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Restoring Plant Succession on Degraded Crusted Soils in Niger: a Case Study Using Half Moons, Tree Seedlings and Grass Seed

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Abstract

We assessed a restoration treatment (planting tree seedlings and sowing grass seeds as nurse plants in water-harvesting half-moon pits) on degraded, compacted soils with surface crusts in Niger. Height and above-ground biomass of herbaceous plant species, tree stem circumference, and relative cover of erosive crust, gravel crust, bare ground, rock, litter, and total vascular plants were assessed at three sites with similar environmental conditions but different treatment periods (3, 5, 7 years). Species richness, evenness and Shannon-Weaver index were lowest at the 7-year site and highest at the 5-year site. Above-ground biomass of herbaceous plants and percent plant cover were lowest at the 3-year site and highest at the 7-year site. Principal components analysis revealed the change in vegetation from 3 to 7 years and spatial heterogeneity in vegetation within sites. Multi-response permutation procedures showed significant variation in species composition between the sites. Redundancy analysis showed that the temporal changes in vegetation, herbaceous plant height and litter cover were associated with a decrease in cover of erosive and gravel crusts, bare ground and rock. The 3-year and 5-year sites were dominated by annual plants, herbaceous perennials and small shrubs, while the 7-year site was dominated by annual plants and trees.

Keywords: Compacted soil, water harvesting systems, nurse plants, biodiversity, self-sustaining processes, resilience, Sahel.

Introduction

Land degradation is the predominate threat to human wellbeing worldwide (Pimentel, 2006), and a direct threat to food security and livelihoods in the Sahel (UNEP, 2012). In the 1960s, 1970s and 1980s, the Sahel faced drought which reduced tree and shrub density (Gonzalez, 2001). Exposed soils in large areas lost much of their top soil due to wind erosion, and the remaining topsoil was then hit by rainfall that broke up soil aggregates and induced soil compaction with physical crusts (Casenave and Valentin, 1990). Due to the soil surfacecrusts, only a small proportion of rainwater can infiltrate the soil (Stroosnijder, 2007). Over 30% of the degraded lands worldwide are in the Sahelian countries (Tidjani et al., 2008). Land with unstable soil surface, due to soil compaction, wind and water erosion, is prone to loss of vital resources such as moisture, nutrients and seeds (Tongway and Ludwig, 2011). These conditions impede seed germination and emergence and allow very slow natural recovery (Stroosnijder, 2008). Fast vegetation recovery in these conditions demands effective restoration methods based on ecological principles such as succession ecology (Gretasdottir et al., 2004). It has been suggested that ecological restoration is a manipulation of natural succession to restore self-sustaining ecosystems (Prach et al., 2007). Accordingly, restoration activities must be based on successional mechanisms and ecological processes (Bradshaw, 1996). In the Sahel, the main techniques used to manipulate natural succession on degraded land are sowing seeds or planting seedlings of native or exotic tree species alone or jointly with water harvesting techniques such as half moons, rock bunds and trenches (Kiema et al., 2008; Soumana, 2008; Douma et al., 2011; Kangabema, 2013). Water harvesting techniques are designed to harvest and concentrate water and wind-blown soil, nutrients and seeds in the soil and, thereby, improve seedling survival and development (Whisenant, 1999). Manipulation of degraded land accelerates establishment of early successional stage species (pioneer), which facilitate the establishment of mid and late successional stage species. The restored land should reflect the initial ecosystem before degradation (SER, 2004) or the remnant plant communities around the restored site (McClain et al., 2011).

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In this study we assessed a restoration technique (planting tree seedlings and sowing grass seeds in half-moon water-harvesting pits) for degraded, compacted soils with surface crusts in Niger. The objectives were to assess how the restoration technique affected succession, vegetation cover and site characteristics over time.

Methodology

Study area Description and Restoration Treatment

The study was carried at three sites in Oumaraoua, located in south-central Niger (latitude = 13°31’58”, longitude = 8°6’13”, altitude = 441 m). The sites have similar environmental conditions but differ in the levels of the treatment (3, 5 and 7 years of restoration). The restoration treatment of the sites was done by jointly planting tree seedlings and broadcast sowing grass seeds in a water harvesting technique known as a half-moon. A half moon is a shallow semi-circular pit that is installed on sloping land: the pit increases in depth from the up-slope to the down-slope side thereby forming a semi-circular micro-catchment pit to capture runoff water, topsoil, litter and seeds. The half moons were installed on compacted and barren soil dominated by gravel, erosive and algal crusts, with a vegetation cover less than 5%, where erosion is very active and infiltration is very low (Casenave and Valentin, 1990). A total of 625 half moons were installed at each site: the dimension of each half moon was 3 m in diameter on the up-slope side, 2 m in length from the up-slope to lower-slope sides, with a maximum depth of 0.25 m on the down-slope side. One seedling of five tree species (*Bauhinia rufescens*, *Acacia senegal, Acacia seyal*, *Acacia laeta*, *Ziziphus mauritiana*) were planted in each half moon, and seeds of four grass species (*Pennisetum pedicellatum, Schyzachyrium exile*, *Zornia glochidiata*, *Andropogon gayanus*) were broadcast-sown in the half moons. These species were selected by the local community because they are well adapted to the area, can rapidly restore degraded lands and provide socio-economical benefits.

