Effects of Soil Compaction and Organic Matter Removal on Ground-flora Diversity:

Seventeen-year Results from the Chippewa National Forest Long-term Soil Productivity Project

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Introduction

Soil is one of the key factors regulating the productivity and diversity of forest ecosystems. Soil organic matter resulting from the decomposition of leaf litter and branch and bole material provides an important reservoir of nutrients for future forest growth. The structure of soils, in conjunction with soil texture, determines the ability of a soil to retain moisture. Forest harvest operations, through the use of heavy equipment and slash management practices, have the potential to damage soil structure and remove organic matter from the forest floor. We lack a clear understanding, however, of which soil types are most susceptible, and what degree of impact soils can sustain before the potential productivity and diversity are reduced.

To address this issue, the US Forest Service initiated a nationwide Long-Term Soil Productivity (LTSP) study to assess the effects of logging operations on the structure and organic matter content of forest soils (Powers et al. 1990). In the Lake States, study plots were installed on the Chippewa, Ottawa, and Huron National Forests. These plots represent the range of soil textures which occur across the Lake States: silt loams, clays, and sands, respectively. Using an experimental approach, different levels of soil compaction and organic matter removal were applied to harvested aspen stands across this soil gradient. Aspen reproduction, forest biomass, and the diversity of the ground-flora layers are being monitored on a periodic basis to assess their response to these treatments. The results of this experiment will allow us to predict the degree of protection required to sustain productivity and floristic diversity in aspen stands across a range of common Lake State soil types.

The Lake States LTSP study included an analysis of floristic diversity to the suite of measurements made on the study plots. Biodiversity and forest management have become critical issues in the Lake States Forests. In Minnesota's Generic Environmental Impact Statement, diversity was one of the key focal issues. Ground-flora has received wide use as ecological indicators and in ecological land classification systems across the Great Lakes (Spies and Barnes 1985, Host and Pregitzer 1991, Coffmann et al. 1983, Shadis et al. 1995, MN DNR 2003). A study by Berger, Peuttmann and Host showed a strong response of ground-flora to on-site operations, particularly on landings and skid trails, which receive a high degree of compaction (Berger, Peuttmann and Host 2004). The rate and degree to which sites recover from compaction, however, is poorly understood. The primary objective of this study was assess changes in species richness, diversity and community composition seventeen years after installation of the LTSP treatments on the Chippewa National Forest of north central Minnesota.

Methods

Study Sites and Sample Design

Replicated LTSP plots were installed on the Chippewa National Forest in 1993. Soils are predominantly silt loam. The Chippewa National Forest had both a pilot installation containing a subset of treatments (at Marcell Experimental Forest; Alban et al. 1994), and a full installation north of Leech Lake. All installations were dominated by relatively mature (60-80 yr old) aspen (*Populus tremuloides* Michx., *Populus grandidentata* Michx.) prior to plot installation. Sites were carefully evaluated to ensure that they were relatively homogeneous in terms of forest cover, topography, soils, and ground-flora, and representative of the characteristic soil types of the region.

Each installation consists of three replicates of a 3 x 3 factorial treatment with three levels of soil compaction: 1) no compaction, 2) moderate compaction, and 3) severe compaction; and three levels of organic matter removal: 1) bole-only removal, 2) total aboveground tree removal, and 3) total aboveground tree + forest floor removal (Table 1). Forest floor was removed by raking off leaf litter down to the mineral soil. There are thus 27 plots in the statistical design of this study. Individual treatment plots are 40 x 40 m in size, with a 10 m buffer strip surrounding each plot. To provide baseline data, the overstory and ground-flora were sampled in all plots prior to harvest. Plots were harvested the following winter when soils were frozen to ca. 0.3 m deep, and treatments were then applied the following spring.

Table 1. Factorial design for an LTSP Installation. Values represent number of replicates in each treatment.

	No Compaction	Moderate Compaction	Severe Compaction
Bole-only	3	3	3
Total Tree Harvest	3	3	3
Total Tree+Forest Floor	3	3	3

On the Chippewa National Forest, a wet spring and summer in 1993 made it impossible to apply the treatments early in the season; as a result, no floristic sampling was done in 1993; the Year 1 sampling for this installation was done on 1994, followed by a 2nd year sampling in 1995; these are reported on in Host (1996). Plots were resampled in summer 2004, representing 10 years since the first post-treatment sampling (Host 2004). Plots in Replicate 3 were resampled in late summer 2009, and in Replicates 1 and 2 in late summer 2010. The 2009 plots were mostly sampled by 1 person from mid-August to mid-September; the 2010 plots were sampled by a 2-person crew from mid-Aug to early September 2011. This timing is a little later than but still consistent with previous sampling efforts and attempts to capture the majority of the summer flora. Unknown specimens were labeled, pressed and dried, and keyed out at the Natural Resources Research Institute Forest Ecology Lab in spring 2011.

Floristic Sampling

In each plot, four subplots were established for sampling vegetation, and four points were established for sampling soils. Sample subplots and points were systematically located within the 40 x 40 m plots, and used as reference points for the rectangular ground-flora releve subplots (Figure 1). To quantify ground-flora composition and abundance, 10 x 15 m subplots were established around each of the permanent sampling points. Subplot corners were permanently monumented with PVC pipe by North Central Experiment Station personnel prior to sampling.

