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SPECIAL ISSUE: THE ROLE OF INNOVATIVE CROPPING SYSTEMS TO ENHANCE SOIL HEALTH AND CLIMATE RESILIENCE

Soil quality assessment of an agroforestry system following long-term management in the Ozark Highlands

Shane Ylagan[1] | **Helen C.S. Amorim**[2] | **Amanda J. Ashworth**[3] | **Tom Sauer**[4] | **Brian J. Wienhold**[5] | **Phillip R. Owens**[6] | **Yuri L. Zinn**[2] | **Kristofor R. Brye**[1]

[1] Crop, Soil, and Environmental Sciences, Univ. of Arkansas, 115 Plant Sciences Building, Fayetteville, AR 72701, USA

[2] Soil Science, Univ. Federal de Lavras, 1001 Av. Doutor Silvio Menicucci, Lavras, Minas Gerais 37200-000, Brazil

[3] USDA-ARS, Poultry Production and Product Safety Research Unit, Univ. of Arkansas, O-303 Poultry Science Center, Fayetteville, AR 72701, USA

[4] USDA-ARS, National Laboratory for Agriculture and the Environment, 1015 N University Blvd., Ames, IA 50011, USA

[5] USDA-ARS, Agroecosystem Management Research Unit, 251 Filley Hall, East Campus, Univ. of Nebraska, Lincoln, NE 68583, USA

[6] USDA-ARS, Dale Bumpers Small Farms Research Center, 6883 South Highway 23, Booneville, AR 72927, USA

Correspondence
Amanda J. Ashworth, USDA-ARS, Poultry Production and Product Safety Research Unit, Univ. of Arkansas, O-303 Poultry Science Center, Fayetteville, AR 72701, USA.
Email: Amanda.Ashworth@usda.gov

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Abstract

The Soil Management Assessment Framework (SMAF) is a quantitative soil quality (SQ) evaluation tool that is widely applied to assess soil response to specific agricultural management practices over time. Considering the reported SQ benefits of agroforestry (AF) systems and the potential usefulness of SMAF, the objective of this study was to evaluate the effects of tree species (pecan [*Carya illinoinensis* (Wangenh.) K. Koch] and northern red oak [*Quercus rubra* L.]), soil fertility source (poultry litter [PL] and inorganic N fertilizer [control]), and soil depth (0–15 and 15–30 cm) on SMAF-derived SQ indices after 17 yr of management at an AF site in northwest Arkansas. Averaged across soil depth, soil organic C scores under red oak with PL application had a lower score (0.48) than red oak fertilized with inorganic N (0.60) and pecan receiving long-term PL applications (0.60), which did not differ from pecan with inorganic N fertilizer application (0.51). Averaged across soil depth, the soil quality index (SQI) for pecan receiving PL applications was 1.1 times greater than that under red oak receiving PL and soils under pecan receiving inorganic N fertilizer. Soil quality assessments use in AF are novel, as SMAF has not been used to identify soil health in these systems, although specific tree crop codes need to be developed in SMAF. Results of this study demonstrate that soils planted under various tree species respond dissimilarly to fertilizer sources and that management may improve overall SQ.

Abbreviations: AF, agroforestry; BD, bulk density; PL, poultry litter; PLS, pure live seed; SMAF, Soil Management Assessment Framework; SOC, soil organic carbon; SQ, soil quality; SQI, soil quality index.

1 | INTRODUCTION

The demand for increased food production has continued to grow since the early 20th century and is only going to increase in order to feed the estimated global human population of 9.7 billion by 2050 (United Nations, 2019).

Additionally, the health and viability of the agroecosystems that produce these foods are greatly dependent on the quality and health of the land, specifically the soil quality (SQ; Dollinger & Jose, 2018). Consequently, human-induced land degradation has continued to increase and become a global issue, where it is estimated that 25% of the current global agricultural land area is highly degraded, 44% is slightly to moderately degraded, and ∼10% is being restored from previous degradation (Gomiero, 2016). Thus, the combination of the growing need for increased food production and the simultaneous degradation of land has led to increased concern for soil conservation.

Agroforestry (AF) is a conservation land management practice that has continued to gain attention and appeal for the practice's multiple benefits. There are multiple types of AF systems (i.e., alley cropping, silviculture, silvopasture, forest farming, windbreaks, and riparian forest buffer), with alley cropping and silvopasture standing out as the most common AF systems. An alley-cropping system consists of trees planted in rows with crops grown in the subsequent alleys, and silvopasture systems are the integration of trees and forages for livestock production (Niyigena et al., 2021). As a result, alley-cropping and silvopasture systems not only have the ability to provide their original product (i.e., crops or livestock products) but also additional food (i.e., nuts and fruits) and other products (i.e., lumber and biofuel) on the same amount of land.

Agroforestry practices have also displayed significant evidence for their potential to improve SQ, while also providing ecosystem services (Dollinger & Jose, 2018). There are numerous potential ecosystem services that AF systems provide, including water quality enhancement, biodiversity improvement, reduced soil erosion, elevated aesthetic value, C sequestration, and climate change mitigation (Jose, 2009; Gurmessa et al., 2021). Soil quality benefits from AF practices have included enhanced soil fertility (Dollinger & Jose, 2018), soil organic C (SOC) storage (Lorenz & Lal, 2014; Schoeneberger et al., 2012; Udawatta & Jose, 2012), soil structure (Gelaw et al., 2015), conservation of biodiversity, and production diversity (Jose, 2009; Nair, 2011). However, further determination of the sustainability of AF and other conservative land management systems are dependent on assessing long-term management effects on dynamic SQ properties (Doran & Parkin, 1994).