The climate in the study area is dry with mean annual rainfall and temperature of 400 to 600 mm and 19 to 33 °C, respectively (data from 1921 to 2007: Direction Nationale de Météorologie du Niger). The soils in the study area represent two geomorphological units: the lateritic plateaus were formed by the deposit of the Continental Hamadien, while dry valleys, sandy terraces and fixed dunes were formed by the Quaternary sands (Mahamane et al., 2009). The principal tree species in the study area are *Sclerocarya birrea, Anogeissus leiocarpa, Combretum micranthum, Cassia singueana*, *Boscia salicifolia* and *Boscia senegalensis* on the lateritic plateaus, and *Prosopis africana*, *Lannea microcarpa, Adansonia digitata, Bauhinia rufescens, Ziziphus spina-christi, Piliostigma reticulatum, Hyphaene thebaica, Annona senegalensis, Faidherbia albida*, *Catunaregam nilotica* and *Albizia chevalieri* on the sandy terraces, fixed dunes and dry valleys (Saadou, 1990).

Data Collection

Vegetation was recorded in rectangular plots (50 m by 20 m) that were randomly placed in the three sites: six plots in the 3-year restoration site, seven plots in the 5-year restoration site, and ten plots in the 7-year restoration site. Within each plot, average height of herbaceous plant species was recorded, and relative cover of erosive crust, gravel crust, bare ground, rock, litter, and total vascular plants were assessed using the Braun-Blanquet (1932) cover-abundance scale (1 = 0.5; 2 = 3; 3 = 15; 4 = 37.5; 5 = 62.5; 6 = 87.5). Above-ground biomass was recorded in five sub-plots within each plot: a 1 m² wire was randomly thrown five times into the plot, and the herbaceous plants that fell in each of the five wire subplots were clipped, placed in sacks, dried and weighed. We also recorded in each plot the stem circumference of all trees measured at breast height (CBH, measured at 1.3 m above ground). If the height of the tree was less than 1.3 m, then circumference was measured at 5 cm above the ground. All the data were collected at the end of September 2013 which coincides with the beginning of the dry season in the Sahel; at this moment plant composition and cover can be underestimated (Saadou, 1990).

Data Analysis

Normality was tested using the test of Kolmogorov-Smirnov. One-way analysis of variance (ANOVA) and Least Significant Difference (LSD) test were carried to compare the differences of biomass, total plant cover and stem circumference of trees among the 3, 5, and 7 restoration sites. Principal Component Analysis (PCA), a multivariate test which weights the variables to maximize differences between individuals (Dytham, 2011), was used to analyze spatial and temporal changes of vegetation communities. The PCA was based on Pearson correlation coefficients among floristic data (108 species, species relative abundance scale) and environmental data (relative cover of erosive crust, gravel crust, bare ground, rock, vegetation and litter; average height of herbaceous layer; and restoration age) from all 23 plots.

Redundancy Analysis (RDA) was used to evaluate how changes in vegetation communities affect environmental variables. Like PCA, the analysis was based on Pearson correlation coefficients among the floristic and environmental data. RDA is a direct ordination method (type of canonical correlation analysis) for finding the directions of variability in floristic data that correlate with the explanatory variables (Lepš and Šmilauer, 2003). RDA can be considered as an extension of PCA in which the main components are constrained to be linear combinations of the environmental variables. RDA not only represents the main patterns of species variation (as much as they can be explained by the measured environmental variables), but also reflects correlations between each species and between each environmental variable in the data (Ramette, 2007).

Multi-Response Permutation Procedures test (MRPP: McCune and Grace, 2002) was used to test the difference in species composition between sites and the heterogeneity within each site. The data matrix for MRPP was the squared Euclidean distance between each pair of the 23 plots based on relative abundance of the 108 species. MRPP is a non-parametric multivariate procedure that tests between species composition of two or more *a priori* sites. MRPP provides three values: A (change-corrected within site agreement) tests the homogeneity within site; when all of the observations within groups are identical, then the observed delta = 0 and A = 1; T (the difference between the observed and expected deltas) tests the difference between two or more groups (sites), and p-value tests the difference between groups (sites).

To identify the most frequent and dominant species at each site, the matrix of 23 plots and 108 species was subjected to Indicator Species Analysis (ISA; Dufrene and Legendre, 1997; McCune and Grace, 2002). ISA has the advantage of combining both the relative frequency (RF) and relative abundance (RA) for calculating the Indicator Value (IV) of each species, and the significance is tested by the Monte Carlo test. All species with a probability less than 0.05 were accepted as more frequent and abundant species. The Indicator Value was calculated using the following formula: $IV_{kj} = RA_{kj} \times RF_{kj} \times 100$, where RA is the relative abundance of a given species j in a given site type k and RF is the proportional frequency of species j in site type k (i.e., the proportion of plots in each site type with species j). Values of IV ranged from 0 to 100 (perfect indication). A perfect indicator value means that a given species occurs only in a given site type and is always in that site type.

For each site, alpha diversity was evaluated through floristic richness (R); and the calculations of Shannon-Weaver H' index (1949) [H' = $-\sum pi\ log2\ pi$, where pi is the relative proportion of the average cover of species i; pi = ni $/\sum ni$, with ni = average cover of species i and $\sum ni$ = total cover of all species] and Eveness (E) of Pielou (1966) [$E = H'/Hmax = H'/\log 2\ S$]. Minitab version 16 (Dytham, 2011) was used for the test of Kolmogorov-Smirnov and one way ANOVA with LSD test. PCA, MRPP and ISA were done using PC-ORD Version 5 (McCune and Grace, 2002). CANOCO version 4.5 (Ter Braak and Smilauer, 1998) was used for RDA.