Percent ground cover was determined for all herbaceous and woody species in the subplot using a Braun-Blanquet cover-abundance scale (Mueller Dombois and Ellenburg 1974). Cover estimates were stratified by height class, as described in Almendinger (1988). Abundance values were determined by traversing the subplot plot several times to record the species present, and then assigning abundance values after species lists were compiled. Nomenclature for vascular plants in this report follows Gleason and Cronquist (1991). In the associated datasets, current synonyms from the USDA Plants database (USDA NRCS 2011), and their ITIS codes are included.

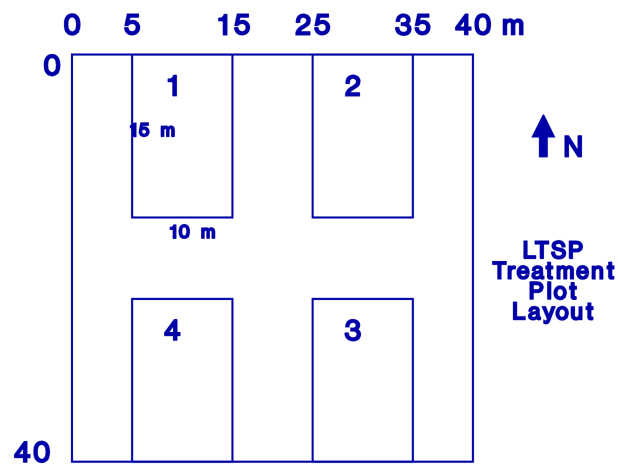


Figure 1. Layout of LTSP Treatment Plot

Statistical Analyses

Floristic response to treatments was evaluated using a number of univariate and multivariate measures. Cover-abundance classes were converted to cover midpoints, and mean cover midpoints were calculated across the four subplots in each plot. Mean cover midpoint values formed the basis for further analyses. Univariate measures included: 1) species richness (S): the number of species per plot; 2) the Shannon diversity index (H'); and 3) evenness or equitability (E = H'/ln[S]). The dataset used for the univariate measures used a combined cover midpoint value for each tree species present in both canopy and sapling/shrub vegetation layers; the cover midpoint values of each tree species present in both canopy and sapling layers were added together. This dataset consisted of 182 taxa in 27 plots.

Community composition was analyzed using multivariate ordination techniques to determine if particular plots or treatments had different overall floristic composition. In this analysis, species that occurred on fewer than 3 plots (10%) were not included in the ordinations (Hill 1979). The dataset used for the ordinations also omitted the midpoint cover values for canopy layer tree species, but it did include the cover midpoint values for tree species in the sapling/shrub layer, as well as all the shrubs, herbs, and graminoids (126 ground-flora taxa x 27 plots). Plots were ordinated with respect to ground-flora composition using detrended correspondence analysis (DCA; Hill 1979). The primary result of a DCA is an ordination space diagram, in which plots which are close together on the plot are similar in species composition. The axes of a DCA are calculated to successively maximize variation in composition; thus DCA Axis 1 is the major compositional gradient in the data set, Axis 2 is the second dominant axis, etc. By displaying treatment codes on the points in the ordination representing the plots, the relationship of community composition to compaction and OM removal levels can be assessed.

Following the DCA, a Non-metric Multidimensional Scaling (NMS) ordination was run. NMS is an ordination method that is appropriate for data that are not normal or are on arbitrary, discontinuous, or otherwise unusual scales (McCune and Mefford 1995). NMS is an iterative search for a ranking and placement of samples on a specified number of axes that minimizes the ‘stress’ of the configuration. Stress is a measure of departure from monotonicity in the relationship between the dissimilarity (distance) in the original sample space and distance in the reduced ordination space. An advantage of NMS is that, being based on ranked distances, it tends to linearize the relation between environmental distance and compositional distance (Beals 1984), relieving the problem of datasets with large numbers of zeros in the full matrix ("zero-truncation problem"), a problem which plagues many ordinations of heterogeneous data sets. In contrast to DCA, ordination axes in NMS are not in a particular order, so the strongest compositional gradients can occur on any axis. NMS was run using relative Sorensen’s distance measure, calculating 2 axes, and using a step length of 0.20. NMS was run with 250 iterations, using coordinates from the DCA ordination as a starting point for the repeated runs, and the time of the run was used as a random number seed. Final stress for the 2-dimensional solution was 15.03, with 0.00 final instability, in 83 iterations.

The statistical significance of treatment effects on species composition was tested using a multiple response permutation procedure (MRPP) following the method of Anderson (2001). MRPPs are nonparametric classification procedures for testing the hypothesis of no differences among one or more groups. The test is based on comparing actual within and between group (i.e. treatment) compositional similarities against a resampled population of similarities based on random assignments of plots to treatments. If the actual values fall within the tails of the simulated distribution of similarities, the null hypothesis is rejected. MRPP does not rely on the assumptions of multivariate normality and homogeneity of variance required in parametric tests (McCune and Mefford 1995). The ground-flora dataset used in the ordinations (126 ground-flora taxa x 27 plots) was tested, and groups were defined by values of soil compaction and organic matter removal.