Developed by Andrews et al. (2004), the Soil Management Assessment Framework (SMAF) is a quantitative SQ evaluation tool that focuses on dynamic SQ properties. The SMAF method has become widely applied to assess soil responses to specific agricultural management systems over time and/or to compare and contrast various management practices (Amorim, Ashworth, Moore, et al., 2020; Amorim, Ashworth, Wienhold, et al., 2020). The SMAF framework for conducting an assessment consists of (a) physical, chemical, and biological indicator selection,(b) indicator interpretation using SMAF algorithms (nonlinear scoring curves), and (c) integration of an overall soil quality index (SQI; Karlen et al., 2008; Stott et al., 2011; Wienhold et al., 2009). The SMAF indices have the potential to aid land-managers in the decision-making process regarding land use for selecting best management practices or specific management goals (Amorim, Ashworth, Moore, et al., 2020; Amorim, Ashworth, Wienhold, et al., 2020). Although SMAF has grown in versatility and applicability in cropping systems, SMAF application in AF systems is limited, thus using SMAF to quantify SQ is a novel approach for identifying how management (i.e., tree species and fertility source) influences dynamic SQ properties.

Core Ideas

- The Soil Management Assessment Framework identified soil quality effects in agroforestry systems.
- Soil quality indices differed by tree species between fertility sources.
- Soils responded dissimilarly to fertilization source per tree species.
- Soil quality was greatest in pecan–poultry litter and red oak–inorganic N combinations.

Considering the reported SQ benefits of AF systems and the potential usefulness of SMAF, the objective of this study was to evaluate the effects of tree species (pecan [*Carya illinoinensis* (Wangenh.) K. Koch] and northern red oak [*Quercus rubra* L.]), soil fertility source (poultry litter [PL] and inorganic N fertilizer [control]), and soil depth (0–15 and 15–30 cm) on SMAF-derived SQ indices after 17 yr of management at an AF site in the Ozark Highlands region of northwest Arkansas. It was hypothesized that SQ will differ among tree species–fertility source combinations and that SQ will be greater in the top 15 cm than in the 15-to-30-cm soil depth interval.

2 | MATERIALS AND METHODS

2.1 | Site description

The study was conducted using a 4.25-ha paddock of land managed for the last 17 yr as AF at the University of Arkansas Agricultural Research and Extension Center in Fayetteville, AR (36˚5′ N; 94˚10′ W, 382 m asl, 3.4% slope). The site is located within the Ozark Highlands, Major Land Resource Area 116A (Soil Survey Staff, 2019a). The climate associated with the study site is subhumid, where, from 2000 to 2015, the annual mean (± SD) maximum and minimum air temperature

