Prioritizing woody species for the rehabilitation of arid lands in western Iran based on soil properties and carbon sequestration Postprint

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Abstract

Plants are an important component in many natural ecosystems. They influence soil properties, especially in arid ecosystems. The selection of plant species based on their adaptations to site conditions is essential for rehabilitation of degraded sites and other construction sites such as check-dams. Other factors to be considered in species selection include their effects on soil properties and their abilities to meet other management objectives. The purpose of this study was to assess the effects of native (Populus euphratica Oliv. and Tamarix ramosissima Ledeb.) and introduced (Eucalyptus camaldulensis Dehnh. and Prosopis juliflora (Swartz) DC.) woody species on soil properties and carbon sequestration (CS) in an arid region of Iran. Soil sampling was collected at three soil depths (0-10, 10-20 and 20-30 cm) at the sites located under each woody species canopy and in an open area in 2017. Soil physical-chemical property was analyzed in the laboratory. The presence of a woody species changed soil characteristics and soil CS, compared with the open area. For example, the presence of a woody species caused a decrease in soil bulk density, of which the lowest value was observed under E. camaldulensis (1.38 g/cm3) compared with the open area (1.59 g/cm3). Also, all woody species significantly increased the contents of soil organic matter and total nitrogen, and introduced species had more significant effect than native species. The results showed that CS significantly increased under the canopy of all woody species in a decreasing order of P. euphratica (9.08 t/hm2)>E. camaldulensis (8.37 t/hm2)>P. juliflora (5.20 t/hm2)>T. ramosissima (2.93 t/hm2)>open area (1.33 t/hm2), thus demonstrating the positive effect of a woody species on CS. Although the plantation of non-native species had some positive effects on soil properties, we recommend increasing species diversity in plantations of native and introduced woody species to provide more diversity for the increased ecosystem services, resilience, health and long-term productivity.

Full Text

Prioritizing Woody Species for the Rehabilitation of Arid Lands in Western Iran Based on Soil Properties and Carbon Sequestration

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Abstract: Plants are important components of many natural ecosystems and exert significant influence on soil properties, particularly in arid ecosystems. Selecting plant species based on their adaptations to site conditions is essential for rehabilitating degraded sites and other construction sites such as check-dams. Other factors to consider in species selection include their effects on soil properties and their ability to meet management objectives. This study assessed the effects of native (*Populus euphratica* Oliv. and *Tamarix ramosissima* Ledeb.) and introduced (*Eucalyptus camaldulensis* Dehnh. and *Prosopis julifora* (Swartz) DC.) woody species on soil properties and carbon sequestration (CS) in an arid region of Iran. Soil samples were collected at three depths (0–10, 10–20, and 20–30 cm) under each woody species canopy and in an open area in 2017, and soil physical-chemical properties were analyzed in the laboratory. The presence of woody species altered soil characteristics and CS compared with open areas. For example, woody species caused a decrease in soil bulk density, with the lowest value observed under *E. camaldulensis* (1.38 g/cm^3) compared with the open area (1.59 g/cm^3). All woody species significantly increased soil organic matter and total nitrogen contents, with introduced species having more significant effects than native species. CS increased significantly under all woody species canopies in decreasing order: *P. euphratica* (9.08 t/hm^2) > *E. camaldulensis* (8.37 t/hm^2) > *P. julifora* (5.20 t/hm^2) > *T. ramosissima* (2.93 t/hm^2) > open area (1.33 t/hm^2), demonstrating the positive effect of woody species on CS. Although plantations of non-native species had some positive effects on soil properties, we recommend increasing species diversity in plantations of native and introduced woody species to provide greater diversity for enhanced ecosystem services, resilience, health, and long-term productivity.

Keywords: arid ecosystem; carbon sequestration; degraded soil; restoration; reforestation; soil management

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1 Introduction

Arid regions occur where evaporation exceeds rainfall (Gaur et al., 2018). More than one-third of Earth's population (2.5$×10^{9}$ people) lives in arid regions, which cover approximately 5.36$×10^{6}$ km^2 (41% of the Earth's surface area) (Mortimor et al., 2009; UNEMG, 2011). In recent decades, these regions have experienced accelerated development along with changes in land use and climate (Song et al., 2018), leading to increasing degradation and a desertification index of 5.8$×10^{6}$ hm^2/a (Lal, 2001). In desert ecosystems, soil carbon content decreases while carbon emissions as CO_2 to the atmosphere accelerate (Lal, 2004; Romm, 2011), contributing to global warming. Additionally, desertification often leads to soil erosion and salinization, loss of vegetation cover and biomass, and decreased soil productivity and quality (Zhao et al., 2006; Ma et al., 2017).

