journal* 78:1977–1986.
- Ahrens, L. 2011. Polyfluoroalkyl compounds in the aquatic environment: A review of their occurrence and fate. *Journal of Environmental Monitoring* 13:20–31.
- Akdemir, E., S.H. Anderson, and R.P. Udawatta. 2016. Influence of agroforestry buffers on soil hydraulic

- properties relative to row crop management. *Soil Science* 181:368–376.
- Alagele, S.M., S.H. Anderson, and R.P. Udawatta. 2019. Biomass and buffer management practice effects on soil hydraulic properties compared to grain crops for claypan landscapes. *Agroforestry Systems* 93:1609–1625.
- Alagele, S., S.H. Anderson, and R.P. Udawatta. 2020a. Agroforestry, grass, biofuel crop, and row-crop management effects on soil water dynamics for claypan landscapes. *Soil Science Society of America Journal* 84:203–219.
- Alagele, S.M., S.H. Anderson, R.P. Udawatta, K.S. Veum, and L.M. Rankoth. 2020b. Long-term perennial management and cropping effects on soil microbial biomass for claypan soils. *Agronomy Journal* 112:815–827.
- Anderson, S.H., and R.P. Udawatta. 2019. Agroforestry: A system for improving soil health. In *Agroforestry for Sustainable Agriculture*, eds. M.R. Mosquera-Losada and R. Prabhu, 317–334. Cambridge, UK: Burleigh Dodds Scientific Publishing.
- Anderson, S.H., R.P. Udawatta, T. Seobi, and H.E. Garrett. 2009. Soil water content and infiltration in agroforestry buffer strips. *Agroforestry Systems* 75:5–16.
- Baah-Acheamfour, M., C.N. Carlyle, E.W. Bork, and S.X. Chang. 2014. Trees increase soil carbon and its stability in three agroforestry systems in central Alberta, Canada. *Forest Ecology and Management* 328:131–139.
- Bainard, L.D., A.M. Kochb, A.M. Gordon, S.G. Newmaster, N.V. Thevathasan, and J.N. Klironomos. 2011. Influence of trees on the spatial structure of arbuscular mycorrhizal communities in a temperate tree-based intercropping system. *Agriculture, Ecosystems, and Environment* 144:13–20.
- Bainard, L.D., A.M. Koch, A.M. Gordon, and J.N. Klironomos. 2012. Temporal and compositional differences of arbuscular mycorrhizal fungal communities in conventional monocropping and tree-based intercropping systems. *Soil Biology and Biochemistry* 45:172–80.
- Bainard, L.D., A.M. Koch, A.M. Gordon, and J.N. Klironomos. 2013. Growth response of crops to soil microbial communities from conventional monocropping and tree-based intercropping systems. *Plant Soil* 363:345–356.
- Bambrick, A.D., J.K. Whallen, R.L. Bradley, A. Cogliastro, A.M. Gordon, A. Olivier, and N.V. Thevathasan. 2010. Spatial heterogeneity of organic carbon in tree-based intercropping systems in Quebec and Ontario, Canada. *Agroforestry Systems* 79:343–353.
- Banerjee, S., M. Baah-Acheamfour, C.M. Carlyle, A. Bissett, A.E. Richardson, T. Siddique et al. 2016. Determinants of bacterial communities in Canadian agroforestry systems. *Environmental Microbiology* 18:1805–1816.
- Bardhan, S., S. Jose, R.P. Udawatta, and F. Fritschi. 2013. Microbial community diversity in a 21-year-old temperate alley cropping system. *Agroforestry Systems* 87:1031–1041.
- Beuschela, R., H. Piephob, R.G. Joergensen, and C. Wachendorf. 2019. Similar spatial patterns of soil quality indicators in three poplar-based silvo-arable alley cropping systems in Germany. *Biology and Fertility of Soils* 55:1–14.
- Borrelli, P., C. Alewell, P. Alvarez, J. Alexandre, A. Anache, J. Baartman, C. Ballabio, et al. 2021. Soil erosion modelling: A global review and statistical analysis. *Science of the Total Environment* 780:146494.
- Boyer, D.G., and J.P.S. Neel. 2010. Nitrate and fecal coliform concentration differences at the soil/bedrock interface in Appalachian silvopasture, pasture, and forest. *Agroforestry Systems* 79:89–96.