Results and Discussion

Pretreatment conditions (from Host 1996)

The dominant ground-flora species in the pretreatment plots were sugar maple (*Acer saccharum*), rice grass (*Oryzopsis asperifolia*), beaked hazel (*Corylus cornuta*) and Pennsylvania sedge *(Carex pensylvanica*). Species richness data at the subplot level were not normally distributed, nor would they be transformed to normality; as a result ANOVA could not be used with subplot-level data. Plot level averages were normally distributed, however, and subsequent analyses were thus based on plot level data. Species richness and Shannon diversity were not significantly different in the pre-treatment plots. Mean species richness (S) at the subplot level was 50, mean Shannon diversity (H') was 3.96.

The abundance of species followed a truncated log-normal distribution as described by Preston (1948): a few common species (e.g. *Populus tremuloides*, *Aster macrophyllus*) dominate the plots, while the majority of species are present at low abundance values (Figure 2). Statistics on species richness alone can therefore be deceptive, in that they do not account for the relative abundances within the community. To account this effect, both composition and abundance were included in the ordinations described below.

Detrended correspondence analysis showed that there were distinct differences in initial ground-flora composition among the three installations. Installation 3 was separated from Installations 1 and 2 on DCA Axis 1. Two violets (*Viola incognita* and *V. adunca*) received strong positive weights on the Axis 1, along with alder (*Alnus viridis*), asters (*Aster spp*.), and pyrolas (*Pyrola* *spp*.). Three species of horsetail (*Equisetum spp*.), greenbriar (*Smilax herbacea*), and lady-slipper orchid (*Cypripedium calceolus*) received strong negative weights on this axis (e.g. they were dominant members of Installations 1 and 2). Installations 1 and 2 separated along DCA Axis 2. The strong positive dominants on this axis were bloodroot (*Sanguinaria canadensis*), greenbriar (*Smilax herbacea*), and *Rosa spp*. Negative dominants were *Lycopodium obscurum*, *Viola incognita*, *Ostrya virginiana*, and *Carex gracillima*. Differences among plots within each installation were relatively minor.

Analysis of summer 2009-10 floristic sampling

The relative effects of soil compaction on species richness results were consistent with those observed in earlier years: moderate levels of soil compaction had the highest levels of species richness (Table 2, Figure 2), with values ranging from 71 to 76 taxa. This was followed by heavy compaction (65 to 71 taxa), with the uncompacted plots having the fewest species (58 to 64 taxa). In some cases, more species were recorded in the 2004 sampling than in 2009-10.

Table 2. Average species richness (S) by treatment level on the Chippewa National Forest

Organic Matter Removal	Compaction Level														
	No Compaction					***Moderate Compaction***					***Severe Compaction***				
	1992	1994	1995	2004	2010	1992	1994	1995	2004	2010	1992	1994	1995	2004	2010
Merchantable Bole Harvest	53	40	52	63	61	55	53	57	79	74	49	45	52	71	66
Total Tree Harvest	44	51	48	57	58	47	58	55	76	76	49	56	51	67	71
Total Tree Harvest + Forest Floor Removal	49	52	54	67	64	51	54	55	69	71	50	57	54	65	69