Selecting appropriate woody species for reclamation and rehabilitation projects in arid regions is crucial because woody species greatly influence the degree of ecosystem recovery success and increase productivity of goods and ecological services. Previous research has examined revegetation in arid regions, such as Kergoat et al. (2018) and Verón et al. (2018), who assessed vegetation cover quantity and type for preventing desertification, soil erosion, and ecosystem deterioration. Nyssen et al. (2009) demonstrated that establishing eucalypt woodlands positively influenced the environment, particularly by ameliorating soil conditions. Tesfay et al. (2015) compared different tree species' ability to improve soil conditions and produce wood fuels, while Reubens et al. (2011) used Decision Support Systems to identify appropriate tree species for rehabilitating arid regions and prioritize woody plants for revegetation based on environmental adaptations. However, species selection is complicated by reclamation goals, existing vegetation, degree of site degradation, and ecosystem processes (Reubens et al., 2011). To date, few studies have evaluated appropriate plant species for reclamation projects in specific arid regions, including western Iran.

Iran is centrally located in Earth' s arid and semi-arid zones, with over 60% of its land area (approximately 105$×10^{6}$ hm^2) classified as arid or semi-arid (Modarres and da Silva, 2007). In Iran, woody species plantations are commonly used to amend soil, combat desertification, revegetate large construction sites, and mitigate dust storms. Selecting suitable woody species adapted to hot, dry conditions is essential. Commonly used species in these regions include eucalyptus (*Eucalyptus camaldulensis* Dehnh.), Euphrates poplar (*Populus euphratica* Oliv.), saltcedar (*Tamarix ramosissima* Ledeb.), and mesquite (*Prosopis julifora* (Swartz) DC.), with *P. euphratica* and *T. ramosissima* being native and *E. camaldulensis* and *P. julifora* introduced. Although these species show good field performance in survival and growth, strategies regarding how different species origins modify the environment and soil are lacking. Therefore, this study assessed the effects of introduced and native woody species on soil properties and carbon sequestration (CS) in arid regions. Our results may help managers and decision-makers select woody species and optimize rehabilitation efforts in degraded arid ecosystems.

2.1 Study Area

The study was conducted in Reza Abad Park (46°13 -46°14 N, 33°09 -33°12 E), a 700 hm^2 area located in Mehran County, Ilam Province, western Iran [Figure 1: see original paper]. Mean annual precipitation is 209 mm, occurring primarily in autumn and winter, with an annual mean temperature of 24.5°C. According to climatic curves, ten months are dry [Figure 2: see original paper], indicating a warm, dry climate. Elevation ranges from 203 to 253 m above sea level, with relatively flat land (<1% slope). The soil is calcareous with >30% surface gravel, low organic matter, shallow depth, and a deep groundwater table (Zamani et al., 2018). Dominant soil texture is sandy loam, and geology is characterized by the Gachsaran formation with alternating layers of anhydrite gypsum, marl, and claystone.

2.2 Woody Species

Study sites included a natural forest stand of native *T. ramosissima* and *P. euphratica* along the Konjancham River and 26-year-old plantations of introduced *E. camaldulensis* and *P. julifora* in Reza Abad Park . Common understory vegetation included *Stipa capensis*, *Plantago ovata*, and *Anchusa strigose*.

2.3 Soil Sampling Design

At each study site, we randomly established eight 20 m$×$20 m plots. In September 2017, soil samples from three depths (0–10, 10–20, and 20–30 cm) were collected from each plot under woody canopies and in open areas (control). Each sample was a composite of four sub-samples taken around one species at the plot center in forests and plantations. Additionally, one intact soil core (5–8 cm height, 8 cm diameter) was collected at each sampling plot for bulk density (BD) determination.

2.4 Soil Physical and Chemical Analyses

Soil samples were sieved through a 2-mm mesh to remove roots and coarse fragments, then stored in plastic bags at room temperature before analysis. BD was measured using the core method (Black and Hartge, 1986). Soil porosity (n) was calculated from BD and particle density (Weil and Brady, 2015). Saturation point (SP) was determined gravimetrically. Field capacity (FC) at 33 kPa and permanent wilting point (PWP) at 1500 kPa were determined using a pressure plate apparatus (Klute, 1986). Soil pH was measured with a glass electrode in soil suspension (1:1 w:v), and electrical conductivity (EC) with an EC meter. Soil organic carbon (SOC) was determined using the Walkley and Black wet oxidation method (Nelson and Sommers, 1986) and multiplied by 1.724 to calculate organic matter (OM) (Weil and Brady, 2015). Total nitrogen (TN) was determined by the Kjeldahl procedure (Bremner and Mulvaney, 1982). Cation exchange capacity (CEC) was measured through sodium acetate replacement (pH=8.5) (Summer and Miller, 1996). Available phosphorus (AP) was determined by $NaHCO_3$ extraction (Olsen and Sommers, 1982). Exchangeable Ca and Mg were extracted using 0.1-M $BaCl_2$ (Hendershot and Duquette, 1986). Equations 1 and 2 were used to estimate total dissolved salts (TDS) (Chang et al., 1983) and CS (Qin et al., 2016), respectively.