Results

Table I. Values of Richness, Shannon index and Evenness for three sites that differed in restoration age.

Variables	3 years restoration	5 years restoration	7 years restoration
Richness (R)	79	80	73
Shannon index (H’)	4.75	5.08	4.71
Evenness (E)	0.78	0.80	0.76

Table II. Relative abundance (RA), frequency (RF), life form (LF), indicator value (IV), and statistical significance of indicator value (P) of plant species in restoration sites (Site) at 3, 5 and 7 years.

Species	Family	LF	Site	RA	RF	IV	P
Schoenefeldia gracilis Kunth.	Poaceae	Th	3 years	49	100	50	0.002
Acacia seyal Del.	Leguminosae-Mimosoideae	McPh	3 years	100	20	20	0.32
Aristida mutabilis Trin. & Rupr.	Poaceae	Th	3 years	46	90	41	0.18
Cassia italica (Mill.) F.W. Anders.	Leguminosae-Caesalpinioideae	Ch	3 years	42	100	42	0.09
Cassia mimosoides L.	Leguminosae-Caesalpinioideae	Th	3 years	37	90	33	0.64
Zornia glochidiata Reichb. Ex DC.	Leguminosae-Papilionoideae	Th	3 years	52	100	52	0.002
Spermacoce radiata (DC.) Hiern.	Rubiaceae	Th	3 years	42	90	38	0.32
Mitracarpus villosus (Sw.) DC.	Rubiaceae	Th	3 years	52	40	21	0.62
Acacia nilotica (L.) Willd.	Leguminosae-Mimosoideae	McPh	3 years	48	14	34	0.23
Aristida adscensionis L.	Poaceae	Th	3 years	74	80	59	0.003
Cassia obtusifolia L.	Leguminosae-Caesalpinioideae	NnPh	3 years	65	80	52	0.01
Citrillus lanatus (Thunb.) Matsumara et Nakai	Cucurbitaceae	Th	3 years	74	40	30	0.16
Indigofera colutea (Burm.f.) Merril. Phill.	Leguminosae-Papilionoideae	Th	3 years	64	80	50	0.01
Cassia occidentalis L.	Leguminosae-Caesalpinioideae	NnPh	3 years	60	70	42	0.08
Cucumis metuliferus Naud.	Cucurbitaceae	Th	3 years	100	20	20	0.31
Cassia singueana Del.	Leguminosae-Caesalpinioideae	McPh	3 years	60	70	42	0.08
Cassia sieberiana DC.	Leguminosae-Caesalpinioideae	McPh	3 years	100	20	20	0.31
Achyrantes aspera L.	Acanthaceae	Th	3 years	100	40	40	0.05
Citrillus colocynthis (L.) Schrad.	Cucurbitaceae	Ch	3 years	68	60	41	0.05