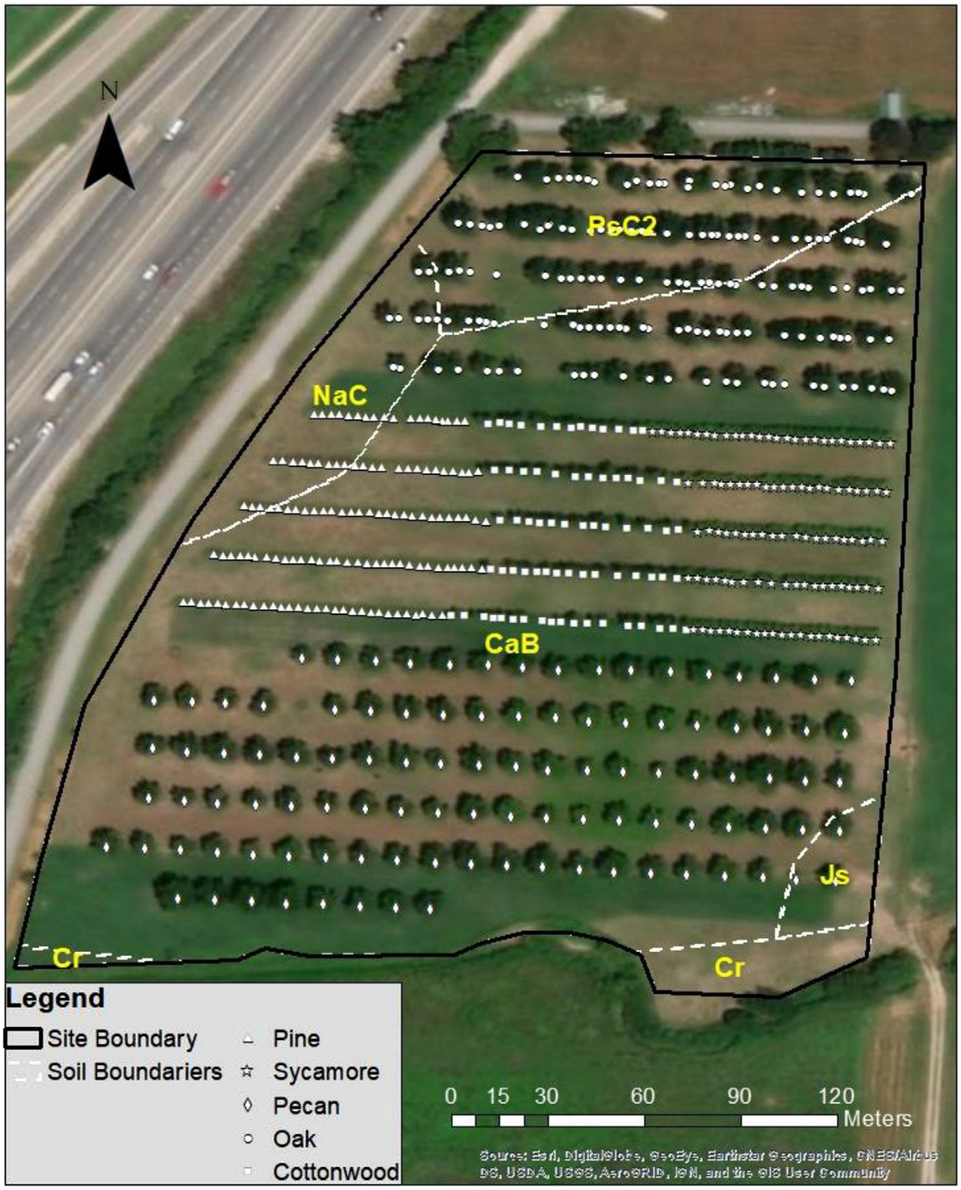

FIGURE 1 The agroforestry site in Fayetteville, AR, is organized into 16 rows, where Row 1 starts at the northernmost row. Rows 1–5 consist of the northern red oak. The western, central, and eastern portion of Rows 6–10 consist of the pitch–loblolly pine, cottonwood, and American sycamore. Rows 11–16 consist of pecan. The soils at the site include Captina silt loam (CaB), Pickwick silt loam (PsC2), Nixa cherty silt loam (NaC), Johnsburg silt loam (Js), and Cleora fine sandy loam (Cr) (Soil Survey Staff, 2019b)

was 20.6 ± 1.0 ˚C and −4.7 ± 1.3 ˚C and the annual mean precipitation was 1,094 ± 231 mm (NOAA, 2016).

Soils within the AF site boundaries are variable. The site is mapped 79% Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudults), 11% Pickwick silt loam (fine-silty mixed, semiactive, thermic Typic Paleudults) toward the north, 2.1% Johnsburg silt loam (fine-silty, mixed, active, mesic, Aquic Fragiudults), 2.8% Cleora fine sandy loam (coarse-loamy, mixed, active, thermic Fluventic Hapludolls), and 4.9% Nixa cherty silt loam (loamy-skeletal, siliceous, active, mesic Glossic Fragiudults) (Soil Survey Staff, 2019b) down the length of the southeast and central–west margins (Adhikari et al., 2018; Figure 1).

The paddock originally consisted of 16 west–east-oriented tree rows of three species including eastern black walnut (*Juglans nigra* L.), northern red oak, and pecan at 15-m spacing during tree establishment in 2000. Pecan was planted in the six southern rows, and northern red oak was planted in the five northern rows. Additionally, the eastern black walnut trees were replaced in 2014 with rows that consisted of three species including: cottonwood (*Populus deltoides* W. Bartram ex Marshall), pitch/loblolly pine (*Pinus rigida* Mill.

× *Pinus taeda* L.), and American sycamore (*Plantanus occidentalis* L.; Figure 1). During fall 2015, alleys between tree rows were seeded with a cool-season species (orchardgrass [*Dactylis glomerata* L., var. Tekapo]) at 17 kg pure live seed (PLS) ha^{-1} and also in spring 2016 with a native warm-season mix (8:1:1 big bluestem [*Andropogon gerardii* Vitman], little bluestem [*Schizachyrium scoparium* (Michx. Nash)], and indiangrass [*Sorghastrum nutans* L.]), seeded spring 2016 at 10 kg PLS ha^{-1}. Throughout the 17-yr study period, there was annual hay harvesting; however, once alleys were reestablished in 2015 and 2016, they rested for 1 yr to allow for native grass establishment.

Each spring between 2001 and 2007, except 2005, 3.9–6.7 Mg PLS ha^{-1} were distributed via broadcast application over the eastern half of the AF site, and the inorganic N fertilizer control applications were broadcast applied at 50–76 kg N ha^{-1}, as NH_4NO_3 fertilizer, over the western half of the site (Sauer et al., 2014). Starting in June 2004, additional fertilizer was surface-applied to the surrounding ground near each tree as an annual application of Osmocote (The Scotts Miracle-Grow Company), a slow-release fertilizer that contained 5.6, 2.4, and 4.6 g of N, P, and K, respectively (Sauer et al., 2014). In 2005, both PL and NH_4NO_3 applications were made in the spring and fall to evaluate the impacts of nutrient source on soil physiochemical properties.

In April 2016, all trees at the AF site were fertilized with three different fertilizers at varying rates and areas surrounding the tree. The pecan trees were fertilized with ∼2.3 kg of NH_4NO_3, ∼5.7 kg of a 13–13–13 fertilizer, and ∼0.27 kg of gypsum in a circular area around each tree with an ∼9.1-m diameter. The sycamore, cottonwood, and loblolly pine trees were fertilized with ∼0.20 kg NH_4NO_3, ∼0.48 kg of a 13–13–13 fertilizer, and ∼0.10 kg of gypsum, where the fertilizers were spread in within a rectangular area around the trees in ∼2.4-m wide strips and ∼2.3 m between adjacent trees. The red oak trees at the AF site were fertilized in a slightly different way. If there were other red oak trees that were ∼2.4 m away on both sides of a red oak tree, the red oak tree was fertilized with ∼0.52 kg NH_4NO_3, ∼1.3 kg of a 13–13–13 fertilizer, and ∼0.27 kg of gypsum in an approximately 2.4-m × 6.1-m rectangular area around the tree. If there were no other red oak trees within ∼2.4 m of either side of a red oak tree, the red oak tree was fertilized with ∼1.0 kg NH_4NO_3, ∼2.6 kg of a 13–13–13 fertilizer, and 0.54 kg of gypsum in an approximately 4.9-m × 6.1-m rectangular area around the tree. If there was a red oak tree that was ∼2.4 m away of a red oak tree on one side only, the red oak tree was fertilized with ∼0.79 kg NH_4NO_3, ∼2.0 kg of a 13–13–13 fertilizer, and ∼0.4 kg of gypsum in an approximately 3.7-m × 6.1-m rectangular area around the tree and offset to the open side of the tree ∼1.2 m and ∼2.4 m. Additional site establishment and management details were reported in Thomas et al. (2008), DeFauw et al. (2014), Sauer et al. (2014), Adhikari et al. (2018), and Dold et al. (2019).