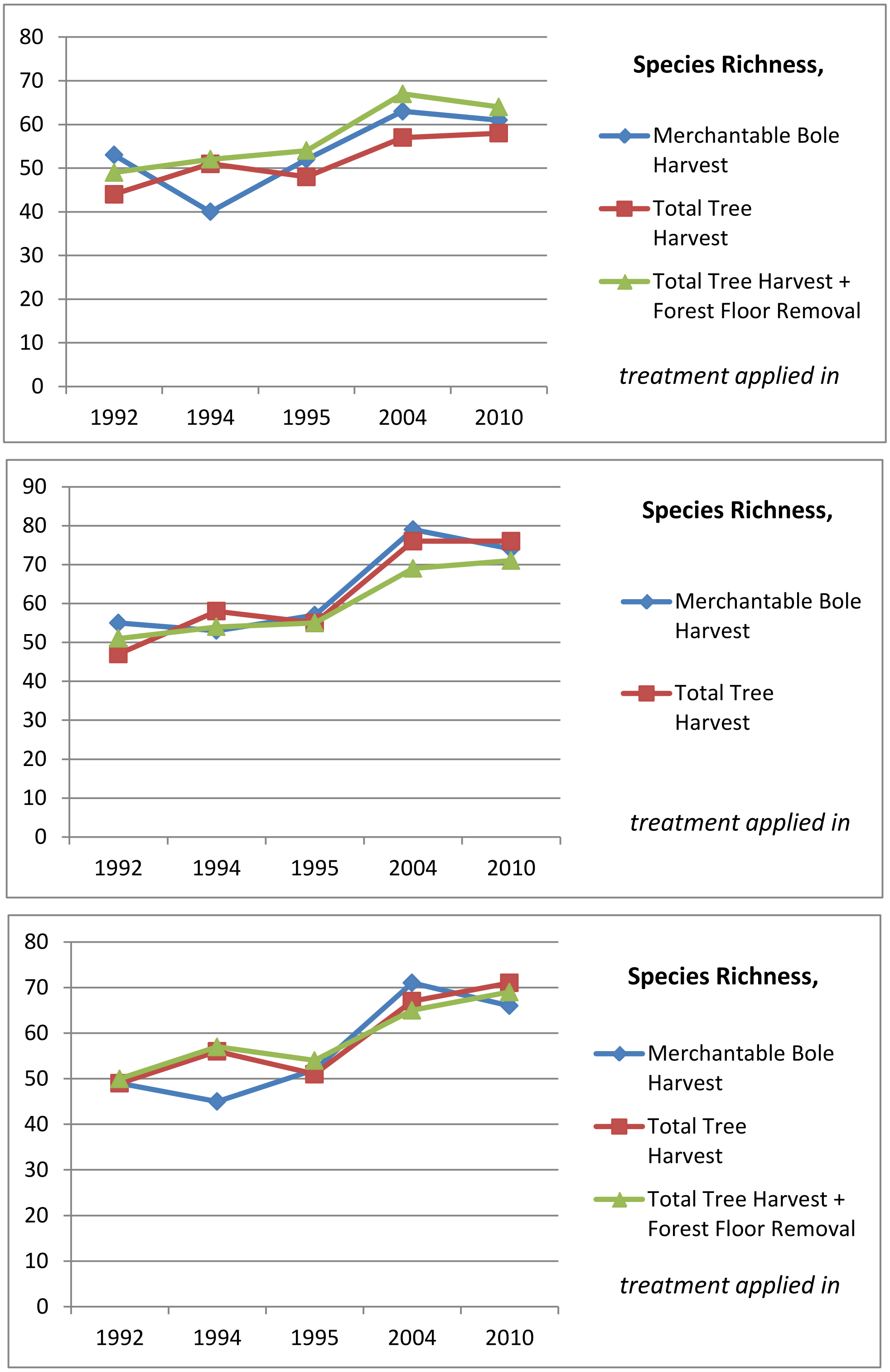


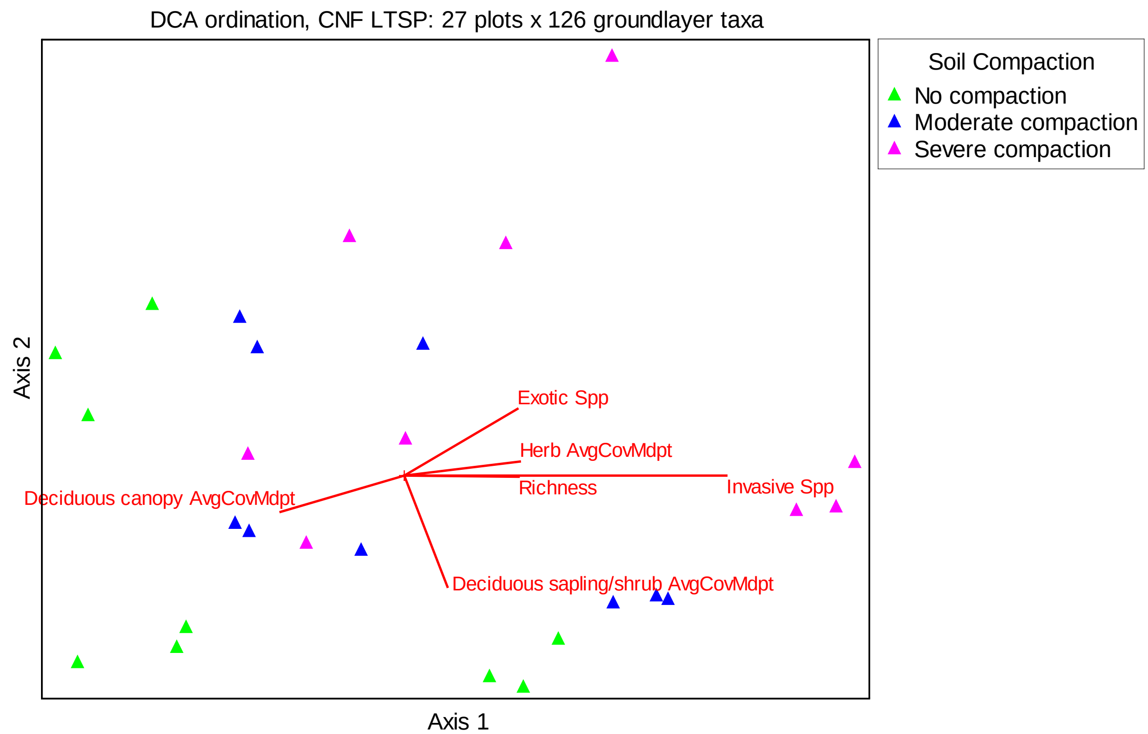
Figure 2. Changes in Species Richness over 17 years since treatments were applied

Also, in the 2009-10 sampling there was somewhat less divergence in species richness between compaction treatments than in 2004. Viewing richness values by compaction level, the highest species richness in 2009-10 were associated with total tree removal and moderate compaction levels, and the lowest were associated with total tree removal and no compaction (Figure 2).

