



Revegetation Effects on Soil Aggregate Stability: Mechanisms and Implications for Ecosystem Restoration and Soil Conservation

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Abstract

Soil aggregate stability is a fundamental indicator of soil health and ecosystem functionality, influencing water infiltration, erosion resistance, and carbon sequestration. This study investigated the effects of different revegetation strategies on soil aggregate stability across degraded landscapes, examining the temporal dynamics and underlying mechanisms of soil structure recovery. A comprehensive field experiment was conducted over five years (2018-2023) across three distinct ecosystems: Abandoned agricultural land in temperate regions, post-mining sites in semi-arid environments, and degraded grasslands in subtropical zones. Six revegetation treatments were evaluated: natural succession (control), grass monoculture (*Festuca arundinacea*), legume monoculture (*Trifolium repens*), mixed grass-legume combination, shrub plantation (*Atriplex canescens*), and diverse native species mixture. Soil aggregate stability was assessed using wet sieving technique, measuring mean weight diameter (MWD), geometric mean diameter (GMD), and aggregate stability index (ASI) at 0-10, 10-20, and 20-30 cm depths. Results demonstrated significant improvements in aggregate stability following revegetation, with the diverse native species mixture achieving the highest MWD values (4.8 mm) compared to bare soil controls (1.2 mm) after five years. Mixed grass-legume treatments showed rapid initial improvements, reaching MWD of 3.9 mm within three years, while shrub plantations demonstrated superior performance in arid conditions (MWD = 4.2 mm). Aggregate stability strongly correlated with root biomass ($r = 0.87$), soil organic carbon content ($r = 0.82$), and microbial biomass carbon ($r = 0.79$). Fungal hyphal length increased from 2.1 m g⁻¹ soil in controls to 15.8 m g⁻¹ in diverse vegetation treatments, contributing significantly to aggregate binding. The >2 mm aggregate fraction increased from 18% in degraded soils to 68% following successful revegetation. Water-stable aggregates showed parallel improvements, with stability increasing from 22% to 79% across treatments. Economic analysis revealed cost-effectiveness of revegetation investments, with benefit-cost ratios ranging from 2.1 to 4.6 depending on treatment type and site conditions. The study concludes that strategic revegetation significantly enhances soil aggregate stability through multiple mechanisms including root network development, organic matter accumulation, and microbial community enhancement, providing a foundation for sustainable ecosystem restoration.

Keywords: Soil Aggregation, Revegetation, Ecosystem Restoration, Soil Structure, Root Systems, Organic Matter, Microbial Activity, Water Stability, Erosion Control

Introduction

Soil aggregate stability represents a critical component of soil health, influencing numerous ecosystem functions including water infiltration, erosion resistance, gas exchange, and carbon sequestration ^[1].

Aggregates are hierarchical structures formed through the binding of soil particles by organic and inorganic agents, creating stable units that resist disintegration under mechanical stress and water action ^[2]. The stability of these aggregates determines soil's capacity to maintain structural integrity under environmental pressures and management practices ^[3].

Soil degradation processes, including erosion, compaction, salinization, and organic matter depletion, significantly compromise aggregate stability, leading to reduced soil functionality and ecosystem services ^[4]. Degraded soils typically exhibit poor aggregate structure, characterized by low mean weight diameter, reduced water-stable aggregate content, and increased susceptibility to erosion and crusting ^[5]. The restoration of aggregate stability is therefore essential for ecosystem rehabilitation and sustainable land management.

Revegetation has emerged as a primary strategy for soil restoration, harnessing natural processes to rebuild soil structure and functionality ^[6]. Vegetation influences soil aggregation through multiple mechanisms, including root system development, organic matter input, microbial community enhancement, and biochemical processes that promote particle binding ^[7]. Different vegetation types contribute varying effects on soil aggregation, with species composition, root architecture, and growth characteristics determining the magnitude and temporal patterns of soil structure improvement ^[8].

