Ecological monitoring of terrestrial ecosystem recovery from man-made perturbation: assessing community complexity

M. Anand, B.C. Tucker & R. Desrochers

Biology Department, Laurentian University, Sudbury, Ontario, Canada

Abstract

The dynamics of ecological complexity are presented from an area severely damaged by air pollution to understand the effect of perturbation intensity on long-term recovery dynamics of forest communities. Perturbation is assumed to be most intense near the smelter and to decrease with distance. Complexity is assessed using Shannon entropy as well as a contemporary measure of structural complexity. We find that while total complexity and diversity increase with decreasing perturbation intensity, structural complexity does not. It is also uncovered that community-level dynamics are more predictable than species-level dynamics. The data were analyzed using multivariate methods to determine how spatial pattern and groupings produce trends in community-level dynamics. The perturbation gradient is characterized by a continuum of understory communities with colonizing and metal-tolerant species proximal to the pollution source and sensitive species at distal sites. The overstory community mimicked this pattern, but vertical structure was found to be important in characterizing the gradient. Ecological monitoring of the multi-level effects of pollution on ecosystems is important for understanding the full implications of multiple stressors in the environment.

1 Introduction

With ever-increasing threats to biodiversity by man-made perturbation, and in particular by industrial pollution, the importance of extensive and long-term monitoring of the effects of these on ecosystem diversity and complexity is critical. Quantification of these attributes, however, is not always intuitive [1]. Understanding spatiotemporal patterns of diversity has been a central question in ecology for over a century, prompting widespread investigation into the best methods of quantification [2, 3]. Diversity indices, though varied, generally include both number of species and their relative proportions. These simple
indices attempt to capture system-level properties, but often fail in their ability to include ecosystem organization and structure. Measures of ecosystem complexity can and should make room for structural components not accounted for by diversity [4,5], however applications of such measures to the study of perturbed ecosystems are scarce. Studies of perturbation gradients using these methods may hold the key to understanding relationships between ecological diversity, complexity and stability [6,7]. Also, it is becoming increasingly apparent that recovery studies need to focus on multiple levels of ecosystem organization (e.g. population and community) [8].

We present an analysis of vegetation community complexity along a perturbation gradient caused by historic air pollution and logging near Sudbury, Ontario, Canada [9,10]. Air pollutants consisted of sulphur dioxide, nickel and copper. Soils became low in pH, with high concentrations of aluminium, copper and nickel. In 1972 decommissioning of the smelters and increased government controls resulted in a 50% reduction of sulphur dioxide concentrations [11]. In 2001 a long-term monitoring program was established to study natural recovery from the historic perturbation. A comprehensive history of the area and related work is documented in [12].

2 Site and Data Description

The vegetation cover prior to the disturbance of the Sudbury area is not known, but ancient stumps suggest pine forested hillsides and cedar swamps [13]. Logging in the area began in 1872 leading to open areas that may have been colonized by Betula papyrifera and Populus tremuloides [12]. The discovery of sulphide ores in 1883 led to open-bed roasting of ore from 1888 to 1929. Upon realizing the extent of its destructiveness, open-bed roasting was replaced by smelting stacks, which resulted in the liberation of emissions higher in the atmosphere and reduction of local damage to vegetation. However, pollutants now travelled greater distances, damaging a larger area. Smoke from smelters could be seen 120km away, sulphur odours extended up to 60km away, and vegetation damage could be seen within a 20-40km radius [11]. Current monitoring sites are situated so as to traverse this historic pollution gradient, starting near the decommissioned smelters east of Sudbury and proceeding in a southerly direction for roughly 35km (Fig. 1). The sites belong to the Canadian Ecological Monitoring and Assessment Network (EMAN; www.eman-rese.ca).

Vegetation data on naturally recovering communities was collected in July 2001 from six sites. Within each site, south-facing slopes on hillsides were surveyed using two parallel 100m transects that were believed to cross natural gradients due to topography (soil moisture/depth/type). Understory species were sampled using the Braun-Blanquet method to estimate cover abundance in 1x1 m contiguous quadrats along the transect. Overstory species were sampled for tree density and height in 5x5 m contiguous quadrats. Overstory height data was collected with the aid of a clinometer in 1m size classes for trees over 1.5m tall.
3 Quantitative Methodology

Diversity was calculated for each sampling unit (quadrat) along a transect using Rényi’s generalized entropy,

\[ H^\alpha = \frac{\ln \sum_{i=1}^{s} p_i^\alpha}{1-\alpha} \]  

(1)

where \( s \) is the total number of species and \( p_i \) is the proportion of the \( i \)th species in the sampling unit. Diversity of order \( \alpha \rightarrow 1 \) was used as it reduces to the well-known Shannon entropy,

\[ H = -\sum_{i=1}^{s} p_i \ln p_i \]  