2.5 Statistical Analyses

Prior to analysis, normality and homogeneity of variances were tested using Kolmogorov-Smirnov and Levene tests, respectively. We used a generalized linear mixed-effects model (GLMM) with Poisson error distribution and log-link function, where species type, depth, and their interaction were fixed factors and individual species was a random factor. GLMM extends generalized linear models by adding random effects to the linear predictor (McCulloch and Neuhaus, 2005).

GLMM analysis was performed separately for all soil physical, chemical, and carbon sequestration response variables using the 'lme4' package (Bates et al., 2015). Stepwise regression determined main factors affecting CS. Before regression, collinearity among independent variables (soil physical and chemical properties) was evaluated using Pearson' s correlation coefficients. BD and SOC were removed from the final model because they were used to calculate CS. Means comparison models (ANOVA, GLMM, or mixed models) evaluate single soil properties but cannot provide general comparison of multivariate overall soil structure among treatments.

Therefore, nonmetric multidimensional scaling (NMDS) using Bray-Curtis similarity matrices was applied to assess overall structural changes in soil physical and chemical properties. After NMDS, ANOVA determined significant differences among NMDS axis groups (Yang et al., 2019). NMDS analysis used the 'vegan' package (Oksanen et al., 2018). All analyses were performed using the latest version of R statistical software (R Core Team, 2018).

3.1 Soil Physical Properties

Soil physical properties were significantly affected by woody species, and soil depth significantly influenced some properties such as BD, n, and FC ($P<0.05$;). The interaction between woody species and sampling depth did not significantly affect any physical properties, indicating that variations in soil physical properties under different woody species were independent of sampling depth.

Woody species decreased BD compared with open areas, with BD significantly lower ($P=0.002$) under *E. camaldulensis* (1.38 g/cm^3) than in open areas (1.59 g/cm^3) [Figure 3: see original paper]. BD increased significantly with depth from 0–10 cm to 20–30 cm under woody species, while no significant differences occurred among depths in open areas [Figure 3: see original paper].

Porosity (n) increased under all woody species, being significantly higher under

E. camaldulensis (20%) than in open areas. The highest n occurred at 0-10 cm depth (53%), while the lowest occurred at 20-30 cm depth (38%), with no significant variation among depths in open areas. SP was significantly higher under *P. euphratica* and *T. ramosissima* (33% and 16%, respectively) than in open areas, but did not differ significantly between open areas and *E. camaldulensis* or *P. julifora* [Figure 3: see original paper]. SP did not vary significantly with soil depth.

FC was significantly higher under *P. euphratica* and *T. ramosissima* (38% and 29%, respectively) than in open areas, but not under *E. camaldulensis* or *P. julifora*. Sampling depth significantly affected FC only under *P. julifora*, with no significant differences among depths under other species. All woody species significantly increased PWP, with highest values observed under *P. julifora* (7.43%) and *E. camaldulensis* (7.08%).

3.2 Soil Chemical Properties

GLMM analysis showed that all chemical properties except AP ($P=0.166$) were significantly affected by woody species. Soil chemical parameters were also significantly affected by depth except for CEC ($P<0.001$) and CS (). The interaction between plant species and sampling depth was significant for pH, EC, TN, Ca, Mg, and TDS ($P<0.05$), indicating that changes in these factors depended on soil sampling depth.

Soil pH increased significantly under all woody species except *P. euphratica* compared with open areas [Figure 4: see original paper]. Soil depth had significant but variable effects on pH depending on species. For example, pH increased with depth under *P. julifora* (0-10 cm, pH=7.49; 10-20 cm, pH=7.50; 20-30 cm, pH=7.57), but decreased with depth under *T. ramosissima* (0-10 cm, pH=7.34; 10-20 cm, pH=7.35; 20-30 cm, pH=7.27).

EC relationships varied by species: *E. camaldulensis* and *T. ramosissima* increased EC by 17% and 27%, respectively, while *P. julifora* decreased EC by 58%. No significant EC difference occurred between *P. euphratica* and open areas. EC increased with depth under *E. camaldulensis* and *P. euphratica* [Figure 4: see original paper].