Solanum incanum L.	Solanaceae	Th	3 years	39	20	8	1
Tephrosia bracteolata Guil. Et Perr.	Leguminosae-Papilionoideae	Th	3 years	60	50	30	0.22
Rogeria adenophylla J. Gay.	Pedaliaceae	Th	3 years	100	30	30	0.09
Jacquemontia tamnifolia (L.) Griseb.	Convolvulaceae	Th	3 years	55	30	11	0.75
Leptadenia hastata (Pers.) Decne.	Asclepiadaceae	McPh	3 years	100	20	20	0.31
Alysicarpus rugosus (Willd.) DC.	Leguminosae-Papilionoideae	Th	3 years	100	10	10	1
Bidens biternata (Lour.) Merrill. et Sherff.	Asteraceae = Compositae	Th	3 years	100	10	10	1
Acacia tortilis (forsk.) Hayne	Leguminosae-Mimosoideae	McPh	3 years	55	40	22	0.52
Leptadenia heterophylla (Del.) Decne.	Asclepiadaceae	NnPh	3 years	100	10	10	1
Brachiaria xantholeuca (Schinz.) Stapf.	Poaceae	Th	3 years	100	10	10	1
Azadirachta indica A. Juss.	Meliaceae	McPh	3 years	100	10	10	1
Tephrosia linearis (Willd.) Pers.	Leguminosae-Papilionoideae	Th	3 years	100	10	10	1
Sida linifolia Juss. ex. Cav.	Malvaceae	Ch	3 years	100	10	10	1
Momordica balsamina L.	Cucurbitaceae	Th	3 years	100	10	10	1
Pandiaka angustifolia (Vahl.) Hepper.	Amaranthaceae	Th	3 years	100	10	10	1
Cucumis prophetarum L.	Cucurbitaceae	NnPh	3 years	100	10	10	1
Tribulus terrestris L.	Zygophyllaceae	Th	3 years	100	10	10	1
Acacia senegal (L.) Willd.	Leguminosae-Mimosoideae	McPh	5 years	64	71	46	0.05
Andropogon gayanus Kunth. Var. gayanus	Poaceae	H	5 years	55	100	55	0.01
Cenchrus biflorus Roxb.	Poaceae	Th	5 years	40	71	39	0.65
Cenchrus prieurii (Kunth.) Maire.	Poaceae	Th	5 years	40	57	36	0.96
Aristida funiculata Trin. & Rupr.	Poaceae	Th	5 years	50	100	50	0.03
Dicoma tomentosa Cass.	Asteraceae = Compositae	Th	5 years	56	86	48	0.02
Spermacoce chaetocephala DC.	Rubiaceae	Th	5 years	54	71	39	0.09
Alysicarpus ovalifolius J. Leon	Leguminosae-Papilionoideae	Th	5 years	51	100	51	0.007
Cucumis melo Naud.	Cucurbitaceae	Th	5 years	40	86	34	0.4
Amaranthus graecizans L.	Amaranthaceae	Th	5 years	81	43	35	0.11
Prosopis juliflora (Sw.) DC.	Leguminosae-Mimosoideae	McPh	5 years	74	29	21	0.36
Stylosanthes erecta P. Beauv.	Leguminosae-Papilionoideae	Th	5 years	49	86	42	0.08
Sphaeranthus senegalensis DC.	Asteraceae = Compositae	Ch	5 years	100	43	42	0.03
Waltheria indica L.	Sterculiaceae	Ch	5 years	38	71	27	0.86
Sesamum alatum Thon.	Pedaliaceae	Th	5 years	63	29	18	0.43
Monechma ciliatum (Jacq.) Miln.-Red.	Acanthaceae	Th	5 years	63	57	21	0.07
Sesbania leptocarpa DC.	Leguminosae-Papilionoideae	Th	5 years	84	86	72	0.001
Entada africana Guill. Et Perr.	Leguminosae-Mimosoideae	McPh	5 years	100	14	14	0.56
Boscia senegalensis (Pers.) Lam. Ex Poir.	Capparaceae	McPh	5 years	49	86	39	0.37
Pergularia tomentosa L.	Asclepiadaceae	NnPh	5 years	52	70	15	0.79
Maerua crassifolia Forsk.	Capparaceae	McPh	5 years	85	57	49	0.02
Cymbopogon schoenantus (L.) Spreng.	Poaceae	H	5 years	100	14	14	0.56
Polycarpea corymbosa Lam.	Caryophyllaceae	Th	5 years	46	71	33	0.33
Panicum laetum Kunth.	Poaceae	Th	5 years	56	71	40	0.1
Calotropis procera (Ait.) R. Br.	Asclepiadaceae	McPh	5 years	100	14	14	0.56
Indigofera astragalina DC.	Leguminosae-Papilionoideae	Th	5 years	52	29	15	0.78
Ipomoea eriocarpa R.Br.	Convolvulaceae	Th	5 years	52	43	22	0.44
Leucas martinicensis (Jacq.) R. Br.	Labiatae = Lamiaceae	Th	5 years	44	29	12	1
Eragrostis tenella (L.) Roem. & Schult.	Poaceae	H	5 years	100	14	14	0.55
Spermacoce ruelliae DC.	Rubiaceae	Th	5 years	100	29	29	0.13
Piliostigma reticulatum (DC.) Hochst.	Leguminosae-Caesalpinioideae	McPh	7 years	41	100	41	0.2
Combretum micranthum G.Don.	Combretaceae	McPh	7 years	26	100	37	0.4
Pennisetum pedicellatum Trin.	Poaceae	Th	7 years	41	100	50	0.008
Schizachyrium exile (Hochst.) Pilger.	Poaceae	Th	7 years	36	100	37	0.75
Citrillus lanatus (Thunb.) Matsumara et Naka	Cucurbitaceae	Th	7 years	49	43	24	0.42
Ceratotheca sesamoides Endl.	Pedaliaceae	Th	7 years	41	50	20	0.86
Sesbania pachycarpa DC.	Leguminosae-Papilionoideae	Th	7 years	64	50	32	0.11
Eragrostis tremula Steud.	Poaceae	Th	7 years	47	100	47	0.07
Eragrostis pilosa (L.) P. Beauv.	Poaceae	Th	7 years	61	67	41	0.06
Dactyloctenium aegyptium (L.) Willd.	Poaceae	Th	7 years	51	50	25	0.39
Digitaria horizontalis Willd.	Poaceae	Th	7 years	58	67	39	0.13
Mollugo nudicaulis Lam.	Molluginaceae	Th	7 years	38	67	26	0.87