(2)
At $\alpha=0$, Rényi’s generalized entropy reduces to species richness. Evenness can be calculated by dividing Shannon entropy by species richness. Kolmogorov complexity was calculated for each sampling unit where total complexity is the total code length from Huffman coding of the frequency distribution in the sampling unit and structural complexity is the difference between total complexity and Shannon entropy. This measure was introduced into the ecological literature to include components of complexity not accounted for by diversity [4,5]. Total complexity, structural complexity, Shannon entropy and species richness were quantified for each sampling unit along each transect to detect patterns at the local level (within a site). To detect differences at the regional level (between sites), means were calculated. Mean cover abundance of three understory species (*Betula papyrifera*, *Deschampsia flexuosa* and *Vaccinium angustifolium*) at the six sites are presented for comparison of species-level dynamics with community-level dynamics (diversity and complexity). These species were selected since they are present at most sites and represent a tree, grass and shrub species. Number of individuals and average number of individuals for an overstory species, *B. papyrifera*, were examined as above for comparison against the community-level descriptors.

Correspondence analysis (CA) was used to determine spatial associations between species and sampling units or sites for the understory data at both the local and regional scales. A square-root transformation was made on the understory data prior to the CA in order to reduce the effect of extreme values. Symmetric weighting was used to favour neither sampling unit nor variables in the analysis. Symmetric weighting ($\alpha=0.5$) resulted in a joint plot where the relative positions of variables (species) and objects (sampling units) indicate the degree of association between them [14].

In order to analyze understory vegetation at the regional level, mean abundance for each species was calculated along each 100m transect. The means from one transect from each monitoring site were then combined into a new data matrix representing all species present in the six sites. Frequency tables of overstory species height classes were analyzed using CA at both the local level and the regional level to determine relationships between species height classes and sampling units or sites. In order to compare vegetation across sites, mean frequencies for each species height class were taken from each 100m transect.

All calculations were made using the ecological software packages MULTIV (15) and SYN-TAX (16).

## 4 Results

No vegetation patterns relating to a natural gradient were detected in complexity, diversity, species richness or cover abundance at the local level. Correspondence analysis also failed to reveal community patterns at the local level. We therefore focus on patterns detected at the regional level. Since both transects at each site showed similar patterns, results from only one transect at each site are presented. Mean Shannon diversity, total complexity, evenness and number of species were found to increase with increasing distance from the smelters, but structural
complexity did not (Fig. 2). Structural complexity increases slightly from sites 1 and 2 to its maximum at site 3 and decreases to a minimum at site 6. This measure is known to decrease with increasing number of species and evenness [4] as is evident through the comparison of site 1 to site 6. At site 1 there are 6 species present at an average evenness of 0.05 and mean structural complexity is 0.38 bits. At site 6 there are 30 species present at an average evenness of 0.79 and mean structural complexity is much smaller (0.12 bits). If the magnitude of structural complexity were dependent upon evenness and number of species alone, one would expect structural complexity to be smaller at site 3 than site 1 as there are 6 species present at both sites, but they occur at a higher average evenness at site 3 than site 1. However this is not the case indicating that evenness and number of species are insufficient to completely describe structural complexity.

Figure 2: Mean values of total complexity, structural complexity, Shannon diversity (top), and cover abundance for Betula papyrifera, Deschampsia flexuosa and Vaccinium angustifolium as well as total number of species in understory (bottom) at six sites.
In contrast to patterns in understory diversity and total complexity, mean cover abundance of *B. papyrifera* and *D. flexuosa* vary in a manner similar to structural complexity where *B. papyrifera* is low at sites 1 and 2, increases to a maximum at site 3 and disappears at site 6, and *D. flexuosa* is absent from sites 1 and 2, mean abundance peaks at site 3 and decreases to a minimum at site 6. Mean cover abundance of *V. angustifolium*, uniquely, is at its minimum at sites 1 and 2, increases to its maximum at site 5 and drops at site 6.

Community-level descriptors for the overstory data show a trend similar to that of the understory descriptors (Fig. 3). Mean Shannon diversity, total complexity, evenness and number of species increase with increasing distance from the pollution source, whereas structural complexity follows a decreasing trend (Fig. 3). The relationship between structural complexity, number of species, and evenness is again demonstrated at site 6, which has the highest number of species occurring at an elevated average evenness of 0.70 and the lowest structural evenness. Mean number of individuals of *B. papyrifera* in each transect is low at proximal sites, increases to a maximum at site 3 then decreases to a low level at site 6.

Figure 3: Mean values of total complexity, structural, Shannon diversity (top), and number of individuals for *Betula papyrifera* as well as total number of species in overstory (bottom) at six sites.
A distinct ordering of species and sites was produced by the CA of understory mean cover (Fig. 4). High canonical correlations were found for both axes (R=0.77 and R=0.50). The monitoring sites are ordered from right to left along Axis 1 according to their proximity to smelters. This suggests that the understory communities at these sites can be considered indicators of spatial proximity to point source pollution (and perturbation intensity). *Agrostis scabra*, which is associated with sites 1 and 2, is the primary understory species at these heavily impacted sites and becomes less important in sites with greater numbers of understory species. This is not surprising given its known metal tolerance [17]. In a similar manner, *B. papyrifera, Deschampsia flexuosa*, and *Vaccinium angustifolium* are placed near sites 3 and 4 and are major contributors to understory cover at these two locations. *B. papyrifera* and *D. flexuosa* are natural colonizers of barren areas, with *D. flexuosa* usually appearing after the establishment of *B. papyrifera* [13]. *V. angustifolium* also persists at these heavily impacted sites and has been noted as an early colonizer of heavily impacted soils in the Sudbury area, often associated with open canopy *B. papyrifera* [18]. Sites at increasing distance along the perturbation gradient are characterized by increasing species richness including sensitive, shade-tolerant woodland species, such as *Aralia nudicaulis, Maianthemum canadense*, and *Trientalis borealis*.