The strong response of ground-flora plant community composition to soil compaction reported in Host (2005) was still pronounced in the 2009-10 sampling period, but more complex. The DCA ordination of the 2004 data showed a strong separation along the first (most important) DCA axis, with uncompacted plots receiving low DCA Axis scores, moderate compaction receiving intermediate scores, and heavily compacted sites receiving high scores. With one exception, there was an almost perfect discrimination among compaction treatments with respect to floristic composition in 2004. This contrasted with the distribution of sites by the organic matter removal, in which there was no discernable pattern of ground-flora composition by treatment level in the 2004 dataset (Host 2005). The DCA ordination of the 2009-10 data had less clear gradients in relation to a single axis, but there are still floristic groups that are correlated with the level of compaction treatment (Figure 3). In contrast there is again no discernable pattern of ground-flora composition in relation to the organic matter removal treatment level (Figure 4).

The soil compaction gradient is a little clearer in the NMS ordination, mainly in relation to axis 2 (Figure 5); with the uncompacted plots receiving higher NMS axis 2 scores, and severely compacted plots receiving low NMS axis 2 scores and often higher axis 1 scores. The gradient in the NMS ordination is angled from the upper left (uncompacted) to the lower right (severely compacted) areas of the graph. In comparison to the 2004 DCA ordination, there is more intermingling of the moderate and severe compaction plots in the 2009-10 dataset in both DCA and NMS ordinations. Even with some convergence in the vegetation patterns, there are still floristic groups that are correlated with the level of compaction treatment (Figure 5). As in the DCA ordinations, the NMS ordination again shows no discernable pattern of ground-flora composition in relation to the organic matter removal treatment level (Figure 6).

The ground-flora which contributed most to the separation among compaction treatments along NMS axis 2 showed strong differences in life history attributes that relate to their ability to colonize and dominate disturbed sites. Important species on the compacted end of the gradient included graminoids, particularly bluegrass (*Poa* sp.) and fringed brome (*Bromus ciliatus),* thorny shrubs such as blackberry (*Rubus alleghaniensis),* red raspberry (*Rubus idaeus),* and prickly rose (*Rosa acicularis),* composites such as yarrow *(Achillea millefolium)*, asters (*Aster umbellatus* and other *Aster* spp.), thistles (mainly *Cirsium arvense* and *C. muticum*), Canada goldenrod (*Solidago canadensis),* and some other early successional species such as American vetch (*Vicia americana)* and Bebb's willow *(Salix bebbiana)*. The more compacted end of the gradient showed significant correlations with higher numbers invasive and exotic species, with greater cover of graminoids and herbs, and with taller graminoids (Figures 3, 5). Species concentrated in uncompacted end of the gradient included later successional forest species such as sugar maple *(Acer saccharum),* red baneberry *(Actaea rubra),* blue-bead lily *(Clintonia borealis),* yellow ladyslipper *(Cypripedium calceolus),* leatherwood *(Dirca palustris),* black and green ashes (*Fraxinus nigra* and *F. pennsylvanica*), American fly honeysuckle (*Lonicera canadensis),* ground pine*(Lycopodium obscurum),* and downy yellow violet *(Viola pubescens)*. The uncompacted end of the gradient showed significant correlations with greater cover and height of deciduous canopy trees (Figures 3, 5).



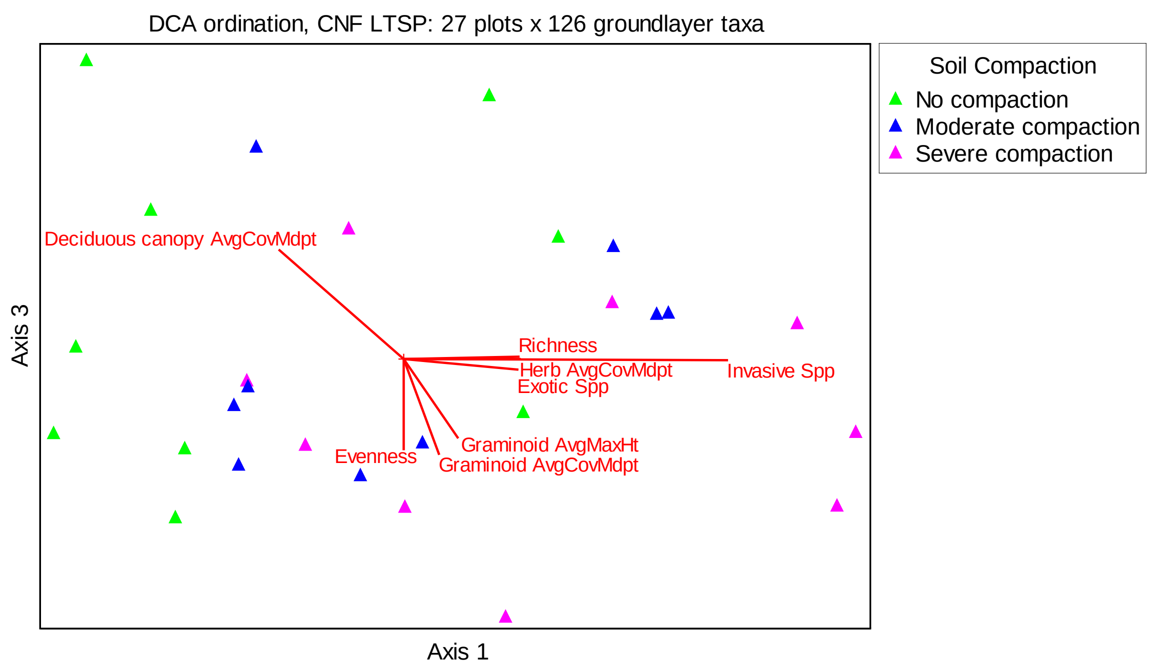


Figure 3: DCA ordinations (top: axes 1 & 2; bottom: axes 1 & 3) with Soil Compaction treatments color-coded for each plot; red vectors indicate significant correlations with descriptive plot features.