OM content increased significantly under *P. euphratica*, followed by *E. camaldulensis*, *P. julifora*, and *T. ramosissima* (83%, 82%, 70%, and 54%, respectively) compared with open areas, with higher content at the surface layer. CEC differed significantly among woody species ($P<0.001$), being higher under all species compared with open areas (6.71 cmol/kg) except *T. ramosissima* (7.46 cmol/kg). CEC did not vary significantly with depth.

TN was significantly higher under all woody species than in open areas (0.001%) except *T. ramosissima* (0.007%). TN was also significantly higher in the upper soil depth (0-10 cm) under all species. Both *T. ramosissima* and *P. euphratica* significantly increased Mg (69% and 8%, respectively) and Ca contents (55%

and 54%, respectively) compared with open areas. Soil CS under all woody species decreased in the order: *P. euphratica* (9.08 t/hm^2) > *E. camaldulensis* (8.37 t/hm^2) > *P. julifora* (5.2 t/hm^2) > *T. ramosissima* (2.93 t/hm^2) > open area (1.33 t/hm^2), demonstrating the positive effect of woody species on CS. No significant CS differences occurred among soil depths [Figure 4: see original paper].

3.3 Factors Affecting Soil CS

Individual models predicting CS content showed that soil CS was affected by FC under *E. camaldulensis*, by Mg and n under *P. julifora*, and by FC and SP under *P. euphratica*. In contrast, soil CS was not affected by any physical or chemical variables under *T. ramosissima* or in open areas. The final regression model showed that soil CS was affected by TN, Mg, TDS, CEC, and PWP ().

3.4 NMDS Test

Soil properties differentiated among treatments in both open areas and woody species sites. One-way ANOVA showed significant differences between treatments in the first axis (F-value=103; P-value=0.000) and second axis (F-value=250.6; P-value=0.000). The most important factors characterizing *T. ramosissima* habitat were EC, SP, Ca, BD, Mg, and FC. In contrast, acidity, exchangeable phosphorus capacity, and n best defined *P. julifora* habitat. Environmental requirements of *P. euphratica* and *E. camaldulensis* were similar regarding OM, TN, and soil CS levels, resulting in minimal distance between them. High TN, OM, and soil CS values (mostly in *P. euphratica*) and PWP (mostly in *E. camaldulensis*) characterized these stands. The control area was located far from study forests and plantations. Axis orientation indicated that minimum OM, CS, and TN amounts in open areas supported the importance of plant species in improving soil conditions [Figure 5: see original paper].

4.1 Comparing Soil Physical Properties in Native and Introduced Woody Species

Woody species in both native and introduced plantations generally affected soil physical properties including BD, n, SP, FC, and PWP, with effects most noticeable compared with open areas. These results are consistent with other studies (Frouz et al., 2013; Kooch et al., 2016), particularly in arid and semi-arid regions (Kalinda et al., 2015; Chen et al., 2016). The lowest BD occurred under *E. camaldulensis*, which also strongly influenced n compared with open areas. Plant litterfall generally increases OM input to soil (Carnol and Bazgir, 2013), as do tree roots, which create numerous pores, increasing n and decreasing BD (Binkley and Fisher, 2012). Tree canopies also positively affect soil mesofauna and macrofauna activity by improving soil moisture and providing energy sources (Heydari et al., 2017; Zagatto et al., 2019). Soil fauna activity reduces BD by creating pores and displacing OM.

E. camaldulensis had stronger effects on BD reduction than other species, possibly due to more extensive root systems and higher OM production (leaves, bark, trunk, and branches). In contrast, Montero and Delitti (2017) reported BD increased under *E. camaldulensis* due to soil compaction. In this study, BD increased and n decreased with depth under woody species, while no significant changes occurred with depth in open areas. Generally, BD increases with depth due to overburden weight and lower OM content, resulting in greater compaction and reduced porosity (Weil and Brady, 2015).

SP and FC were highest under *P. euphratica* among all woody species and open areas, likely due to increased soil OM from understory trees (Hofstede et al., 2002; Farley et al., 2004). SP and FC stability with depth may result from uniform soil texture throughout the profile (Zhao et al., 2011; Weil and Brady, 2015). AP was not influenced by introduced or native woody species, consistent with Isichei and Muoghalu (1992) and Son et al. (1992) who found plantations did not affect AP. Phosphorus has low mobility in soil (Havlin et al., 2016), and climate factors have greater effects on soil P than vegetation. Heydaei et al. (2019) reported soil phosphorus was significantly influenced by climate but not management. The lack of phosphorus differences between plantations and natural forest may indicate it is not limiting in this study area.