- Brandle, J.R., L. Hodges, and X.H. Zhou. 2004. Windbreaks in North American agricultural systems. *Agroforestry Systems* 61:65–78.
- Cardinael, R., K. Hoeffner, C. Chenu, T. Chevallier, C. Béal, A. Dewisme, and D. Cluzeau. 2018. Spatial variation of earthworm communities and soil organic carbon in temperate agroforestry. *Biology and Fertility of Soils* 55(2):171–183.
- Chang, S.W., S.J. Lee, and C.H. Je. 2005. Phytoremediation of atrazine by poplar trees: Toxicity, uptake and transformation. *Journal of Environmental Science Health, Part B* 40:801–811.
- Chu, B., K.W. Goyne, S.H. Anderson, C.H. Lin, and R.P. Udawatta. 2010. Veterinary antibiotic sorption to agroforestry buffer, grass buffer, and cropland soils. *Agroforestry Systems* 79:67–80.
- De Stefano, A., and M.G. Jacobson. 2018. Soil carbon sequestration in agroforestry systems: A meta-analysis. *Agroforestry Systems* 92(2):285–299.
- Dwyer, J., D. Wallace, and D.R. Larsen. 1997. Value of woody river corridors in levee protection along the Missouri River in 1993. *Journal of the American Water Resources Association* 33(2):481–489.
- Gantzer, C.J., G.A. Buyanovsky, E.E. Alberts, and P.A. Remley. 1987. Effects of soybean and corn residue decomposition on soil strength and splash detachment. *Soil Science Society of America Journal* 51:202–206.
- Garibaldi, L.A., F.J. Oddi, F.E. Miguez, I. Bartomeus, M.C. Orr, E.G. Jobbágy, C. Kremen, et al. 2021. Working landscapes need at least 20% native habitat. *Conservation Letters* 14(2).
- Giese, L.A.B., W.M. Aust, R.K. Kolka, and C.C. Trettin. 2003. Biomass and carbon pools of disturbed riparian forests. *Forest Ecology Management* 180:493–508.
- Gomes, H.I. 2012. Phytoremediation for bioenergy: Challenges and opportunities. *Environmental Technology Reviews* 1:59–66.
- Hickey, M.B.C., and B. Doran. 2004. A review of the efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. *Water Quality Research Journal* 39(3):311–317.
- Jacobs, T.C., and J.W. Gilliam. 1985. Riparian losses of nitrate from agricultural drainage waters. *Journal of Environmental Quality* 14:472–478.
- Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems* 76:1–10.
- Jose, S., A.R. Gillespie, and S.G. Pallardy. 2004. Interspecific interactions in temperate agroforestry. *Agroforestry Systems* 61:237–255.
- Khaleel, A.A., T.J. Sauer, and J.C. Tyndall. 2020. Changes in deep soil organic carbon and soil properties beneath tree windbreak plantings in the U.S. Great Plains. *Agroforestry Systems* 94(2):565–581.
- Kremer, R.J., and L.F. Hezel. 2013. Soil quality improvement under an ecologically based farming system in northwest Missouri. *Renewable Agriculture & Food Systems* 28:245–254.
- Kremer, R.J., L.F. Hezel, and K.S. Veum. 2015. Soil health improvement in an organic orchard production system in northwest Missouri. *Proceedings of the Organic Agriculture Research Symposium, LaCrosse, WI*.
- Kumar, S., S.H. Anderson, L.G. Bricknell, R.P. Udawatta, and C.J. Gantzer. 2008. Soil hydraulic properties influenced by agroforestry and grass buffers for grazed pasture systems. *Journal of Soil and Water Conservation* 63(4):224–232. <https://doi.org/10.2489/jswc.63.4.224>.
- Kumar, S., S.H. Anderson, R.P. Udawatta, and R.L. Kallenbach. 2012. Water infiltration influenced by agroforestry and grass buffers for a grazed pasture system. *Agroforestry Systems* 84:325–335.
- Lacombe, S., R.L. Bradley, C. Hamel, and C. Beaulieu. 2009. Do tree-based intercropping systems increase the diversity and stability of soil microbial communities? *Agriculture, Ecosystems, and Environment* 131:25–31.