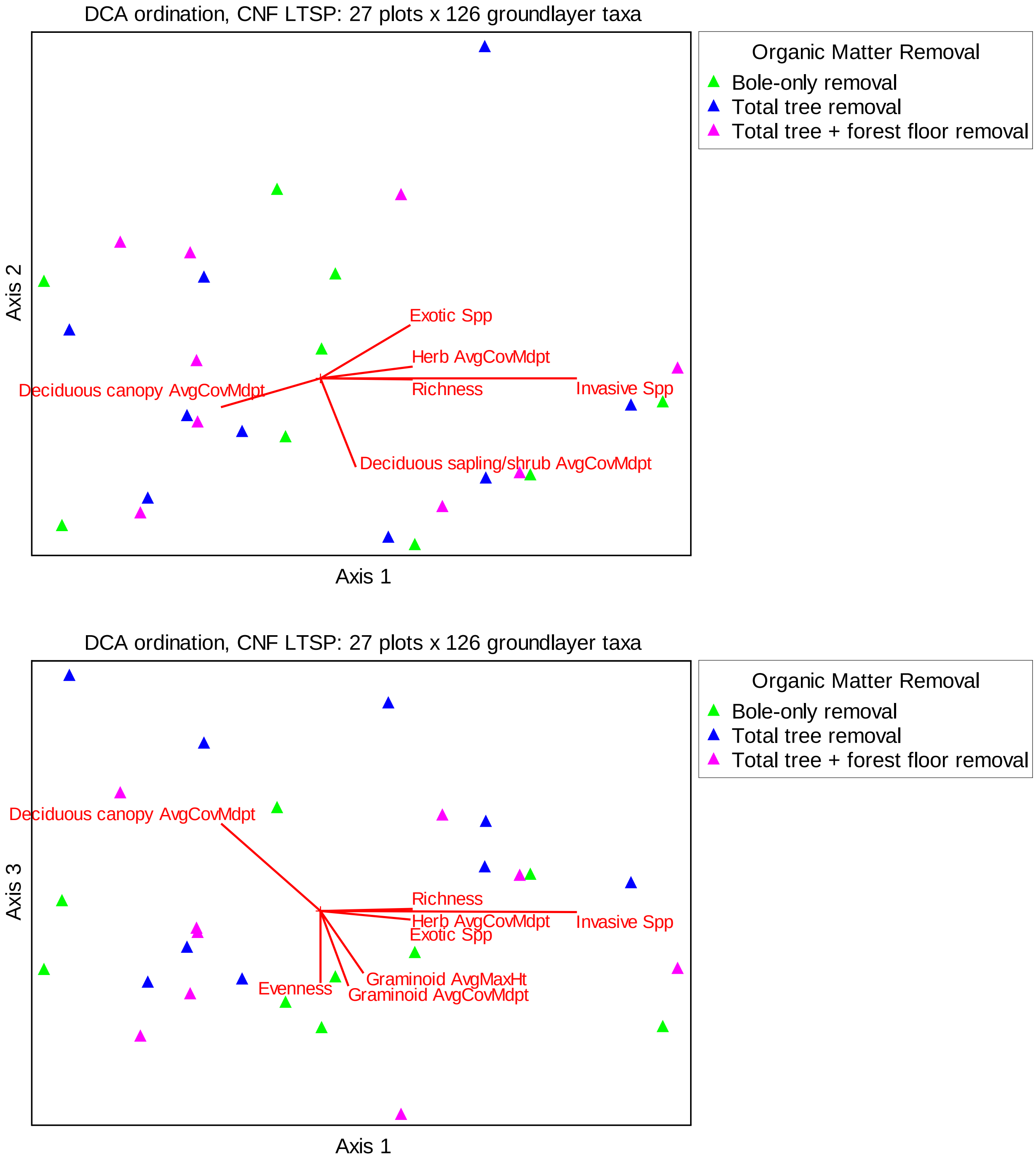


Figure 4: DCA ordinations (top: axes 1 & 2; bottom: axes 1 & 3) with Organic Matter Removal treatments color-coded for each plot; red vectors indicate significant correlations with descriptive plot features.