4.2 Comparing Soil Chemical Properties in Native and Introduced Woody Species

All chemical properties including pH, EC, SOM, TN, exchangeable Mg and Ca, CEC, and TDS were affected by woody species, demonstrating important plant influences on soil chemistry. Many studies have reported tree canopy and shrub species effects on soil chemical properties (Yang et al., 2011; Waring et al., 2015; Habashi et al., 2019). Soil depth also significantly affects most chemical properties (Weil and Brady, 2015). Root secretion and soil microbial biomass affect chemical properties more than physical properties (Bardgett, 2005; Binkley and Fisher, 2012). Nutrient and water-soluble material movement from topsoil to subsoil through leaching creates horizon differences (Lee and Jose, 2005; Buol et al., 2011).

Among studied species, *E. camaldulensis* and *P. euphratica* had greater effects on OM, TN, CEC, and TDS. Soil OM is higher under woody species than open areas due to litterfall and root inputs (Prescott, 2002). Both *E. camaldulensis* and *P. euphratica* are fast-growing trees with large canopies producing more litterfall than other species (Singh et al., 1989; Williams and Wardle, 2007). *E. camaldulensis* leaves contain high tannin and aromatic contents, increasing resistance to microbial decomposition and resulting in OM accumulation (Coleman et al., 2004; Brennan et al., 2009). Annual bark shedding under *E. camaldulensis* provides greater input than under *P. euphratica* (Cornelissen et al., 2017). Positive correlations exist between OM and CEC (Helling et al., 1964; Obalum et al., 2017), suggesting these woody species may increase soil fertility and productivity by improving nutrient and water holding capacity in arid regions. Increased nutrient accumulation in forest plantations may create "fertile islands," with development degree depending on canopy size, developmental stage, and litter accumulation duration (Li et al., 2008).

Soil pH was highest and EC lowest under *P. julifora.* Bruckner (2012) found negative relationships between soil pH and EC because pH decreases while hydrogen concentration increases in soil solution, leading to higher EC. In contrast, EC increased under *E. camaldulensis* and *T. ramosissima.* Some species like *T. ramosissima* uptake salt from groundwater, transport it to leaves, and return it to soil through litterfall, increasing soil salinity (Arndt et al., 2004; Stromberg et al., 2009). Exchangeable Ca and Mg under native species (*P. euphratica* and *T. ramosissima*) were higher than under introduced species or in open areas. Leaf cation content varies among species, affecting nutrient return to soil. Meiresonne et al. (2006) reported higher exchangeable Ca under poplar species due to foliar litter accumulation. In this study, natural forest native trees were older than introduced plantation species, and higher above- and belowground biomasses in natural forests may result in higher exchangeable Ca and Mg contents (Binkley and Fisher, 2012).

Woody species increased soil CS, with higher values under *E. camaldulensis* and *P. euphratica* than other species. Trees sequester atmospheric CO_2 via photosynthesis and store it in shoot and root biomass, with carbon entering soil as OM when trees shed leaves, roots, twigs, bark, and wood. Therefore, CS is higher in forests and plantations than open areas. Grünzweig et al. (2003) reported positive tree canopy effects on increased CS in arid areas. Higher soil CS under *E. camaldulensis* and *P. euphratica* may result from high biomass production from rapid canopy and root growth. Quideau et al. (2001) and Pérez-Bejarano et al. (2010) reported soil CS amounts are closely related to plant species. Other studies show litterfall inputs increase soil carbon content and promote microbial activity and nutrient cycling (Xuluc-Tolosa et al., 2003; HagenThorn et al., 2004).

FC was the best CS predictor under *E. camaldulensis* and *P. euphratica*, while n had greatest impact under *P. julifora.* Arid ecosystems are characterized by soil moisture restrictions (Gaur et al., 2018), and water availability and use efficiency play critical roles in CS (de Deyn et al., 2008), particularly in arid ecosystems. Complementarity and facilitation traits regarding water storage, use, and protection from drought and solar radiation likely enhance CS (Schenk and Jackson, 2002). Plant traits enabling opportunistic precipitation use are vital for CS in arid ecosystems (de Deyn et al., 2008). Therefore, *E. camaldulensis* and *P. euphratica* may more effectively use available water (precipitation and groundwater) due to traits such as higher leaf area and deep-rooting systems. Dense canopies of *E. camaldulensis* and *P. euphratica* likely reduce water and carbon losses (Arriaga and Maya, 2007), resulting in optimum water use and higher soil CS, as supported by the highest soil carbon content observed under these species.

Finally, native and introduced woody species caused different changes in soil properties, consistent with other reports (Pei et al., 2016; Wartenberg et al., 2017). Therefore, selecting suitable woody species adapted to improve soil properties and meet management goals in arid and semi-arid regions is important.