2.2 | Soil sampling and analyses

In 2016, soil cores were manually collected within the tree rows from the 0-to-15- and 15-to-30-cm depths using a 3.3-cm-diam. probe at 1 m either east or west of trees within each of the fertilizer- and PL-treated areas. Since the inorganic N fertilizer and PL applications were the intended treatments and tree rows within each treatment were the considered replicates, 15 samples that were made up of nine soil cores each characterized each PL- and inorganic-N-treated area (Sauer et al., 2014). Prior to physical and chemical property determinations, the collected soil cores were air dried and passed through a 2-mm sieve. Soil samples were assessed for selected nutrients (i.e., P, K, Ca, Mg, and S) via Mehlich-3 extraction (Mehlich, 1984) with extracts analyzed by inductively coupled, argon–plasma optical emissions spectrometry (ICAP–OES; Soltanpour et al., 1996). A roller mill was used to powderized a 15-g sample of air-dried, sieved soil for total C and N determinations using the dry-combustion method (FisonNA 1500 elemental analyzer, ThermoQuest Corporation). Since soil did not effervesce upon treatment with dilute HCl, all measured soil C was assumed to be SOC. Additional samples of air-dried, sieved soil were used to determine pH in water (1:1 soil/water), and bulk density (BD) was determined using the core method (Blake, 1965). Table 1 summarizes the minimum, maximum, and mean measured soil properties across the study site.

2.3 | SQ assessment using SMAF

Soil quality indices were calculated using the SMAF (Andrews et al., 2004) based on soil samples collected in 2016. Five indicators of SQ were used in this study following the general SMAF guidelines, which recommend using a minimum of five indicators with at least one each representing soil chemical, physical, and biological properties and processes (Karlen et al., 2008). In the SMAF assessment, soil pH and extractable soil P and K concentrations represented chemical indicators, since they reflect nutrient availability and affect plant growth. Physical effects were represented by BD, which is closely related to soil aeration and water dynamics. Soil organic C was used as the biological indicator due to SOC's critical role in nutrient cycling, storage, and energy supply to soil microorganisms (Gurmessa et al., 2021). Measured values of soil indicators were converted into scores between 0 and 1 using established algorithms in Excel, with 0 representing the lowest SQ value and 1 indicating the largest SQ value for each indicator (Andrew et al., 2004; Wienhold et al., 2009). The algorithms, or scoring curves, developed for each indicator account for inherent soil properties, climatic factors, cropping history, and selected analytical methods for soil chemical properties. Algorithms were described by Andrews et al.

TABLE 1 Summary of the minimum, maximum, and average measured soil properties (soil organic C [SOC], pH, P, K, and bulk density [BD]) per treatment combination (tree species [red oak or pecan], fertility source [inorganic N fertilizer or poultry litter], and soil depth [0–15 or 15–30 cm])

			SOC			pH			P			K			BD		
Tree species	Fertility source[a]	Depth	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
		cm	%						mg kg^{-1}			mg kg^{-1}			g cm^{-3}		
Red oak	INF	0–15	0.88	2.3	1.6	5.1	6.7	6.1	9.4	129	55.7	56.2	189	103	0.98	1.41	1.17
		15–30	0.41	1.7	0.80	5.1	6.9	6.0	3.0	126	25.4	33.9	88.1	48.5	1.31	1.74	1.49
	PL	0–15	0.88	1.9	1.3	4.8	6.6	5.8	19.8	166	63.9	44.5	180	107	0.97	1.40	1.16
		15–30	0.49	0.8	0.63	5.0	6.6	5.7	4.7	81.3	14.6	29.4	93.9	48.2	1.39	1.64	1.49
Pecan	INF	0–15	0.79	1.7	1.4	5.6	6.8	6.4	7.1	26.5	14.3	33.3	147	82.7	1.05	1.38	1.17
		15–30	0.4	1.7	0.64	5.2	6.8	6.4	1.2	16.3	4.4	25.6	126	38.6	1.34	1.61	1.46
	PL	0–15	0.74	2.5	1.7	6.0	6.9	6.5	14.9	100	62.6	52.7	179	105	0.89	1.39	1.14
		15–30	0.27	1.3	0.74	5.3	7.1	6.4	2.8	46.4	18.1	27.0	87.5	47.9	1.17	1.68	1.46

[a]INF, inorganic N fertilizer; PL, poultry litter.

TABLE 2 Summary of the algorithms for interpretation of the Soil Management Assessment Framework (SMAF) soil quality indicators which used the soil property values that were included in Table 1

Indicator[a]	Algorithm	Constant	Site-specific factors
SOC	$y = a/[1 + b \times \exp(-c \times \mathrm{SOC})]$	$a = 1.0$; $b = 50.1$	$c = f$ (organic matter class, texture, climate)
BD	$y = a - b \times \exp(-c \times \mathrm{BD}^d)$	$a = 0.994$	$b, c, d = f$ (texture, mineralogy)
pH	$y = a \times \exp[-(\mathrm{pH} - b)^2/(2c^2)]$	$a = 1.0$	$b, c = f$ (crop)
P	If P ≤ max (for culture and method), then $y = (ab + c \times \mathrm{P}^d)/(b + \mathrm{P}^d)$; if P > max (for declivity and method), then $y = a - b \times \exp(-c \times \mathrm{P}^d)$, and $y = 1$	$a = 9.26 \times 10^6$; $c = 1.0$; $d = 3.06$	$b = f$ (crop, SOC, texture, method, slope, weathering class)
K	$y = a[1 - \exp(-b \times \mathrm{K})]$	$a = 1.05$; $b = -0.00981$	$a, b = f$ (crop, texture)

Note. Adapted from Amorim et al. (2021) and da Luz et al. (2019).