- Lal, R. 2010. Managing soil and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Bioscience* 60:708–721.

- Lin, C.-H., K.W. Goyne, R.J. Kremer, R.N. Lerch, and H.E. Garrett. 2010. Dissipation of sulfamethazine and tetracycline in the root zone of grass and tree species. *Journal of Environmental Quality* 39:1269-1278.
- Lin, C.-H., R.N. Lerch, K.W. Goyne, and H.E. Garrett. 2011. Reducing herbicides and veterinary antibiotics losses from agroecosystems using vegetative buffers. *Journal of Environmental Quality* 40:791-799.
- Liu, X., X. Zhang, and M. Zhang. 2008. Major factors influencing the efficacy of vegetated buffers on sediment trapping: A review and analysis. *Journal of Environmental Quality* 37:1667-1674.
- Mayer, P.M., S.K. Reynolds, and T.J. Canfield. 2005. Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness: A Review of Current Science and Regulations. Washington, DC: US Environmental Protection Agency.
- Mayer, P.M., S.K. Reynolds, Jr., M.D. McCutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. *Journal of Environmental Quality* 36:1172-1180.
- Mayrinc, R.C., C.P. Laroque, B.Y. Amichev, and K.V. Rees. 2019. Above- and below-ground carbon sequestration in shelterbelt trees in Canada: A review. *Forests* 10(10):922.
- Montgomery, D.R. 2007. Soil erosion and agricultural sustainability. *PNAS* 104:13268-13272.
- Morris, C., and J.G. Arbuckle. 2021. Conservation plans and soil and water conservation practice use: Evidence from Iowa. *Journal of Soil and Water Conservation* 76(5):457-471. <https://doi.org/10.2489/jswc.2021.00166>.
- Muth, D. 2014. Profitability versus environmental performances: Are they competing? *Journal of Soil and Water Conservation* 69(6):203A-206A. <https://doi.org/10.2489/jswc.69.6.203A>.
- Naiman, R.J., H. Decamps, and M.E. McClain. 2005. Structural pattern. In *Riparia: Ecology, Conservation, and Management of Streamside Communities*, ed. R.J. Naiman et al., 79-123. New York: Elsevier.
- Nair, P.K.R. 2012. Carbon sequestration studies in agroforestry systems: A reality check. *Agroforestry Systems* 86:243-253.
- Nair, V.D., and D.A. Graetz. 2004. Agroforestry as an approach to minimizing nutrient loss from heavily fertilized soils: The Florida experience. *Agroforestry Systems* 61:269-279.
- NCA (National Climate Assessment). 2014. Highlights. <https://nca2014.globalchange.gov/highlights>.
- Nearing, M.A. 2001. Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century. *Journal of Soil and Water Conservation* 56(3):229-232.
- Nearing, M.A., F.F. Pruski, and M.R. O'Neal. 2004. Expected climate change impact on soil erosion rates: A review. *Journal of Soil and Water Conservation* 59:43-50.
- Oklahoma Historical Society. 2021. The Great Depression, the Dust Bowl, and the New Deal in Oklahoma. Oklahoma City, OK: Oklahoma Historical Society. <https://www.okhistory.org/learn/depression3>.
- Ong, C., C.R. Black, J. Wilson, C. Muthuri, J. Bayala, and N.A. Jackson. 2014. Agroforestry: Hydrological impacts. In *Encyclopedia of Agriculture and Food Systems*, Vol. 1 (2nd ed.), ed. N.K. Van Alfen, 244-252. Amsterdam: Academic Press.
- Pavlidis, G., and V.A. Tsihrintzis. 2018. Environmental benefits and control of pollution to surface water and groundwater by agroforestry systems: A review. *Water Resources Management* 32:1-29.
- Paudel, B.R., R.P. Udawatta, R.J. Kremer, and S.H. Anderson. 2011. Agroforestry and grass buffer effects on soil quality parameters for grazed pasture and row-crop systems. *Applied Soil Ecology* 48:125-132.
- Pauli, N., T. Oberthur, E. Barrios, and A.J. Conacher. 2010. Fine-scale spatial and temporal variation in earthworm surface casting activity in agroforestry fields, western Honduras. *Pedobiologia* 53:127-139.
- Peterjohn, W.T., and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. *Ecology* 65(5):1466-1475.