![Figure 4](image-url)

*Figure 4:* (Left) CA on understory cover means at 6 sites. Axis 1 has a canonical correlation of R=0.77. *Agrostis scabra* (AS), *Betula papyrifera* (BP), *Deschampsia flexuosa* (DF), *Vaccinium angustifolium* (VA), *Maianthemum canadense* (MC), *Trientalis borealis* (TB), *Aralia nudicaulis* (AN) are labelled. (Right) CA on height class overstory frequency means. Axis 1 has a canonical correlation of R=0.92. Scores for *Betula papyrifera* (B) *Pinus strobus* (P) and *Acer rubrum* (A) are labelled; number following alpha code is height class in metres.
Correspondence analysis of the overstory data also resulted in the ordering of monitoring sites along Axis 1 of the CA joint plot as shown in Figure 4. From right to left, the sites are arranged in order of their proximity to the smelters. Species composition and height class characterize simultaneously the first ordination axis, which has a canonical correlation of $R= 0.92$ while the second axis has a canonical correlation of $R= 0.57$. The systematic arrangement of the monitoring sites suggests that these parameters are also important in characterizing the spatial gradient. Only $B. papyrifera$ of the 2m and 3m height class are associated with sites 1, 2, and 3. Site 4 is associated with taller $B. papyrifera$, shorter $Pinus resinosa$, and $Quercus rubra$. Site 5 is associated with taller $B. papyrifera$, $Pinus strobus$, $P. resinosa$, $Populus grandidentata$, $Picea glauca$, $Q. rubra$ and $Acer rubrum$. Site 6 is associated with $Abies balsamea$, $Corylus cornuta$, Amelanchier sp., and tall $A. rubrum$, $P. glauca$, $P. strobus$, $P. resinosa$, $P. grandidentata$, and $B. papyrifera$.

Overstory heights increase with increasing distance from the smelter as is shown by the ordination plots. Tree height classes progressively increase from site 1 to site 6 in the ordination, with the largest height classes (e.g. $P. strobus$ 20m, $P. resinosa$ 30m) being found at site 6. The species composition of the community also changes. Three species, $B. papyrifera$, $A. rubrum$ and $P. strobus$ illustrate this in Figure 4. At sites close to the smelters $B. papyrifera$ exists at low height classes; as noted above, $B. papyrifera$ is a natural colonizer of the highly degraded soils of the Sudbury area. The height of $B. papyrifera$ and $A. rubrum$ increase with distance but near site 5 $P. strobus$ also begins to characterize the sites. The height of the $P. strobus$ population also increases with distance from the smelter, until near site 6 very tall (+19 m) are detected. $P. strobus$ has been shown to be particularly sensitive to atmospheric exposure to sulphur dioxide [9].

5 Discussion

We found, unsurprisingly, that community measures such as diversity and total complexity increased with distance from a historic pollution source [19] (but see [20] showing that diversity was insensitive to pollution levels). Multivariate analyses revealed that our data were strongly structured and were extremely efficient in detecting the community-level gradients. The perturbation gradient manifests itself by a systematic alteration of species groups, tree density and vertical structure. Interestingly, the gradient would be undetectable if we were to focus on individual community components such as $Betula papyrifera$, $Deschampsia flexuosa$ and $Vaccinium angustifolium$. This phenomenon (known also as an emergent property) occurs as a result of complex and nonlinear multi-species interactions [21].

What we did find surprising was that structural complexity did not increase monotonically with a decrease in perturbation intensity. This indicates that the relationship between community-level response and perturbation intensity may not be as simple as it appears. It is here where we may be seeing interactive effects of multiple stressors on the environment [22].
abiotic factors relating to air quality and climate change will help to tease apart these relationships.

An understanding of natural recovery pathways is required for the successful restoration of sustainable ecological communities and the creation of persistent systems that provide essential ecosystem services [23,24]. Of course, what is of interest to us is the long-term dynamics, which we believe will be even more complex and provide a better understanding of recovery pathways [25,26]. In the 1970's a large-scale restoration effort took place in the Sudbury region. Almost 20% of barren lands were reclaimed at a cost of 15 million Canadian dollars through the application of lime and fertilizers and planting of grasses, legumes, (many non-native) and trees [12]. Future work will make use of this 'living laboratory' and include a long-term comparison of ecosystem complexity between communities at varying degrees of natural recovery and those artificially reclaimed through this restoration effort.

References

350  Air Pollution X