[a]SOC, soil organic C; BD, bulk density.

(2004) and Wienhold et al. (2009) and are summarized in Table 2.

The SMAF algorithms were modified by factor classes. The organic matter factor “4” (suborder Udults) was based on the soil classification and was used to modify SOC and P. The texture factor class “3” (silt loam), also based on the soil classification, was used to modify SOC, BD, and P. The climate factor class “3” was based on the number of degree days and the mean annual temperature of the study site (≤170 ˚C d and ≥550 mm precipitation) and was used to modify SOC. The mineral factor class “3” represented soil mineralogy other than smectitic and glassy and was used to modify BD. The crop code “3” (tall fescue) was used for pH and P interpretations to represent the forage component of the AF system. The current version of SMAF does not include codes for tree species, which may be a limitation of SMAF in AF systems. The slope (“2”, 2–5%) and weathering factor (“3”, slightly weathered) classes were used for modifying soil P. The soil-test P code, used to modify the chemical extraction method, was “2” for Mehlich 3.

2.4 | Data analyses

The PROC GLIMMIX procedure in SAS (version 9.4, SAS Institute) was used to evaluate the effects of tree species, fertility source, soil depth, and their interactions on SQIs after 17 yr of management. A split-split-plot design was used, with tree species (whole plot), fertility source (split-plot), and soil depth (split-split plot) considered as fixed effects and replication considered as a random effect. When appropriate, means were separated using Fisher’s LSD at the .05 level. Additionally, regression models were adjusted using R (R version 4.0.5, R Foundation for Statistical Computing) to evaluate the

TABLE 3 Analysis of variance summary of individual effects of tree species (red oak and pecan), fertility source (poultry litter [PL] and inorganic N treatment), soil depth (0–15 and 15–30 cm), and their interactions on individual soil indicator scores and overall soil quality index (SQI) after 17 yr of agroforestry management in the Ozark Highlands region of northwest Arkansas

	Soil indicators[a]					
Source of variation	SOC	pH	P	K	BD	SQI
Tree species	0.55[b]	**<0.01**	0.03	0.50	0.52	0.71
Fertility	0.64	0.16	<0.01	0.09	0.88	0.39
Tree species × fertility	**<0.01**	0.22	<0.01	0.08	0.66	**<0.01**
Depth	**<0.01**	**0.02**	<0.01	**<0.01**	**<0.01**	**<0.01**
Tree species × depth	0.47	0.75	<0.01	0.83	0.31	0.06
Fertility × depth	0.89	0.88	<0.01	0.96	0.42	0.13
Tree species × fertility × depth	0.43	0.14	**<0.01**	0.98	0.39	0.12

[a]SOC, soil organic C; BD, bulk density.
[b]Significant effects ($p < .05$) are indicated by bolded text.

TABLE 4 Soil depth effects, averaged across tree species and fertility sources, on individual soil indicator scores and overall soil quality index (SQI) after 17 yr of agroforestry management in the Ozark Highlands region of northwest Arkansas

	Soil indicators[a]					
Soil depth	SOC	pH	P	K	BD	SQI
cm						
0–15	0.83a[b]	0.94a	0.97a	0.77a	0.94a	4.44a
15–30	0.27b	0.93b	0.87b	0.49b	0.49b	3.05b

[a]SOC, soil organic C; BD, bulk density.
[b]Means in a column followed by the same letter do not differ ($p > .05$).

TABLE 5 Interactive effects of soil depth, tree species, and fertility source on soil P individual scores after 17 years of agroforestry management in the Ozark Highlands region of northwest Arkansas

Soil depth	Tree species	Fertility	Soil indicator
cm			
0–15	Red oak	Inorganic N fertilizer	0.98a[a]
		Poultry litter	0.92a
	Pecan	Inorganic N fertilizer	0.99a
		Poultry litter	0.99a
15–30	Red oak	Inorganic N fertilizer	0.94a
		Poultry litter	0.95a
	Pecan	Inorganic N fertilizer	0.65b
		Poultry litter	0.96a

[a]Means followed by the same letter do not differ ($p > .05$).

relationship between individual soil properties and the overall SQI.

3 | RESULTS AND DISCUSSION

3.1 | Long-term AF management effects on SQ

Individual and interactive effects ($p < .05$) of tree species, fertility source, and soil depth were observed on all SQIs evaluated (Table 3). Soil organic C score and the overall SQI differed by tree species and fertility source and differed between soil depths (Table 3). Soil pH score differed between tree species and differed between soil depths (Table 3). Soil K and BD scores differed between soil depths. Soil P score differed among tree species–fertility–soil depth treatment combinations (Table 3).

Averaged across tree species and fertilizer sources, greater SQ scores were measured in the 0-to-15- vs. the 15-to-30-cm soil depth (Table 4). Measured SOC, pH, K, and BD scores were approximately 207, 1.1, 57, and 92% greater in the 0-to-15- vs. the 15-to-30-cm soil depth (Table 4). These increased individual scores led to a 46% greater SQI in the top 15 cm compared with the 15-to-30-cm depth (Table 4). Compared with subsurface layers, upper soil layers are anticipated to have greater SQI as a result of enriched SOC concentration and its resulting positive impact on other soil indicators, such as aggregation, water retention, and soil fertility (Amorim, Ashworth, Wienhold, et al., 2020; Cherubin et al., 2016). Understanding the negative correlation between increased soil depth and decreased SQ could be beneficial to land managers and researchers who are interested in the development and implementation of best management practices (i.e., deep tree root fertilization) that can increase subsurface SQ in AF management.