5 Conclusions

Selecting suitable woody species is one way to increase carbon accumulation and soil nutrients. Fast-growing species can sequester more carbon in tissues at higher rates short-term than slow-growing species, though slow-growing species are often longer-lived and store carbon for longer periods. In this study, fast-growing species such as *E. camaldulensis* are preferred for increasing soil nutrients and improving soil properties in arid and semi-arid regions because they produce higher litterfall and OM amounts.

Accordingly, we suggest establishing plantations with species such as eucalyptus and restoring native forests with species such as *P. euphratica* to increase soil CS and fertility. Additionally, selecting salt-tolerant plants (*T. ramosissima*) to reclaim saline soils could serve as an alternative management approach. Increasing plant species cover and diversity while considering positive effects of non-native species on soil ecology seems desirable when designing rehabilitation plans for arid and semi-arid regions. Mixed plantations of native and non-native, fast- and slow-growing, short- and long-lived species may increase biodiversity, optimize CS and soil improvement, enhance resistance and resilience to disturbances and environmental stresses, and provide more diverse ecosystem goods and services.

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References

Arndt SK, Arampatsis C, Foetzki A, et al. 2004. Contrasting patterns of leaf solute accumulation and salt adaptation in four phreatophytic desert plants in a hyperarid desert with saline groundwater. *Journal of Arid Environments*, 59(2): 259–270.

Arriaga L, Maya Y. 2007. Spatial variability in decomposition rates in a desert scrub of northwestern Mexico. *Plant Ecology*, 189(2): 213–225.

Bardgett R. 2005. *The Biology of Soil: A Community and Ecosystem Approach.* Oxford: Oxford University Press, 119–138.

Bates D, Mächler M, Bolker B, et al. 2015. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67.

Binkley D, Fisher RF. 2012. *Ecology and Management of Forest Soils.* New York: John Wiley & Sons, 75–137.

Black GR, Hartge KH. 1986. Bulk density. In: Klute A. *Method of Soil Analysis.*

Part I. Physical and Mineralogical Method of Soil Analysis. Part I. (2nd ed.) Agronomy Monograph No. 9 (Part 1). Madison: American Society of Agronomy Inc.

Bremner JM, Mulvaney CS. 1982. Nitrogen—total. In: Page AL. *Methods of Soil Analysis*, Madison: American Society of Agronomy Inc., 595-624.

Brennan KE, Christie FJ, York A. 2009. Global climate change and litter decomposition: more frequent fire slows decomposition and increases the functional importance of invertebrates. *Global Change Biology*, 15(12): 2958-2971.

Bruckner MZ. 2012. *Water and Soil Characterization, pH and Electrical Conductivity*. Montana: Montana State University Bozeman, 15-36.

Carnol M, Bazgir M. 2013. Nutrient return to the forest floor through litter and throughfall under 7 forest species after conversion from Norway spruce. *Forest Ecology and Management*, 309: 66-75.

Chang C, Sommerfeldt TG, Carefoot JM, et al. 1983. Relationships of electrical conductivity with total dissolved salts and cation concentration of sulfate-dominant soil extracts. *Canadian Journal of Soil Science*, 63(1): 79-86.

Chen LF, He ZB, Zhu X, et al. 2016. Impacts of afforestation on plant diversity, soil properties, and soil organic carbon storage in a semi-arid grassland of northwestern China. *Catena*, 147: 300-307.

Cornelissen JH, Grootemaat S, Verheijen LM, et al. 2017. Are litter decomposition and fire linked through plant species traits? *New Phytologist*, 216(3): 653-669.

de Deyn GB, Cornelissen JH, Bardgett RD. 2008. Plant functional traits and soil carbon sequestration in contrasting biomes. *Ecology Letters*, 11(5): 516-531.

Farley KA, Kelly EF, Hofstede RG. 2004. Soil organic carbon and water retention after conversion of grasslands to pine plantations in the Ecuadorian Andes. *Ecosystems*, 7(7): 729-739.

Frouz J, Livečková M, Albrechtová J, et al. 2013. Is the effect of trees on soil properties mediated by soil fauna? A case study from post-mining sites. *Forest Ecology and Management*, 309: 87-95.

Gaur MK, Squires VR. 2018. Geographic extent and characteristics of the world' s arid zones and their peoples. In: Mahesh KG, Victor RS. *Climate Variability Impacts on Land Use and Livelihoods in Drylands*. Switzerland: Springer, 3-20.

Grünzweig JM, Lin T, Rotenberg E, et al. 2003. Carbon sequestration in arid-land forest. *Global Change Biology*, 9(5).