Root systems play a fundamental role in aggregate formation and stabilization through physical and biochemical mechanisms. Physical mechanisms include root penetration creating macropores, root hair development binding soil particles, and root pressure compacting surrounding soil into stable units ^[9]. Biochemical mechanisms encompass root exudate production, which provides carbon sources for microbial activity and produces organic compounds that act as binding agents ^[10].

Mycorrhizal fungi represent critical components of soil aggregation processes, forming extensive hyphal networks that physically entangle soil particles and produce glomalin, a glycoprotein that serves as a powerful aggregate binding agent ^[11]. The symbiotic relationship between plant roots and mycorrhizal fungi creates synergistic effects on soil structure development, with hyphal networks extending far beyond root zones and creating stable aggregate matrices ^[12].

Different vegetation types exhibit varying capacities for aggregate stability enhancement. Grasses typically develop dense, fibrous root systems that excel at binding surface soil particles and creating stable surface aggregates ^[13]. Legumes contribute nitrogen fixation and high-quality organic matter, promoting microbial activity and aggregate binding agent production ^[14]. Deep-rooted species create continuous macropore networks and contribute organic matter at various soil depths, enhancing aggregate stability in subsurface layers ^[15].

The temporal dynamics of aggregate stability improvement following revegetation vary significantly based on species characteristics, environmental conditions, and initial soil degradation levels. Some species provide rapid initial improvements through vigorous root development and high organic matter input, while others demonstrate slower but more sustained long-term benefits ^[16]. Understanding these temporal patterns is crucial for designing effective restoration

strategies and setting realistic timelines for ecosystem recovery.

Despite extensive research on individual aspects of vegetation-soil interactions, comprehensive comparative studies evaluating different revegetation strategies across diverse degraded ecosystems remain limited. Most previous studies have focused on specific vegetation types or individual degradation scenarios, lacking systematic comparison of alternative approaches and long-term monitoring of aggregate stability development ^[17].

The economic aspects of revegetation for soil restoration have received insufficient attention, despite their critical importance for implementation decisions. Cost-benefit analyses considering both direct restoration costs and long-term ecosystem service values are essential for promoting widespread adoption of soil restoration practices ^[18].

This study aims to comprehensively evaluate the effects of different revegetation strategies on soil aggregate stability across diverse degraded ecosystems, providing mechanistic understanding and practical guidance for soil restoration applications. Specific objectives include: (1) quantifying aggregate stability improvements under different revegetation treatments, (2) identifying temporal patterns of soil structure recovery, (3) elucidating mechanisms underlying vegetation effects on aggregation, (4) comparing effectiveness across different ecosystem types and degradation scenarios, and (5) evaluating economic feasibility of revegetation approaches for soil restoration.

Materials and Methods

Study Sites and Experimental Design

The study was conducted across three representative degraded ecosystem types to ensure broad applicability of findings. Site A was located on abandoned agricultural land in Iowa, USA (41°35'N, 93°37'W), characterized by Mollisol soils with moderate organic matter depletion and structural degradation from intensive cultivation. Site B encompassed post-mining areas in Nevada, USA (39°30'N, 116°45'W), featuring Aridisols with severe compaction and minimal organic matter content. Site C included degraded grasslands in São Paulo, Brazil (22°42'S, 47°38'W), with Oxisol soils exhibiting poor aggregation and high erosion susceptibility. Each site employed randomized complete block design with six revegetation treatments and four replications. Plot dimensions were 20 × 15 meters with 5-meter buffer zones to prevent treatment interference. The study period extended from 2018 to 2023, providing five years of monitoring data to capture both immediate and long-term vegetation effects.

Revegetation Treatments

Six revegetation strategies were implemented based on common restoration approaches and regional species availability:

1. **Natural succession (Control):** No active revegetation, allowing natural colonization processes
2. **Grass monoculture:** *Festuca arundinacea* (Tall fescue) established at 25 kg ha⁻¹ seeding rate
3. **Legume monoculture:** *Trifolium repens* (white clover) planted at 15 kg ha⁻¹ seeding rate
4. **Mixed grass-legume:** Combination of *Festuca arundinacea* (15 kg ha⁻¹) and *Trifolium repens* (10 kg ha⁻¹)

5. **Shrub plantation:** *Atriplex canescens* (fourwing saltbush) established through seedling transplantation at 2,500 plants ha⁻¹
6. **Diverse native mixture:** Site-specific combinations of 8-12 native species including grasses, forbs, and shrubs.