When assessing the interactive effects of tree species, fertility source, and soil depth on soil P score, the lowest P score (0.65) was measured in the 15-to-30-cm depth under pecan managed with inorganic N fertilizer (Table 5). In the 0-to-15-cm depth, P scores ranged between 0.92 and 0.99, whereas soil P score in the 15-to-30-cm depth under red oak and pecan that received PL applications ranged between 0.94 and 0.96, in which soil P score did not differ among these remaining

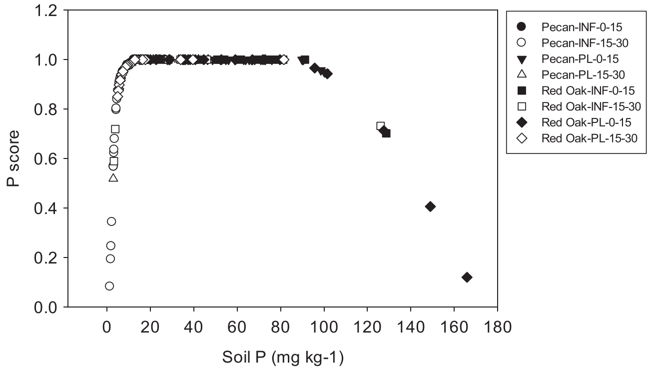

FIGURE 2 Soil P concentration (mg kg^{-1}) and respective P scores per tree species (red oak and pecan), fertility source (inorganic N fertilizer [INF] and poultry litter [PL]), and soil depth (0–15 and 15–30 cm) combination

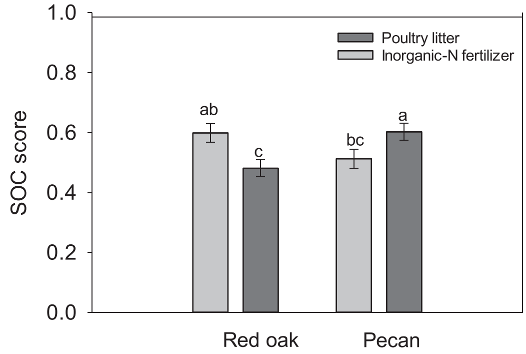

FIGURE 3 Interactive effects of tree species and fertility source, averaged across soil depths, on soil organic C (SOC) individual scores after 17 yr of agroforestry management in the Ozark Highlands region of northwest Arkansas. Bars with different letters are different at $p < .05$. Error bars represent standard errors

treatment combinations (Table 5). The reduced P score is a reflection of the reduced soil P concentration in the subsoil managed with inorganic N fertilizer; however, it is unclear why this trend was not observed for both tree species. Low P concentrations in soils at the 15-to-30-cm depth under pecan that received inorganic N fertilizer applications resulted in very low P scores (Figure 2). However, soils at the 15-to-30-cm depth under red oak that received inorganic N fertilizer applications only had a few low P concentration, resulting in a few low P scores, which were not enough to reduce the average (Figure 2). A potential explanation for why the trend in the P score was not observed for both tree species may be related to soil pH, where across fertilizer source, the average soil pH in the 15–30 cm surrounding the red oak and pecan trees was 5.9 and 6.4, respectively (Table 1). Soil P is most available between a pH of 6.5–7.5; thus, the greater average soil pH under the pecans could have resulted in potential differences in P solubility, altering P mobility and plant uptake. Another potential explanation for why the trend in the P score was not observed for both tree species may be related to landscape position. The red oak trees that received inorganic N fertilizer applications are in the northwest corner of the AF site, which is precisely where the local landscape receives runoff (i.e., runon) from the up-slope, surrounding landscape. The runoff could be transporting and depositing sediment-bound and dissolved forms of P, resulting in a greater P concentration, and thus greater P score, from P leaching to the 15-to-30-cm depth interval under the red oaks that received inorganic N fertilizer applications compared with the 15-to-30-cm depth interval under pecans that received inorganic N fertilizer applications that were located at a lower landscape position within the AF site.

Averaged across soil depth, SOC score under red oak with PL application had a lower score (0.48) compared with under red oak with inorganic N fertilizer applications (0.60) and under pecan with PL application (0.60), which did not differ from that under pecan with inorganic N fertilizer application (0.51; Figure 3). The differences in SOC scores among tree species–fertility source combinations after long-term management was a likely result of distinctive organic matter accumulation owing to greater leaf litter deposition in red oak AF systems and PL inputs (O'Brien et al., 2020). A potential explanation for the lower SOC score under red oak with PL application than that from under red oak with inorganic N fertilizer application is related to an accumulation of heavy metals in the soils under red oak with PL application and greater CO_2 gas exchange (Adams et al., 2021) and root decomposition (Ashworth et al., 2021). In addition to PL's P and N content, PL is also known to have significant concentrations of heavy metals (i.e., Cu, Cd, Pb, Mn, Fe, Se, Zn, and As; Brye & Pirani, 2006; Kpomblekou-A et al., 2002; Kunkle et al., 1981), where repeated application of PL have been shown to cause accumulations of heavy metals in soils (Kingery et al., 1994; Gupta & Charles, 1999; Han et al., 2000; Wadman et al., 1987). Furthermore, large concentration of heavy metals in soils may be toxic to plants (i.e., trees and forages), potentially causing a decrease in primary productivity and, in turn, causing a reduced amount organic C input to the soil (Sharma & Agrawal, 2005). Additionally, another plausible explanation may be differential elemental compositions of the trees' leaf litter that consequently decomposed at different rates under the two fertility sources. Considering, Dold et al. (2019) observed greater tree-stand woody biomass and C sequestration for oak relative to pecan at this site (7.1 and 3.4 Mg ha^{-1} for pecan and 26.6 and 12.7 Mg ha^{-1} for oak tree-stand woody biomass and C, respectively). In this study, this corresponded to a C sequestration rate of 0.75 and 0.20 Mg C ha^{-1} yr^{-1}, respectively, with total N uptake being approximately 66 and 71 g N $tree^{-1}$ yr^{-1} for oak and pecan, respectively.