Habashi H, Moslehi M, Shabani E, et al. 2019. Chemical content and seasonal variation of throughfall and litterflow under individual trees in the Hyrcanian forests of Iran. *Journal of Sustainable Forestry*, 38(2): 183-197.

Hagen-Thorn A, Callesen I, Armolaitis K, et al. 2004. The impact of six European tree species on the chemistry of mineral topsoil in forest plantations on former agricultural land. *Forest Ecology and Management*, 195: 373-384.

Havlin JL, Tisdale SL, Nelson WL, et al. 2016. *Soil Fertility and Fertilizers*. Delhi: Pearson India Education, 215-245.

Hendershot WH, Duquette M. 1986. Exchangeable cation and effective CEC by the $BaCl_2$ method. In: Carter MR. *Soil Sampling and Methods of Analysis*. Canadian Society of Soil Science, Boca Raton, FL: CRC Press LLC, 168-170.

Heydari M, Prévosto B, Abdi T, et al. 2017. Establishment of oak seedlings in historically disturbed sites: Regeneration success as a function of stand structure and soil characteristics. *Ecological Engineering*, 107: 172-182.

Isichei AO, Muoghalu JI. 1992. The effects of tree canopy cover on soil fertility in a Nigerian savanna. *Journal of Tropical Ecology*, 8(3): 329-338.

Kalinda C, Mburu D, Ngamau K, et al. 2015. Short term leguminous trees-tillage interactions and their effect on soil-water content in a semi-arid agroforestry parkland. *Open Journal of Forestry*, 5(7): 668-677.

Klute A. 1986. Water retention laboratory methods. In: Page AL, Miller RH, Keeney DR. *Method of Soil Analysis Part 1. Physical and Mineralogical Methods*. Madison: American Society of Agronomy Inc., 635-662.

Kooch Y, Rostayee F, Hosseini SM. 2016. Effects of tree species on topsoil properties and nitrogen cycling in natural forest and tree plantations of northern Iran. *Catena*, 144: 65-73.

Lal R. 2001. Potential of desertification control to sequester carbon and mitigate the greenhouse effect. *Climatic Change*, 51(1).

Lal R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677): 1623-1627.

Lee KH, Jose S. 2005. Nitrate leaching in cottonwood and loblolly pine biomass plantations along a nitrogen fertilization gradient. *Agriculture, Ecosystems & Environment*, 105(4): 615-623.

Li PX, Wang N, He WM, et al. 2008. Fertile islands under *Artemisia ordosica* in inland dunes of northern China: effects of habitats and plant developmental stages. *Journal of Arid Environments*, 72(6): 953-963.

Ma Q, Fehmi JS, Zhang D, et al. 2017. Changes in wind erosion over a 25-year restoration chronosequence on the south edge of the Tengger Desert, China: implications for preventing desertification. *Environmental Monitoring and Assessment*, 189(9): 463.

McCulloch CE, Neuhaus JM. 2005. Generalized linear mixed models. In: Peter A, Theodore C. *Encyclopedia of Biostatistics*. New York: John Wiley & Sons, 4.

Meiresonne L, Schrijver AD, Vos BD. 2006. Nutrient cycling in a poplar plantation (*Populus trichocarpa*×*Populus deltoids* 'Beaupré') on former agricultural land in northern Belgium. *Canadian Journal of Forest Research*, 37(1): 141-155.

Modarres R, da Silva VDP R. 2007. Rainfall trends in arid and semi-arid regions of Iran. *Journal of Arid Environments*, 70(2).

Montero LL, Delitti W. 2017. Effects of *Eucalyptus* and *Pinus* forest management on soil organic carbon in Brazilian wooded savanna. In: Gopal S, Sumit C. *Forest Biomass and Carbon*. London: IntechOpen Limited, doi: 10.5772/intechopen.72684.

Nelson DW, Sommers LE. 1982. Total carbon, organic carbon and organic matter. In: Page AL. *Methods of Soil Analysis: Part 3—Chemical Methods*. Madison: Soil Science Society of America, 961-1010.

Nyssen J, Haile M, Naudts J, et al. 2009. Desertification? Northern Ethiopia re-photographed after 140 years. *Science of the Total Environment*, 407(8): 2749-2755.

Obalum SE, Chibuike GU, Peth S, et al. 2017. Soil organic matter as sole indicator of soil degradation. *Environmental Monitoring and Assessment*, 189(4): 176.

Oksanen J, Blanchet FG, Kindt R, et al. 2018. Vegan: Community Ecology Package. [2019-01-17]. https://CRAN.R-project.org/package=vegan.