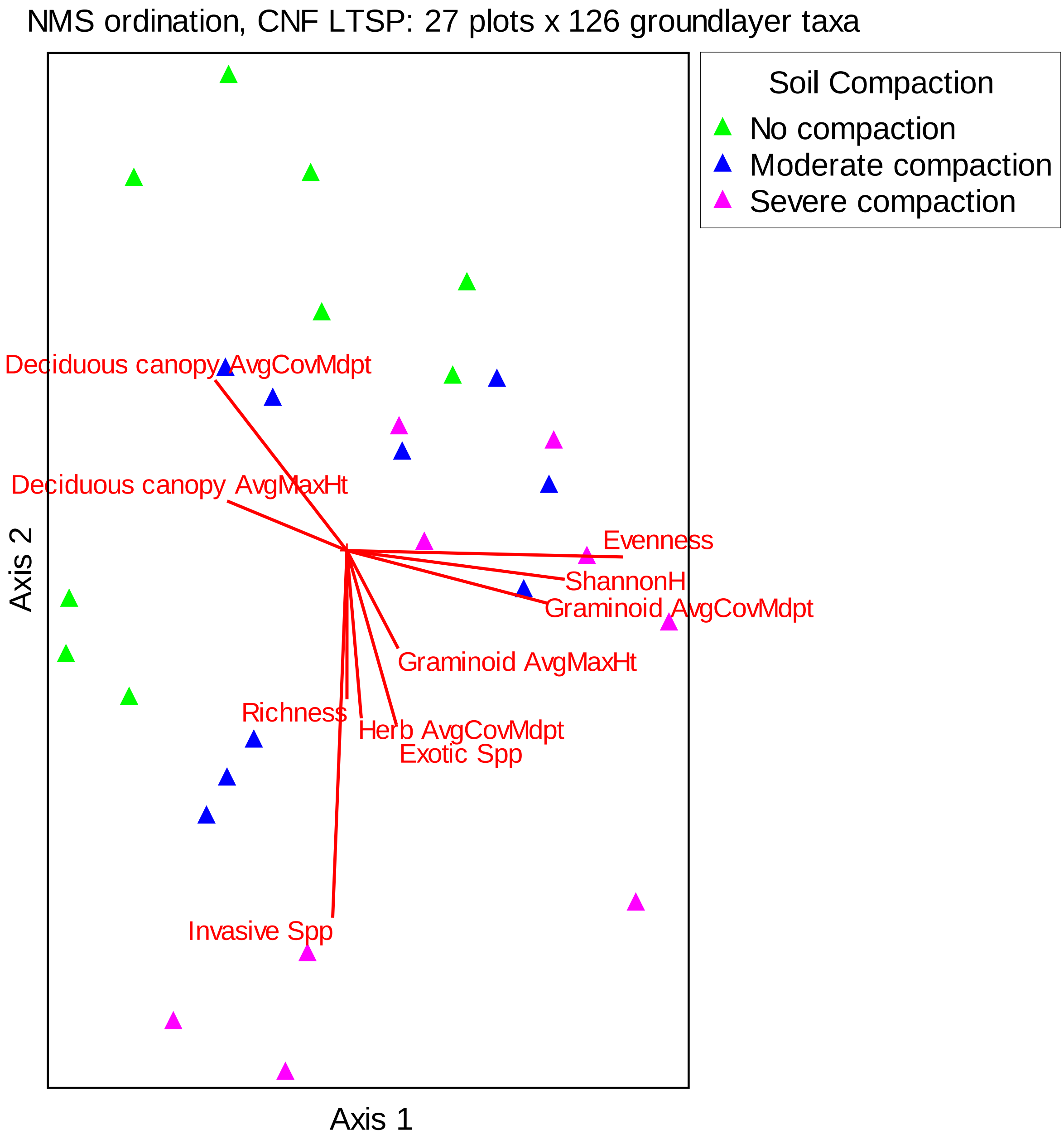


Figure 5: NMS ordination with Soil Compaction treatments color-coded for each plot; red vectors indicate significant correlations with descriptive plot features.