The SOC storage potential is expected to differ in AF systems with varying management practices, such as tillage

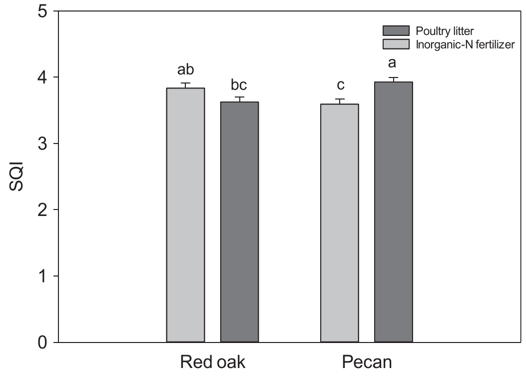

FIGURE 4 Interactive effects of tree species and fertility source, averaged across soil depths, on soil quality index (SQI) after 17 yr of agroforestry management in the Ozark Highlands region of northwest Arkansas. Bars with different letters are different at $p < .05$. Error bars represent standard errors

and no-tillage (Borges et al., 2018; Dollinger & Jose, 2018). Borges et al. (2018) assessed the impacts of 17 yr of soil management practices (no-tillage or tillage) on soil C sequestration and the labile SOC fractions in soils below chestnut (*Castanea sativa* Mill.) orchards under Mediterranean conditions. Borges et al. (2018) measured greater total organic C, active hot-water-extractable C, and particulate organic C in the topsoil (0–10 cm) of the nontilled orchard than from the tilled orchard (Dollinger & Jose, 2018). The SMAF indices have potential to guide land managers when selecting best management practices (i.e., tree species selection) and/or specific management goals (Amorim, Ashworth, Moore, et al., 2020; Amorim, Ashworth, Wienhold, et al., 2020). Therefore, this information could be beneficial for land managers and AF system planners in further understanding the effect of long-term management on SOC concentrations and the potential of AF systems for SOC sequestration. However, further work should be conducted to evaluate deeper profile SQIs for these systems.

Similar to SOC score, averaged across soil depth, overall SQI differed by tree species between fertility sources (Figure 4). Soils under pecan that received PL applications had greater SQI (3.93) than soils under red oak that received PL applications (3.63) and soils under pecan that received inorganic N fertilizer applications (3.59), which did not differ from soils under oak and those that received inorganic N fertilizer applications (3.84; Figure 4). The SQI of soils under pecan that received PL applications was 1.1 times greater than that from soils under red oak that received PL applications and soils under pecan that received inorganic N fertilizer applications (Figure 4). In contrast with SOC score, there was no difference in the SQI from soils under red oak that received PL applications and soils that received inorganic N fertilizer application, whereas the SQI from soils under pecan that received PL applications was greater than that received inorganic N fertilizer applications (Figure 4). This information could be useful for AF system planners interested in improving long-term SQ, SOC storage, and optimizing nutrient use and cycling. For instance, pecan trees managed with PL applications could potentially result in greater SQ, when compared with red oak trees managed with PL applications in long-term AF management systems. In contrast, long-term AF management systems with red oak trees managed with inorganic N fertilizer applications could potentially result in greater SQ, compared with pecan trees managed with inorganic N fertilizer applications.

The lack of crop codes in SMAF for tree species (i.e., red oak and pecan) may have limited the ability to differentiate the effect of tree species on SQ. Crop codes are used to modify the optimum thresholds of soil pH and *P* values for each crop and reflect the impacts of each crop on nutrient uptake and availability. Thus, providing the understory vegetation crop code (tall fescue) rather than individual crop codes for red oak and pecan may have prevented SQ distinctions between tree species to be fully captured by the SQ indices. Therefore, SQ assessment tools such as SMAF, should develop specific tree crop codes in order to evaluate how management affects soil health in these systems. Notably, it is important to collect soil information within the tree diameter spacing (rather than alleys) so that SQIs can be used for specific tree cropping systems. Future work should also focus on deeper sampling depths to evaluate how management affects whole profile soil health, as well as how foliar tree litterfall interacts with decomposition and SOC in these important, yet understudied tree-based crop production systems.

In an effort to evaluate SQ benefits of AF systems and the potential usefulness of SMAF, the relationship between individual soil properties and the overall SQI was explored (Figure 5). Linear regression models were adjusted to SOC, K, and BD, following the "more is better" and "less is better" SMAF functions (Wienhold et al., 2009). A quadratic model was performed to reflect the mid-optimum relationship between P and SQ, also described in the SMAF algorithms. Soil organic C and K had a positive relationship with SQI ($p < .05$; Figure 5a, b), confirming that increased SOC and fertility improves SQ. However, SQI values reached a plateau from SOC and K concentrations greater than 1.5% and 100 mg kg^{-1} (Figure 5a, b), respectively, suggesting that these variables may not follow a more-is-better relationship with SQI in AF systems. Instead, research groups aiming to use SMAF in such systems should identify available datasets and redefine the mathematical relationship between these soil indicators and SQ. Soil quality index as a function of P adjusted to the quadratic model ($p < .05$; Figure 5c), indicating that values up to 75 mg kg^{-1} contribute to increased SQ, but values greater than that can reduce SQ. Lastly, BD had a negative relationship with SQI ($p < .05$; Figure 5d), indicating that lower BD values favor increased SQ in AF systems.

