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Experimental Techniques for Evaluating the Success of Restoration Projects

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ABSTRACT: The ecological background of a restoration project is complex and difficult to determine without experimentation. A useful context for experiments is the well-studied process of natural succession, because the factors that drive or inhibit succession are also at work during reclamation (a form of primary succession) and restoration (which often resembles secondary succession). Using experimental studies on urban wasteland reclamation, we have tested for factors that stimulate or inhibit succession during early phases of woodland development in the Northeastern United states. The emphasis has been on mutualisms (seed dispersal, pollination, and mycorrhizae) and microsite limitations in the recruitment, growth, and reproduction of woody plants. Using plantings of seeds, seedlings, and clusters of reproductively mature plants on abandoned landfills, we have observed that (1) soil microsite deficiencies lead to very poor germination (<0.1%) and seedling survival (<0.01%) of most native species; (2) seed dispersal by birds is a significant and reliable source of woody plant recruitment; however (3) proximity effects are strong, with most (up to 95%) of seed rain falling in the vicinity of planted clusters that are closest to putative seed sources; and (4) remnant natural woodlands are critical components of the recruitment process. To emphasize the last point, in one case, we found that the destruction of approximately 50% of nearby natural woodland vegetation led to a commensurate decline in seed rain. In another case, we found that the species richness of recruits was strictly limited by the species composition of nearby source plant communities, with no evidence of community enrichment by long distance dispersal over 5 years. We conclude from these results that the size and proximity of remnant natural populations are critical considerations when planning reclamation and restoration programs that rely on natural successional processes.

Key words: Reclamation, Remnant natural populations, Restoration

INTRODUCTION

Restoration ecology holds promise as a means of ecological experimentation (Bradshaw 1983, 1984, 1992, Harper 1987), and we believe that ecological experiments, conducted during restoration campaigns, can also guide reclamation and restoration programs (Robinson *et al.* 1992, Handel *et al.* 1994, Robinson and Handel 1999). Basic theories of reproductive ecology, for example, can be used to plan more effective restoration (Montalvo *et al.* 1997), and a restoration project can be evaluated to test the applicability of ecological theory by examining the contribution of reproductive ecology to community formation (Robinson and Handel 1994, Handel 1997, 1999). One of the best studied ecological phenomena is succession, and its relevance to habitat reclamation and ecological restoration has been widely discussed (e.g., Aber 1987, Ashby 1987, Robinson and Handel 1993, Parker 1997, Luken 1997). We have been studying woodland reclamation as a successional process, with emphasis on identifying similarities and differences between natural succession and land reclamation. We began by characterizing sites that had been colonized by native successional plants, and recording the species that had arrived (Robinson *et al.* 1992, Robinson and Handel 1993). Then taking those results, we designed experiments to test our observations, emphasizing recruitment dynamics, including the fates of seeds and seedlings, the spatial dynamics of natural recruitment, and the accompanying formative ecological interactions (in particular mutualisms) that one expects to develop during the course of ecosystem succession (Handel 1997). Our principal tool has been plantings of early successional woody species in arrays designed to test methods for stimulating and accelerating successional processes.

Early successional woody species in temperate northeastern North America are primarily animal-dispersed (Stapanian 1986,

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Table 1. Attributes of early successional woody plants and their usefulness in habitat reclamation and restoration

Characteristic	Usefulness
Habitat generalists	Successful in a variety of open habitats
Rapid maturity	Immediate sources of propagules
Large relative reproductive effort	Large colonization potential
Cast shade	Resist invasions by weedy herbs
Provide perching structures	Attract avian seed dispersers
Provide physiognomic complexity	Increase habitat heterogeneity
Generalist pollination	Attract multiple pollinating species
Produce and trap litter and debris	Accumulate soil organic matter

Stiles 1989), with some notable exceptions, such as members of the Salicaceae, the invasive tree *Robinia Pseudoacacia*, white ash (*Fraxinus americana*), and the coastal shrub *Baccharis halimifolia*, in the Asteraceae. As a group, they mature rapidly and channel substantial resources to early and copious fruit production, promising traits for restoring both plant and animal communities. A partial list of these and other useful attributes of these plants is given in Table 1. One potential drawback in their use for restoration is a general requirement for pollination, however pollinators appear to be at least as reliable as seed vectors, in our experience (Yurlina 1998, Mattei, unpublished data. In the following two sections, we explore some of our results, beginning with artificial seed introduction experiments, and moving to recruitment induction experiments, drawing from published work and studies in progress.