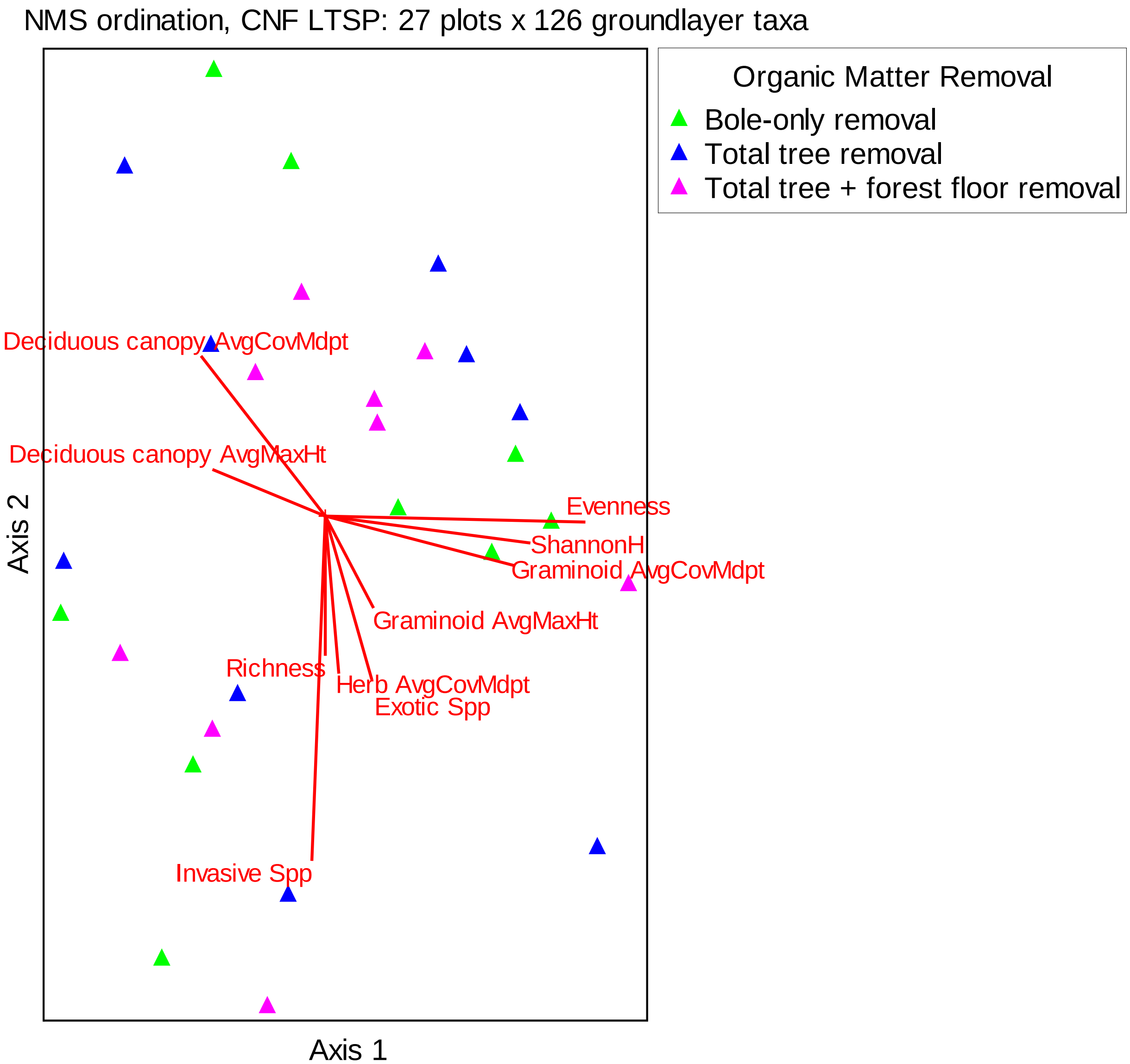


Figure 6: NMS ordination with Organic Matter Removal treatments color-coded for each plot; red vectors indicate significant correlations with descriptive plot features.

The significance of ground-flora compositional differences were tested using Multiple Response Permutations Procedures (MRPP) and compared with earlier MRPP tests. The post-treatment effects from soil compaction continued to be highly significant in 2009-10. There was no compositional response to different levels of organic matter removal (Table 3).

Table 3. Probability levels for MRPP tests of species composition compared to treatments on the Chippewa National Forest

	1992	1994	1995	2004	2010
OM Removal	0.546	0.530	0.665	0.651	0.717
Soil Compaction	1.000	0.000	0.000	0.000	0.018

Summary

At the Chippewa National Forest LTSP site it has been 17 years since organic matter removal and soil compaction treatments were applied to 27 releve plots with silt loam soils. Analysis of vegetation composition in 2009-10 has shown some significant effects from soil compaction, but none from different amounts of organic matter removal. With increased levels of soil compaction we found an increase in the numbers of invasive and early successional species present, and decreases in forest ground-flora species, as well as decreases in cover of and height of deciduous canopy trees when compared to plots with no compaction. While species richness has shown a general increase since the 1995 sampling period, the relative ranking of the compaction treatments is the same.

It may appear counterintuitive that the disturbance treatments increase diversity, but this finding is consistent with the life history and establishment strategies of ruderal species in disturbed environments. Many of the grasses, thistles and other ruderals are able to compete successfully under the droughty and more nutrient poor conditions imposed by the treatments. At the same time, many species previously existing on the site remain present on the plots, but in reduced numbers, resulting in high species richness numbers. A critical error to avoid in interpreting these findings, of course, is to believe that any increase in the number of species (one measure of biodiversity) is beneficial to the environment, and should therefore become a biodiversity management objective. The species that increased in abundance were those that have life history attributes developed for colonizing disturbed habitats, and their success was related to degree of disturbance. Thus, while the diversity increased with disturbance, this does not provide a complete picture of the shift in community composition that occurred. The compositional data for the compacted soil plots show a clear change away from species that colonize mesic, nutrient-rich closed forest habitat toward those characteristic of open and more xeric environments. While this shift is a natural community transition following disturbance, it appears to be intensified under moderate and heavy soil compaction levels.

The standard metrics of species diversity and floristic composition indicate that after 17 years, the plots have converged somewhat in terms of the number of species, relative abundances, and composition of the vegetation. It is also clear from the 2009-10 data that the plots where soil was not compacted are producing greater cover and height of deciduous canopy trees than the plots which received moderate and severe soil compaction treatments.

Acknowledgments

Carol Reschke and Elizabeth McGarry conducted the field sampling for this project. Carol Reschke completed data entry, management of plant specimens, and data analysis. We greatly appreciate the efforts of John Elioff, now retired from the North Central Experiment Station, for marking the subplot corners prior to field sampling. This study was supported in part by a grant from the Chippewa National Forest; their continued support and recognition of the importance for the Long-Term Soil Productivity project is greatly appreciated.

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