Peristrophe bicalyculata (Retz.) Nees.	Acanthaceae	Th	7 years	42	86	35	0.3
Evolvulus alsinoides (L.) L.	Convolvulaceae	Th	7 years	44	83	37	0.39
Bauhinia rufescens Lam.	Leguminosae-Caesalpinioideae	McPh	7 years	50	83	42	0.13
Cyperus amabilis Vahl.	Cyperaceae	Th	7 years	54	33	18	0.52
Tephrosia purpurea (L.) Pers.	Leguminosae-Papilionoideae	Th	7 years	51	67	34	0.19
Microchloa indica (L. f.) P. Beauv.	Poaceae	Th	7 years	40	83	33	0.56
Sida ovata Forsk.	Malvaceae	Ch	7 years	43	67	29	0.46
Guiera senegalensis J.F. Gmel.	Combretaceae	McPh	7 years	67	100	67	0.003
Diospyros mespiliformis Hochst. ex. A. DC.	Ebenacae	McPh	7 years	63	17	10	0.56
Acacia laeta R.Br. Ex Benth.	Leguminosae-Mimosoideae	McPh	7 years	55	20	11	0.75
Balanites aegyptiaca (L.) Del.	Balanitaceae	McPh	7 years	77	33	26	0.18
Indigofera aspera Perr.	Leguminosae-Papilionoideae	Th	7 years	41	17	7	1
Ziziphus mauritiana Lam.	Rhamnaceae	McPh	7 years	42	50	21	0.77
Faidherbia albida (Del.) A. Chev.	Leguminosae-Mimosoideae	McPh	7 years	63	17	10	0.56
Hibiscus asper Hook. f.	Malvaceae	Th	7 years	56	50	28	0.22
Merremia pinnata (Choisy.) f.	Convolvulaceae	Th	7 years	78	50	39	0.07
Kohautia senegalensis Cham. et Schlec.	Rubiaceae	Th	7 years	100	33	33	0.06
Chrozophora brocchiana Vis.	Euphorbiaceae	NnPh	7 years	100	17	17	0.25
Albizia chevalieri Harms.	Leguminosae-Mimosoideae	McPh	7 years	54	17	9	0.71
Ipomoea ochracea (Lindl.) Sweet.	Convolvulaceae	Th	7 years	100	33	33	0.05
Cymbopogon schoenantus (L.) Spreng.	Poaceae	H	7 years	100	17	17	0.25
Panicum subalbidum Kunth.	Poaceae	Th	7 years	100	17	17	0.25
Vernonia ambigua Kotschy et Peyre.	Asteraceae = Compositae	Th	7 years	54	17	9	0.7
Ipomoea asarifolia (Desr.) Roem. & Schult.	Convolvulaceae	Ch	7 years	100	17	17	0.25
Pupalia lappacea (L.) Juss.	Amaranthaceae	Th	7 years	100	17	17	0.25
Lannea microcarpa Engl. et K. Krauze	Anacardiaceae	McPh	7 years	54	17	9	0.72
Feretia apodanthera Del.	Rubiaceae	NnPh	7 years	54	17	9	0.71
Corchorus tridens L.	Tiliaceae	Th	7 years	54	17	9	0.72
Anogeissus leiocarpa (DC.) Guill. Perr.	Combretaceae	MgPh	7 years	100	17	17	0.26

Raunkiaer (1934) lifeforms: Ch = Chamaephyte (small shrubs and herbaceous perennials with exposed buds less than 50 cm above ground level), H = Hemycryptophyte (small shrubs and herbaceous perennials with exposed buds at ground level), McPh = Microphanerophyte (trees with exposed buds 2 to 8 m above ground level), MgPh = Megaphanerophyte (trees with exposed buds at least 30 m above ground level), NnPh = Nanophanerophyte (trees with buds 0.25 to 2 m above ground evel), Th = Therophyte (annual plants).

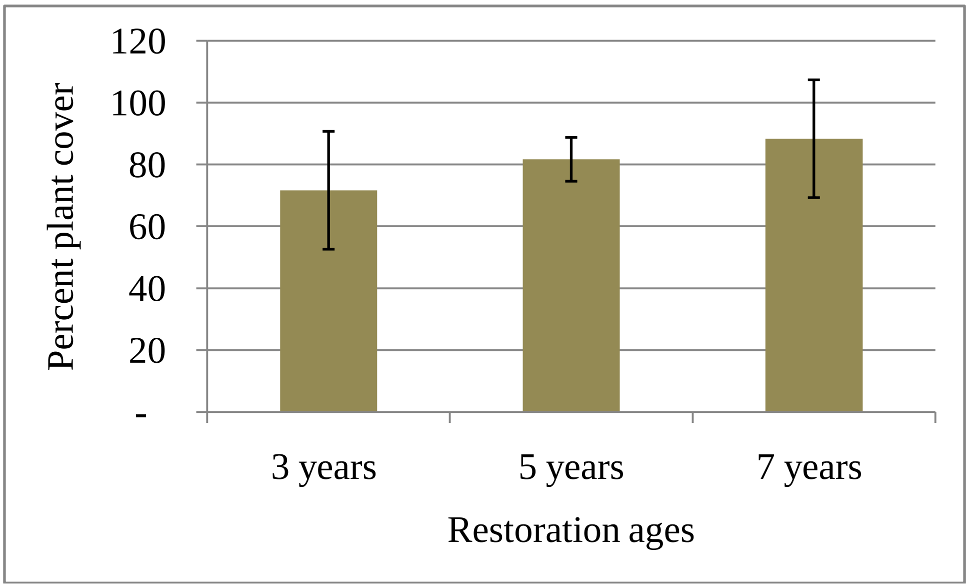

Figure 1. Mean and standard error of percent plant cover at three sites that differed in restoration age. Percent plant cover differed significantly among restoration ages (P < 0.05).