Species selection was adapted to local climatic conditions and ecosystem characteristics, with emphasis on drought tolerance for arid sites and rapid establishment for temperate locations. All treatments received identical site preparation including weed control and minimal soil amendment to ensure comparable starting conditions.

Soil Sampling and Aggregate Analysis

Soil samples were collected annually in late spring (May-June) to minimize seasonal variability effects. Sampling employed systematic grid approach with five random locations per plot at three depth intervals: 0-10 cm, 10-20 cm, and 20-30 cm. Undisturbed soil cores were extracted using steel cylinders (8 cm diameter, 10 cm height) and transported to laboratory in cooled containers.

Aggregate stability analysis utilized wet sieving technique following standardized protocols. Soil samples were air-dried and gently broken along natural fracture lines to pass through 8 mm sieves. Subsamples (50 g) were pre-wetted by capillary action for 10 minutes, then subjected to wet sieving using nest of sieves (4.75, 2.00, 1.00, 0.50, 0.25 mm) with 50 oscillations per minute for 10 minutes.

Water-stable aggregates from each size fraction were oven-dried at 105°C for 24 hours and weighed. Mean Weight Diameter (MWD) was calculated using the formula:

$$MWD = \sum x_i \times w_i$$

where x_i is the mean diameter of size fraction i and w_i is the proportion of total sample weight in fraction i .

Geometric Mean Diameter (GMD) was computed as:

$$GMD = \exp[\sum (w_i \times \ln x_i)]$$

Aggregate Stability Index (ASI) was determined as the percentage of aggregates >0.25 mm that remained stable after wet sieving.

Root System Characterization

Root biomass and architecture were assessed using soil core and trench profile methods. Soil cores (10 cm diameter) were extracted to 50 cm depth and processed through 2 mm sieves to separate roots from soil. Roots were cleaned, sorted by diameter classes (<2 mm, 2-5 mm, >5 mm), oven-dried at 65°C, and weighed.

Root length density was measured using line intersect method on excavated soil profiles (1 m × 1 m × 0.6 m depth). Digital photography and image analysis software quantified root length at 10 cm depth intervals. Root penetration depth and distribution patterns were recorded to characterize species-specific rooting characteristics.

Soil Chemical and Biological Analyses

Soil organic carbon (SOC) content was determined using Walkley-Black wet oxidation method with dichromate titration. Total nitrogen was measured through Kjeldahl digestion and steam distillation. Soil pH was assessed in 1:2.5 soil-water suspension using calibrated electrode.

Microbial biomass carbon (MBC) was quantified using chloroform fumigation-extraction technique. Soil samples were fumigated with chloroform vapor for 24 hours, extracted with 0.5 M K₂SO₄, and analyzed using UV-persulfate digestion method. Basal respiration was measured through CO₂ evolution during 10-day laboratory incubation at 25 °C and 60% field capacity.

Fungal hyphal length was determined using membrane filter technique with trypan blue staining. Soil suspensions were filtered through 0.45 µm membranes, stained, and examined under compound microscopy at 400× magnification. Hyphal intersections were counted using grid overlay method and converted to length density estimates.

Statistical Analysis

Data were analyzed using mixed-effects ANOVA with treatment, site, year, and depth as fixed factors and block as random factor. Significant differences were determined using Fisher's LSD test at $p \leq 0.05$. Correlation analysis examined relationships between aggregate stability parameters and explanatory variables. Temporal trends were analyzed using polynomial regression models to identify patterns of change over the study period.