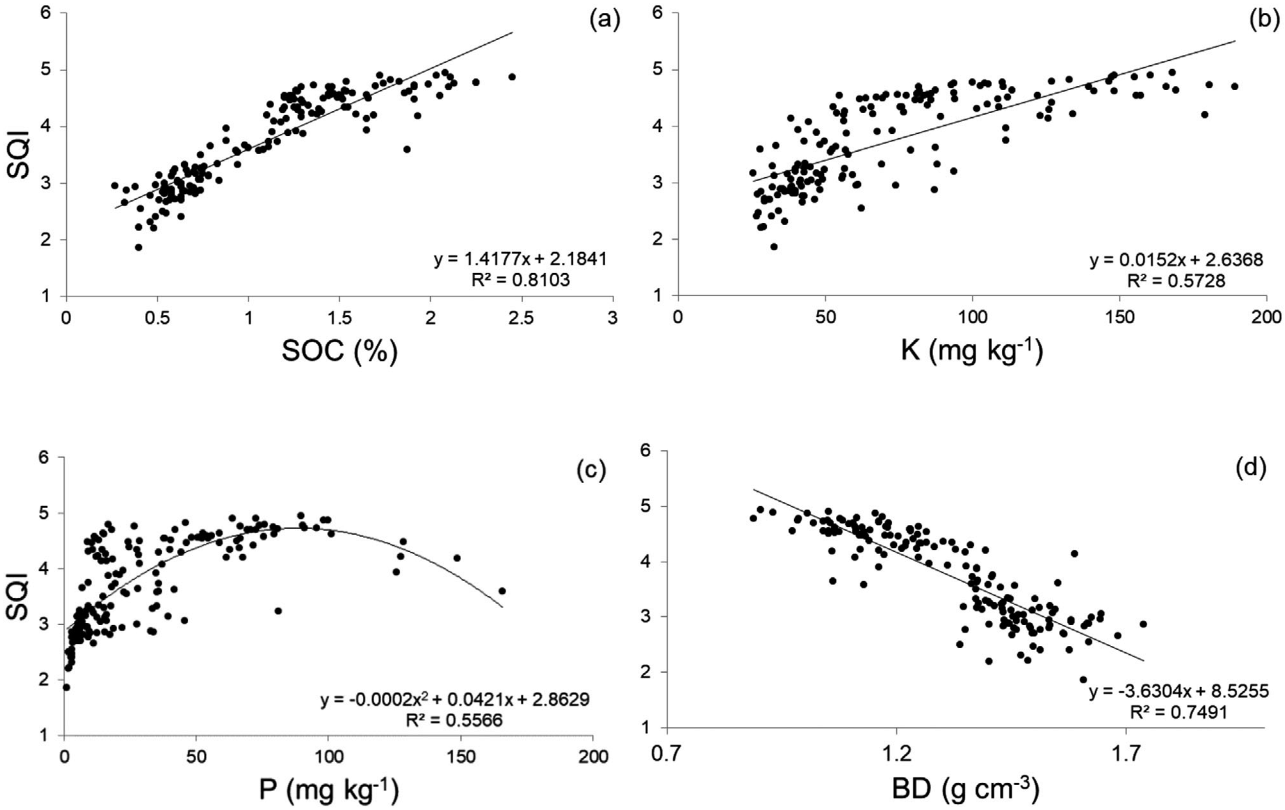

FIGURE 5 The relationship between individual soil properties ([a] soil organic C [SOC], [b] K, [c] P, and [d] bulk density [BD]) and the overall soil quality index (SQI) after 17 yr of agroforestry management in the Ozark Highlands region of northwest Arkansas

4 | CONCLUSIONS

This study used SMAF to assess SQ impacts in an AF system after 17 yr of management with different tree species and fertility source combinations. Such SQ assessments in AF systems are novel compared with prior applications of SMAF, although distinct crop codes for tree species (i.e., red oak and pecan) are needed. Nonetheless, useful information was generated from the application of SMAF in the AF system evaluated. Based on the individual SOC, BD, P, K, and pH scores, the application of SMAF demonstrated that the greatest SQ resulted from growing pecan managed with PL applications, which did not differ from soils under red oak receiving inorganic N fertilizer applications. This study also confirmed that increased SOC and fertility improved SQ; however, SQI values reached a plateau when SOC and K concentrations were greater than 1.5% and 100 mg kg^{-1}, respectively, suggesting that these variables may not follow a more-is-better relationship with SQI in AF systems.

Results of this study demonstrated that not only do different tree species benefit dissimilarly from fertilizer sources, but also that different treatment combinations and management plans can likely result in improved SQ. This information can be valuable for AF system managers. However, not only is additional development of SMAF (i.e., crop codes) necessary to improve the framework's accuracy and applicability, but also more research is necessary to determine SMAF's ability to assess SQ impacts of long-term management practices in AF systems when matching tree species on landscapes and identifying how fertility source affects SQ.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Amanda J. Ashworth https://orcid.org/0000-0002-3218-8939
Tom Sauer https://orcid.org/0000-0002-7047-1233

Phillip R. Owens https://orcid.org/0000-0002-5460-8500
Kristofor R. Brye https://orcid.org/0000-0001-9353-4009

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