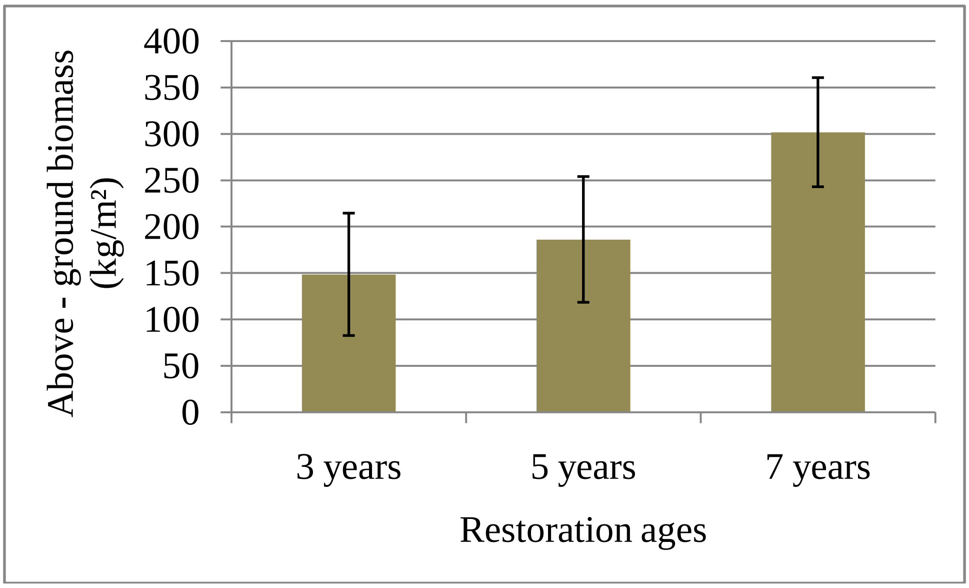

Figure 2. Mean and standard error of above-ground biomass at three sites that differed in restoration age. Above-ground biomass differed significantly among restoration ages ($P < 0.05$).

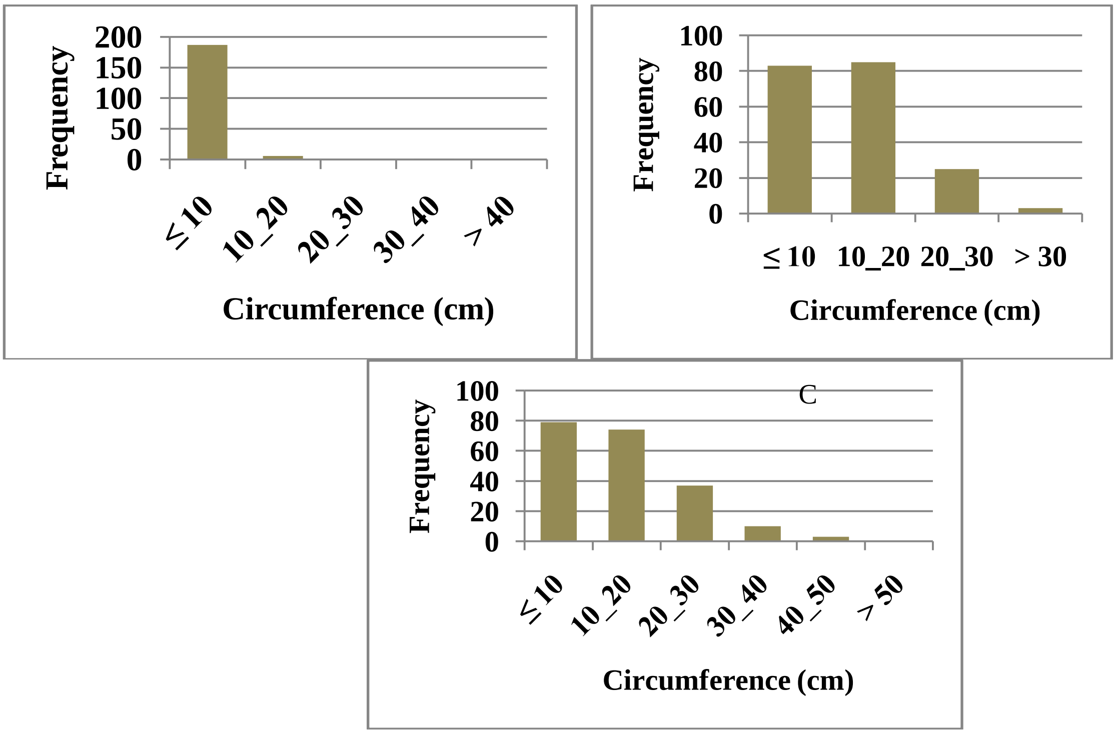

Figure 3. Stem circumference distributions of woody plants in the three sites: A = 3-year restoration, B = 5-year restoration and C = 7-year restoration.

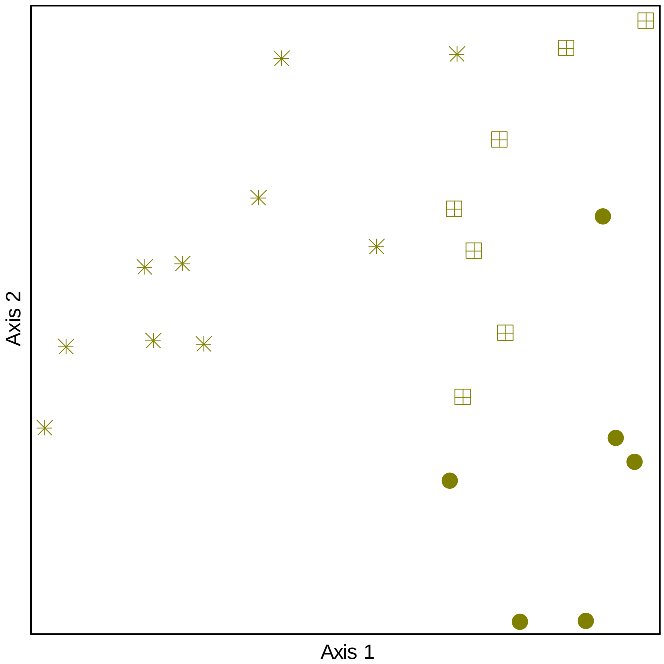

Figure 4. Restoration plots arranged along the first two principal components based on vegetation: ✳ = 7 years restoration plots, ⊞ = 5 years restoration plots, ● = 3 year restoration.