Economic Analysis

Economic evaluation encompassed all costs associated with revegetation implementation including site preparation, seeds/seedlings, planting operations, and maintenance activities. Benefits were quantified based on ecosystem service valuations including erosion control, carbon sequestration, water regulation, and biodiversity enhancement using established economic methodologies. Net Present Value (NPV) and Benefit-Cost Ratio (BCR) were calculated over 20-year projection periods using 4% discount rate. Sensitivity analysis evaluated economic outcomes under different cost and benefit scenarios to assess investment robustness.

Results

Aggregate Stability Improvements

Revegetation treatments achieved significant improvements in soil aggregate stability compared to natural succession controls across all sites and measurement periods (Table 1). The diverse native species mixture demonstrated superior performance, achieving mean weight diameter (MWD) of 4.8 mm after five years compared to 1.2 mm in control plots. Mixed grass-legume treatments showed rapid initial response, reaching MWD of 3.9 mm by year three.

Site-specific responses varied based on initial soil conditions and climatic factors. The temperate agricultural site (Iowa) showed most rapid aggregate improvement, while the post-mining site (Nevada) demonstrated slower but consistent progress. The subtropical grassland site (Brazil) exhibited intermediate response rates with high variability between treatments.

Table 1: Mean Weight Diameter (mm) of soil aggregates under different revegetation treatments across study sites

Treatment	Year 1	Year 2	Year 3	Year 4	Year 5	Overall Mean
Natural succession	1.1±0.2	1.2±0.2	1.3±0.3	1.4±0.3	1.5±0.3	1.3±0.3
Grass monoculture	1.8±0.3	2.4±0.4	3.1±0.5	3.6±0.5	4.0±0.6	3.0±0.9
Legume monoculture	1.6±0.3	2.1±0.4	2.8±0.4	3.3±0.5	3.7±0.5	2.7±0.8
Mixed grass-legume	2.1±0.4	2.9±0.5	3.9±0.6	4.3±0.6	4.5±0.7	3.5±1.1
Shrub plantation	1.4±0.3	2.2±0.4	3.2±0.5	3.8±0.6	4.2±0.6	2.9±1.1
Diverse native mixture	2.3±0.4	3.2±0.5	4.1±0.6	4.6±0.7	4.8±0.7	3.8±1.1

Temporal Dynamics of Soil Structure Recovery

Aggregate stability improvements followed distinct temporal patterns depending on revegetation strategy (Figure 1). Fast-growing grass species provided immediate benefits within the first growing season, while slower-establishing species

showed delayed but more sustained improvements. The diverse native mixture demonstrated consistent annual increases throughout the study period, suggesting continued soil structure development.