- Possu, W.B., J.R. Brandle, G.M. Domke, M. Schoeneberger, and E. Blankenship. 2016. Estimating carbon storage in windbreak trees on U.S. agricultural lands. *Agroforestry Systems* 90:889-904.
- Price, G.W., and A.M. Gordon. 1998. Spatial and temporal distribution of earthworms in a temperate intercropping system in southern Ontario, Canada. *Agroforestry Systems* 44:141-149.
- Rivest, D., M. Lorente, A. Olivier, and C. Messier. 2013. Soil biochemical properties and microbial resilience in agroforestry systems: Effects on wheat growth under controlled drought and flooding conditions. *Science of the Total Environment* 463-464:51-60.
- Rockwood, D.L., C.V. Naidu, D.R. Carter, M. Rahmani, T.A. Spriggs, C. Lin, G.R. Alker, J.G. Isebrands, and S.A. Segrest. 2004. Short-rotation woody crops and phytoremediation: Opportunities for agroforestry? *Agroforestry Systems* 61:51-63.
- Sahin, H., S.H. Anderson, and R.P. Udawatta. 2016. Water infiltration and soil water content in claypan soils influenced by agroforestry and grass buffers compared to row crop management. *Agroforestry Systems* 90:839-860.
- Salceda G., M., R.P. Udawatta, K.A. Nelson, S.S. Mendis, and S. Bardhan. 2022. Spatial and temporal variability of soil organic carbon on a corn-soybean watershed with 23 years of agroforestry. *Agronomy Journal In Press*. <https://doi.org/10.1002/ajg2.20948>.
- Sanft, C. 2010. The great Stalin plan for the transformation of nature. In *Natural Resources Environmental History*, ed. C. Sanft, 15(4):670-700. <https://academic.oup.com/envhis/article/15/4/670/385092>.
- Sauer, T.J., C.A. Cambardella, and J.R. Brandle. 2007. Soil carbon and tree litter dynamics in a red cedar-scotch pine shelterbelt. *Agroforestry Systems* 71(3):163-174.
- Schoeneberger, M., G. Bentrup, H. De Gooijer, R. Soolanayakanahally, T. Sauer, J. Brandle, X. Zhou, and D. Current. 2012. Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture. *Journal of Soil and Water Conservation* 67(5):128A-136A. <https://doi.org/10.2489/jswc.67.5.128A>.
- Schoonover, J.E., K.W.J. Williard, and I. Flower. 2003. Ground water nitrate reduction in giant cane and forest riparian buffer zones. *Journal of the American Water Resources Association* 44(1):347-354.
- Schulte, L.A., J. Niemi, M.J. Helmers, M. Liebman, J.G. Arbuckle, D.E. James, R.K. Kolka, M. E. O'Neal, M.D. Tomer, J.C. Tyndall, H. Asbjornsen, P. Drobney, J. Neal, G. Van Ryswyk, and C. Witte. 2017. Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn-soybean croplands. *PNAS* 114(42):11247-11252.
- Schultz, R.C., T.M. Isenhardt, J.P. Colletti, W.W. Simpkins, R.P. Udawatta, and P.L. Schultz. 2009. Riparian and upland buffer practices. In *North American Agroforestry, An Integrated Science and Practice*, 2nd edition, ed. H.E. Garrett, 163-218. Madison, WI: American Society of Agronomy.
- Schultz, R.C., R.P. Udawatta, T.M. Isenhardt, J.P. Collette, and W.W. Simpkins. 2022. Riparian and upland buffer practices. In *North American Agroforestry, 3rd Edition*, eds. H.E. Garrett, S. Jose, and M.A. Gold, 197-271. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.
- Seiter, S., E.R. Ingham, R.D. William, and D.E. Hibbs. 1995. Increase in soil microbial biomass and transfer of nitrogen from alder to sweet corn in an alley cropping system. In *Growing a Sustainable*

- Future, eds. J.H. Ehrenreich, D.L. Ehrenreich, and H.W. Lee, 56–158. Boise, ID: University of Idaho.
- Seobi, T., S.H. Anderson, R.P. Udawatta, and C.J. Gantzer. 2005. Influences of grass and agroforestry buffer strips on soil hydraulic properties. *Soil Science Society of America Journal* 69:893–901.