Changes in Vegetation Structure

A total of 108 vascular plant species was recorded on the restored crusted soils. Richness (R), Shannon index (H') and Evenness (E) differed with restoration ages. The highest values of R, H' and E were recorded at the 5-year site and the lowest values were at the 7-year site (Table 1). Above-ground biomass and percent plant cover increased significantly with restoration ages (ANOVA, $P < 0.005$). LSD tests of the above-ground biomass and percent plant cover revealed significant differences between all pairs of restoration sites. Values for above-ground biomass and percent plant cover were lowest for the 3-year restoration site and highest for the 7-year restoration site (Figures 1 and 2). Stem circumference of trees was significantly different among the three restoration treatment levels (ANOVA, $P < 0.001$). In all three sites, the distribution was inverse J-shaped, indicating that most trees had a small stem circumference (Figure 3). The 3-year restoration site was practically dominated by stems in the smallest circumference class (Figure 3a). Trees with larger stem circumference (> 20 cm) appeared at the 5-year restoration site and their frequency increased with restoration age (Figure 3b and 3c). The frequency of trees in the smallest circumference class decreased with restoration age.

Successional Trends

The first and second principal components accounted for 35 and 14 %, respectively of the variance in vegetation among the restoration plots. The graph of the 23 restoration plots on the first two principal components (Figure 4) shows spatial and temporal gradients. There was considerable scatter of the vegetation samples within and between sites in the ordination space, thus reflecting high variability of vegetation within and between sites. This indicates a spatial gradient of vegetation within sites and between sites. The ordination space discriminated plots from the 3-year old restoration (right), plots from the 7-year old restoration (left) and, between these two groups, plots form the 5-year old restoration site. This indicates a temporal gradient in vegetation.

Redundancy analysis indicated strong positive Pearson correlations between axis 1 and cover of erosive crust ($r = 0.85$), gravel crust ($r = 0.90$), bare ground ($r = 0.93$) and rock ($r = 0.89$), and strong negative Pearson correlations between axis 1 and restoration age ($r = –0.88$), height of the herbaceous layer ($r = –0.49$), vegetation cover ($r = –0.91$) and litter cover ($r = –0.95$). Therefore, axis 1 reflects a temporal gradient of recovering vegetation, herbaceous height and litter, and corresponding decrease in the cover of erosive and gravel crusts, bare ground and rock.

Changes in Vegetation Communities

The Multi-Response Permutation Procedures (MRPP) based on the floristic and environmental variable data sets showed significant temporal variation in species composition between the three sites, i.e. treatment levels ($P < 0.001$). The difference between the excepted (0.32) and observed delta (0.50) values confirms the strong temporal variation in species composition between treatment levels. The value of *A* was low (0.34) indicating significant variation in species composition among plots within sites and between sites, reflecting the heterogeneity of the sites. Hence, the MRPP result was consistent with the PCA indicating spatial and temporal differences of vegetation communities.

Indicator Species Analysis identified particular indicator species for each treatment level (Table 2). These included Phanerophyes (trees or shrubs which buds are exposed over 25 cm), Chamaephytes (small shrubs and herbaceous perennials with exposed buds less than 50 cm above ground level) and Therophytes (annual plants). The 7-year restoration site, which had high values for total plant cover, herbaceous plant height and litter cover, was dominated by native Phanerophytes (*Maerua crassifolia*, *Guiera senegalensis*) and Therophytes (*Merremia pinnata*, *Kohautia senegalensis*, *Ipomoea ochracea*). The 3-year restoration site, which had high values for cover of erosive crust, gravel crust, bare ground and rocks, was dominated by native Therophytes (*Citrillus colocynthis*, *Achyrantes aspera*, *Indigofera colutea*, *Cassia obtusifolia, Aristida adscensionis*, *Schoenefeldia gracilis*) and a Chamaephyte (*Cassia italica*). Species that characterized the 5-year restoration site were Therophytes (*Aristida funiculata*, *Alysicarpus ovalifolius*, *Dicoma tomentosa*, *Sphaeranthus senegalensis*) and a Chamaephyte (*Sesbania leptocarpa*).

Discussion

Colonization of Degraded Site and Community Development

The restoration treatment in this study (planting tree seedlings and broadcast sowing grass seed in half moons) facilitated colonization by other plant species and succession on degraded crusted soils. The patterns of change in plant communities and site characteristics reflected ecosystem development, in which early successional species (in general annual plants) are replaced by mid successional species (mainly shrubs and grasses) and with time developing into a community of trees, shrubs, grasses and annual plants. Several restoration ecology studies have also demonstrated changes in plant composition and diversity due to the restoration treatment and time, for example on restored mine sites (Holl, 2002; Martínez-Ruiz et al., 2007; Alday et al., 2011b) or restored ecosystems (Gretarsdottir et al., 2004; Řehounková and Prach, 2008), on mine wastes (Alday et al., 2011a; Erskine and Fletcher 2013), on sand dunes (Sarah and Rudgers, 2010; Lichter, 2000), on new substrates such as glacial moraines (Chapin et al., 1994; Chad and del Moral, 2009) and lava (del Moral and Lacher, 2005; del Moral et al., 2010).