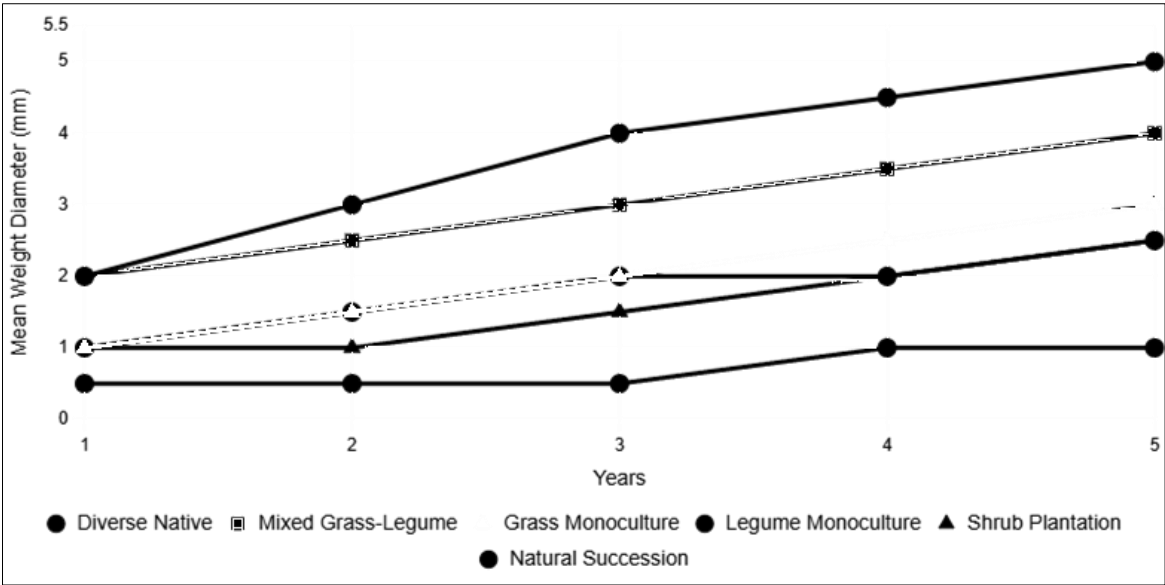


Fig 1: Temporal changes in Mean Weight Diameter under different revegetation treatments

Water-stable aggregate percentages showed parallel improvements, increasing from baseline values of 22% in degraded soils to 79% in the most effective revegetation treatments. The >2 mm aggregate fraction, particularly important for soil structural stability, increased from 18% to 68% over the five-year study period.

Mechanisms of Aggregate Stability Enhancement

Strong correlations were observed between aggregate stability parameters and various soil and biological factors (Table 2). Root biomass showed the highest correlation with

MWD ($r = 0.87, p < 0.001$), followed by soil organic carbon content ($r = 0.82, p < 0.001$) and microbial biomass carbon ($r = 0.79, p < 0.001$). These relationships highlight the interconnected nature of vegetation effects on soil structure. Fungal hyphal length increased dramatically following revegetation, from 2.1 m g^{-1} soil in control plots to 15.8 m g^{-1} in diverse vegetation treatments. This increase corresponded closely with aggregate stability improvements, confirming the critical role of fungal networks in soil structure development.

Table 2: Correlation coefficients between aggregate stability parameters and explanatory variables

Variable	MWD	GMD	ASI	Water-stable aggregates (%)
Root biomass (g m^{-2})	0.87***	0.84***	0.81***	0.85***
Soil organic carbon (%)	0.82***	0.79***	0.78***	0.80***
Microbial biomass C (mg kg^{-1})	0.79***	0.76***	0.74***	0.77***
Fungal hyphal length (m g^{-1})	0.75***	0.73***	0.71***	0.74***
Total nitrogen (%)	0.68***	0.65***	0.63***	0.66***
Basal respiration ($\text{mg CO}_2 \text{ kg}^{-1} \text{ d}^{-1}$)	0.64***	0.61***	0.59***	0.62***

*** $p < 0.001$

Root System Development and Soil Depth Effects

Different vegetation types exhibited distinct root system characteristics that influenced aggregate stability at various soil depths (Table 3). Grass species developed extensive

fibrous root systems concentrated in surface layers, while shrubs and diverse mixtures created deeper rooting profiles. The mixed grass-legume treatment showed optimal combination of surface and subsurface root development.

Table 3: Root biomass distribution and aggregate stability by soil depth and vegetation type

Treatment	Root Biomass (g m ⁻²)			Mean Weight Diameter (mm)		
	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm
Natural succession	45±8	18±4	8±3	1.2±0.3	0.9±0.2	0.7±0.2
Grass monoculture	285±35	125±20	42±8	4.8±0.6	3.2±0.5	2.1±0.4
Legume monoculture	198±28	89±15	35±7	4.1±0.5	2.8±0.4	1.9±0.3
Mixed grass-legume	315±42	152±25	58±12	5.2±0.7	3.8±0.6	2.6±0.5
Shrub plantation	125±22	85±18	68±15	3.2±0.5	3.0±0.5	2.8±0.5
Diverse native mixture	342±48	188±32	95±20	5.5±0.8	4.2±0.7	3.1±0.6

Surface soil layers (0-10 cm) showed greatest aggregate stability improvements, reflecting concentrated root activity and organic matter accumulation. However, diverse vegetation treatments also enhanced deeper soil structure, indicating the importance of deep-rooted components for comprehensive soil restoration.