- Sharrow, S.H., and S. Ismail. 2004. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. *Agroforestry Systems* 60:123–130.
- Sidle, R.C. 1985. Factors influencing the stability of slopes. *In* Proceedings of a Workshop on Slope Stability: Problems and Solutions in Forest Management, USDA Forest Service Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-180, ed. D. Swanston, April 1985, 17–25.
- Thevathasan, N.V., and A.M. Gordon. 2004. Ecology of tree intercropping systems in North temperate region: Experiences from southern Ontario, Canada. *Agroforestry Systems* 61–62:257–268.
- Tufekcioglu, A., J.W. Raich, T.M. Isenhardt, and R.C. Schultz. 2003. Biomass, carbon, and nitrogen dynamics of multi-species riparian buffers within an agricultural watershed in Iowa, USA. *Agroforestry Systems* 57:187–198.
- Udawatta, R.P. 2022. Flood control and air cleaning regulatory ecosystem services of agroforestry. *In* Ecosystem Services of Agroforestry, eds. R.P. Udawatta and S. Jose, 305–330. The Netherlands: Springer Nature. *In Press*.
- Udawatta, R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2008. Influence of prairie restoration on CT-measured soil pore characteristics. *Journal Environmental Quality* 37:219–228.
- Udawatta, R.P., S.H. Anderson, R.J. Kremer, and H.E. Garrett. 2022. Agroforestry soil services *In* North American Agroforestry, 3rd Edition, eds. H.E. Garrett, S. Jose, and M.A. Gold, 345–376. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.
- Udawatta, R.P., S.H. Anderson, P.P. Motavalli, and H.E. Garrett. 2011a. Clay and temperature influences on sensor measured volumetric soil water content. *Agroforestry Systems* 82:61–75.
- Udawatta, R.P., C.J. Gantzer, and S. Jose. 2017. Agroforestry practices and soil ecosystem services. *In* Soil Health and Intensification of Agroecosystems, eds. M.M. Al-Kaisi and B. Lowery, 305–334. Elsevier Academic Press.
- Udawatta, R.P., H.E. Garrett, and R.L. Kallenbach. 2011b. Agroforestry buffers for nonpoint source pollution reductions from agricultural watersheds. *Journal of Environmental Quality* 40:800–806.
- Udawatta, R.P., and S. Jose. 2012. Agroforestry strategies to sequester carbon in temperate North America. *Agroforestry Systems* 86:225–242.
- Udawatta, R.P., R.J. Kremer, H.E. Garrett, and S.H. Anderson. 2009. Soil enzyme activities and physical properties in a watershed managed under agroforestry and row-crop system. *Agriculture, Ecosystems, and Environment* 131:98–104.
- USEPA (US Environmental Protection Agency). 2007 Preliminary interpretation of the ecological significance of atrazine stream-water concentrations using a statistically-designed monitoring program. Alexandria, VA: Office of Prevention, Pesticides, and Toxic Substances.
- USDA NAC (USDA–National Agroforestry Center). 2016. How can agroforestry help landowners adapt to increased rain intensity? Lincoln, NE: USDA NAC.
- USDA NRCS (USDA Natural Resources Conservation Services). 2013. Assessment of the effects of conservation practices on cultivated cropland in the Lower Mississippi River Basin.
- Venkatraman, K., and N. Ashwath. 2016. Canopy rainfall intercepted by nineteen tree species grown on a phytocapped landfill. *International Journal of Waste Resources* 6:1.
- Wall, D.H., and J. Six. 2015. Give soils their due. *Science* 347:694–695.
- Weerasekara, C., R.P. Udawatta, S. Jose, R.J. Kremer, and C. Weerasekara. 2016. Soil quality differences in a row-crop watershed with agroforestry and grass buffers. *Agroforestry Systems* 90:829–838.
- Wickramaratne, N. 2017. Groundwater nitrogen and phosphorus dynamics under cattle grazing and row crop management in two contrasting soils in Missouri. Master's thesis, University of Missouri.
- Zak, D.R., W.E. Holmes, D.C. White, A.D. Peacock, and D. Tilman. 2003. Plant diversity, soil microbial communities, and ecosystem function: Are there any links? *Ecology* 84:2042–2050.