The oldest succession stage in this study (7 years) had the highest vegetation cover, frequency of trees, above-ground biomass, and inversely the lowest biodiversity including species richness, evenness and the Shannon index. The intermediate succession stage (5 years) had the highest biodiversity, and intermediate values for vegetation cover, frequency of trees and above-ground biomass. The youngest succession stage (3 years) had intermediate values for biodiversity, but the lowest vegetation cover, frequency of trees and above-ground biomass. As vegetation and litter cover increased over time, there was a corresponding decrease in the cover of erosive and gravel crusts, bare ground and rocks, which in turn facilitated seedling recruitment. Time appears to be the significant variable that affects vegetation recovery following a restoration effort.

Changes in plant composition over time in this study were accompanied by changes in the dominant plant life forms. The youngest succession stage was dominated by Therophytes, the intermediate stage was dominated by Therophytes and Chamaephytes, and the oldest stage was dominated by Phanerophytes and Therophytes. Similar increases of Phanerophytes abundance (i.e., trees and large shrubs) with succession age were observed by Hazarika et al., (2006). The high abundance of Therophytes (annual plants) at each successional stage confirms the hostility of the Sahelian environment (Saadou, 1990).

Initially, the biodiversity in the restored sites increased with the arrival of seeds from species growing in the vicinity of the study sites. The recruitment of seedlings facilitated higher vegetation cover, above-ground biomass, tree density and litter cover over time. These changes and the water harvesting system effect of the half moons reduced soil erosion and increased nutrient and water infiltration. Vegetation provides shade that creates a favorable microclimate for soil organisms, and attracts birds and herbivores that disperse seeds. When vegetation cover and tree density increase, competition increases among species for nutrients, light and/or space. Species with high fitness can inhibit the establishment of weaker species, and this can lead to a decline in biodiversity, which was observed in this study after five years of restoration. A similar decrease in biodiversity was reported by del Moral (1998), where shade tolerant-species inhibited the establishement of pionneer species.

Improved environmental conditions such as greater vegetation cover, biomass production and litter accumulation combined with a reduction of physical crusts on the soil can lead to persistent ecosystems. The spatial variability of vegetation among plots within the sites in this study indicates different successional trajectories and high heterogeneity in recovering plants species. This patchiness in species assortment may be due to environmental gradients (such as changes in soil nutrients and moisture with topography), limited seed dispersal, low frequency of efficient colonizer species and/or local disturbances (Wood and del Moral, 1987; Alday et al., 2010).

Our results indicate that ecosystem development is affected by interacting abiotic and biotic factors including environmental conditions, seed dispersal and species interactions. Harsh environmental conditions such as soil compaction and erosion can be reduced by restoration treatments. Seed dispersal and seedling establishment increase biodiversity but long distances, land form and isolation can restrict plant colonization. In addition, species interactions, including facilitation, tolerance and inhibition mechanisms, affect species abundance and dominance, and community composition (Connell and Slatyer, 1977).

Processes Recovery

Soils with a physical surface crust and compacted layer below have poor aeration and restrict soil organism movement (Whisenant, 1999). This limits available water and oxygen in the soil, disrupts nutrient cycling, and results in high water runoff. The restoration treatment in this study was designed to stabilize the soil surface by reducing ground-surface wind speed and water runoff, and trapping wind-blown seeds, soil and litter. The half-moon water harvesting technique also increases water infiltration that maintains nurse plants which facilitate germination of dispersed seeds and seedling survival in more favorable micro environmental conditions. Nurse plants increase soil surface roughness which enhances infiltration, thereby increasing the soil moisture and nutrient levels. Improved soil conditions promote more productive plant communities (Gairola and Soni, 2010) resulting in increased biomass production. Increasing biomass production leads to higher litter accumulation, and litter degradation by soil organisms ensures functional nutrient cycling. Soil stability, water infiltration, energy and nutrient recycling are autogenic processes that are self-sustaining. Hence, the restoration effort initiated a self-sustaining process which is the key to ecosystem resilience (Whisenant, 1999).

Conclusions and Implications for Land Restoration

Crusted soils are barren, compacted and prone to erosion. These conditions are unsuitable to seed germination and seedling development. Planting and sowing nurse plants in water harvesting systems such as half moons can overcome thresholds that impede vegetation recovery. This restoration treatment changes the site conditions by reducing soil erosion, increasing soil water infiltration, increasing soil organic matter accumulation, trapping windblown seeds, and creating a more favorable microclimate for seed germination and seedling development.

Although the restoration treatment had a positive effect on vegetation recovery, the results of this study emphasize the role of the surrounding vegetation as a seed source. Vegetation on restored sites can trap wind-blown seeds and attract animals that disperse the seeds from the nearby vegetation. Effective restoration efforts must target degraded sites that are close enough to surrounding vegetation (i.e., seed source) to facilitate seed dispersal to the degraded site.

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