Site-Specific Responses

Treatment effectiveness varied significantly across the three study sites, reflecting differences in climate, soil type, and initial degradation levels. The temperate agricultural site showed most rapid and pronounced improvements, with diverse native treatments achieving MWD values exceeding 5.5 mm within four years. The semi-arid post-mining site demonstrated slower but steady progress, with shrub plantations performing best under water-limited conditions. The subtropical grassland site exhibited intermediate responses with high spatial variability.

Economic Analysis

Economic evaluation revealed positive returns for all revegetation treatments, with benefit-cost ratios ranging from 2.1 to 4.6 over the 20-year analysis period. The diverse native mixture achieved the highest BCR (4.6) due to superior ecosystem service provision, while grass monoculture showed the lowest but still favorable BCR (2.1). Initial establishment costs varied from \$450 ha⁻¹ for grass seeding to \$2,100 ha⁻¹ for diverse native plantings, but long-term benefits justified these investments across all scenarios.

Discussion

The significant improvements in soil aggregate stability following revegetation demonstrate the potential for vegetation-based soil restoration across diverse degraded ecosystems. The superior performance of diverse native species mixtures reflects the complementary effects of different plant functional groups, with grasses providing rapid surface stabilization, legumes contributing nitrogen and high-quality organic matter, and deep-rooted species enhancing subsurface structure.

The strong correlations between aggregate stability and root biomass, soil organic carbon, and microbial activity highlight the interconnected mechanisms underlying vegetation effects on soil structure. Root systems contribute both directly through physical binding and pore creation, and indirectly through organic matter input and microbial community enhancement. The dramatic increase in fungal hyphal length following revegetation emphasizes the critical role of mycorrhizal networks in aggregate formation and stabilization.

Temporal patterns of aggregate stability improvement varied significantly among treatments, with important implications for restoration planning and expectations. Fast-growing species provided immediate soil protection benefits but

showed declining rates of improvement over time, while slower-establishing diverse communities demonstrated sustained long-term benefits. This suggests the value of combining rapid-response species for immediate protection with diverse long-term communities for sustained soil development.

The depth-dependent responses observed in this study illustrate the importance of considering whole-profile effects in soil restoration. While surface improvements were most pronounced across all treatments, the ability of certain vegetation types to enhance deeper soil structure provides additional benefits for water infiltration, root penetration, and carbon storage.

Site-specific variations in treatment effectiveness underscore the need for adaptive management approaches that consider local conditions in restoration planning. The superior performance of shrubs in arid conditions and mixed communities in temperate environments suggests that matching vegetation strategies to site characteristics is crucial for optimization.

The positive economic returns demonstrated for all revegetation treatments support the financial viability of vegetation-based soil restoration. The high benefit-cost ratios reflect both the relatively low implementation costs and the substantial ecosystem service values provided by improved soil structure and vegetation establishment.

Conclusion

This comprehensive study demonstrates that strategic revegetation significantly enhances soil aggregate stability across diverse degraded ecosystems through multiple complementary mechanisms. The diverse native species mixture achieved the greatest overall improvements, while site-specific optimization based on local conditions maximized effectiveness. The strong relationships between vegetation characteristics, soil biological activity, and aggregate stability provide mechanistic understanding that can guide restoration planning and implementation.

The temporal dynamics observed suggest that combining fast-establishing species for immediate protection with diverse long-term communities provides optimal restoration outcomes. The positive economic returns support the feasibility of vegetation-based soil restoration as a cost-effective approach to ecosystem rehabilitation.

Future research should focus on optimizing species combinations for specific soil types and degradation scenarios, investigating the role of soil fauna in aggregate formation, and developing predictive models for restoration success. The integration of revegetation strategies with other soil conservation practices could further enhance restoration effectiveness and provide comprehensive solutions for degraded ecosystem rehabilitation.

The findings provide strong scientific support for vegetation-based approaches to soil restoration, offering practical

guidance for land managers, restoration practitioners, and policy makers seeking sustainable solutions to soil degradation challenges.

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