Olsen SR, Sommers LE. 1982. Phosphorus. In: Page AL. *Methods of Soil Analysis. Part 2* (2nd ed.). Madison: American Society of Agronomy Inc., 403-431.

Pei Z, Eichenberg D, Bruelheide H, et al. 2016. Soil and tree species traits both shape soil microbial communities during early growth of Chinese subtropical forests. *Soil Biology and Biochemistry*, 96: 180-190.

Pérez-Bejarano A, Mataix-Solera J, Zornoza R, et al. 2010. Influence of plant species on physical, chemical and biological soil properties in a Mediterranean forest soil. *European Journal of Forest Research*, 129(1): 15-24.

Prescott CE. 2002. The influence of the forest canopy on nutrient cycling. *Tree Physiology*, 22(15-16): 1193-1200.

Qin Z, Dunn JB, Kwon H, et al. 2016. Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. *GCB Bioenergy*, 8(1): 66-80.

Quideau SA, Chadwick OA, Benesi A, et al. 2001. A direct link between forest vegetation type and soil organic matter composition. *Geoderma*, 104(1-2): 41-60.

R Core Team, 2018. *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing, Vienna, Austria. [2019-05-21]. http://www.R-project.org/.

Reubens B, Moeremans C, Poesen J, et al. 2011. Tree species selection for land rehabilitation in Ethiopia: from fragmented knowledge to an integrated multi-criteria decision approach. *Agroforestry Systems*, 82(3): 303-330.

Romm J. 2011. Desertification: The next dust bowl. *Nature*, 478(7370): 450-451.

Schenk HJ, Jackson RB. 2002. Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems. *Journal of Ecology*, 90(3): 480-494.

Singh K, Chauhan HS, Rajput DK. 1989. Report of a 60-month study on litter production, changes in soil chemical properties and productivity under poplar (*P. deltoides*) and eucalyptus (*E. hybrid*) interplanted with aromatic grasses. *Agroforestry Systems*, 9(1): 37-45.

Song XP, Hansen MC, Stehman SV, et al. 2018. Global land change from 1982 to 2016. *Nature*, 560(7720): 639-643.

Stromberg JC, Chew MK, Nagler PL, et al. 2009. Changing perceptions of change: the role of scientists in *Tamarix* and river management. *Restoration Ecology*, 17(2): 177-186.

Summer ME, Miller WP. 1996. Cation exchange capacity and exchange coefficient. In: Sparks DL. *Methods of Soil Analysis. Part 3.* Madison: American Society of Agronomy Ltc., 1201-1230.

Verón SR, Blanco LJ, Texeira MA. 2018. Desertification and ecosystem services supply: The case of the arid Chaco of South America. *Journal of Arid Environments*, 159: 66-74.

Wartenberg AC, Blaser WJ, Gattinger A, et al. 2017. Does shade tree diversity increase soil fertility in cocoa plantations? *Agriculture, Ecosystems and Environment*, 248: 190-199.

Weil RR, Brady NC. 2015. *The Nature and Properties of Soils* (15th ed.). New Jersey: Pearson Prentice Hall, 1104.

Williams MC, Wardle GM. 2007. Pine and eucalypt litterfall in a pine-invaded eucalypt woodland: the role of fire and canopy cover. *Forest Ecology and Management*, 253(1-3): 1-10.

Xuluc-Tolosa FJ, Vester HF, Ramırez-Marcial N, et al. 2003. Leaf litter decomposition of tree species in three successional phases of tropical dry secondary forest in Campeche, Mexico. *Forest Ecology and Management*, 174(1-3): 401-412.

Yang C, Liu N, Zhang YJ. 2019. Soil aggregates regulate the impact of soil bacterial and fungal communities on soil respiration. *Geoderma*, 337: 444-452.

Zagatto MR, de Araujo Pereira AP, de Souza AJ, et al. 2019. Interactions between mesofauna, microbiological and chemical soil attributes in pure and intercropped *Eucalyptus grandis* and *Acacia mangium* plantations. *Forest Ecology and Management*, 433: 240-247.

Zamani T, Karimi H, Tavakoli M, et al. 2018. Factors affecting the groundwater drawdown in Mehran Plain, Ilam Province. *Hydrogeology*, 2(2): 17-28.

Zhao HL, Guo YR, Zhou RL, et al. 2011. The effects of plantation development on biological soil crust and topsoil properties in a desert in northern China. *Geoderma*, 160(3-4): 367-372.

Zhao HL, Zhou RL, Zhang TH, et al. 2006. Effects of desertification on soil and crop growth properties in Horqin sandy cropland of Inner Mongolia, north China. *Soil and Tillage Research*, 87(2): 175-185.

Note: Figure translations are in progress. See original paper for figures.