Safe site limitations that inhibit succession on derelict lands

The concept of a safe site (Harper 1977), a regeneration niche required for seeds to germinate and seedlings to survive, has particular relevance to plant succession (Bazzaz 1990) and to the use of plants in restoration and reclamation (van der Valk 1989, Bradshaw 1994, Urbanska1997). In our ongoing research into methods of rehabilitating degraded lands, such as closed landfills, we have learned that many early successional plant species, particularly animal-dispersed trees and shrubs, do not recruit naturally. direct seeding of trees and shrubs as part of the landscaping procedure.

Previous studies have indicated that certain woody species can be successfully introduced as seeds on recovering lands. In many of those cases, the goal was to establish starter vegetation on extremely poor soils (e.g., Archibold, 1979; Ashby *et al.*, 1985). Although seed collection and preparation is time-consuming, the cost is very small compared to planting nursery-grown material. In addition, woody plants grown directly from seed do not have their root systems disturbed, a severe stress that often reduces the health and growth potential of transplants (Little & Somes, 1964). However, germination and survival of woody plant seedlings are typically low. Our observations of low recruitment rates could be attributed to either to (1) a failure of seeds to arrive, (2) a failure of seeds to germinate, or (3) a failure of seedlings to establish.

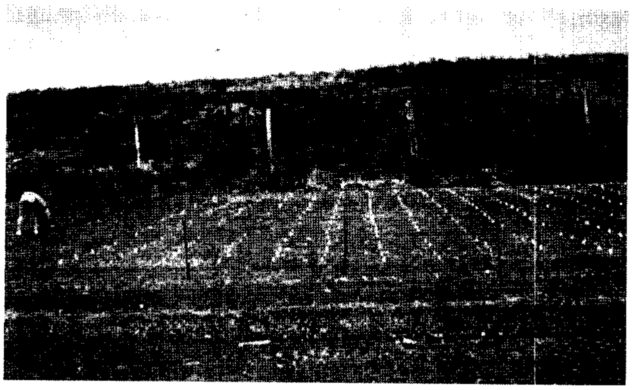

Plate 1. Site of direct seeding experiments, fenced section (September 1991). The area is a lower slope of a closed section of the Fresh Kills Landfill, Staten Island, New York. White markers are seed planting positions; 20-100 seeds of one species (depending on seed size) were planted at each position.

To test for safe site limitations, we planted seeds of 27 native woody species on a closed section of the Fresh Kills Landfill on Staten Island, New York (Plate 1). The site was a southeast-facing slope, newly covered with a cover of impermeable clay, overlain with 60 cm of coarse substrate with an upper 15 cm layer of transported soil. Prior to our seeding study, the site was planted with a sparse cover of grass (*Festuca* sp.) Seeds were collected from remnant native forests in New York, New Jersey, and Eastern Pennsylvania. Nineteen of the species can be considered early successional or pioneer plants, generally representative of formative stages of a Northeast deciduous forest, but biased toward animal-dispersed species, which typically fruit during summer and fall, the period of our collecting effort. We report here on results from trials of these 19 species.

Laboratory germination tests were conducted to establish baseline germination rates for comparison with the literature (Young & Young, 1992) and with our field trials. In our field trials, for each species collection, 10-50 seeds (depending on size and availability) were planted in 20 randomly chosen locations, ten within a fenced plot, 10 in an unfenced plot (Table 2). The amount of replication was chosen to compensate for expected heterogeneity in the newly-spread soil, and for potential soil moisture differences due to slope position. In addition to the fenced versus unfenced treatments, which examined the potential for seedling damage by rabbits (*Sylvilagus floridanus*), we studied the potential impact of seed-eating animals on buried seeds.

To test for seed predation, fifty seeds each of the19 species were placed in seed "cafeteria" trays in both fenced and unfenced areas. Seed trays were left in the field for three weeks and examined twice per week. Zero of the 1800 seeds were

Table 2. Summary of germination and survival for species tested in field germination trials. Per cent survival is the percentage of individuals that germinated which survived for the first post-germination year of the study. Mean germination and survival rates over all species pooled are statistically indistinguishable between treatments

Species	Per cent laboratory germination	Number of seeds planted	Per cent field germination		Per cent survival	
			fenced	unfenced	fenced	unfenced
Aronia arbutifolia	60.0	1500 (3)*	24.9	26.9	71.7	55.4
Betula populifolia	1.0	1000 (1)	0.2	0	0	0
Celtis occidentalis	30.0	1800 (5)	52.6	52.0	83.1	73.3
Cornus amomum	16.0	800 (3)	43.5	38.8	77.6	79.4
Cornus stolonifera	3.0	200 (2)	2.1	3.6	66.7	40.0
Fraxinus americana	4.0	400 (2)	0	1.5	0	66.7
Juniperus virginiana	3.0	500 (1)	1.6	3.6	75.0	33.3
Myrica pensylvanica	61.0	400 (2)	13.0	11.0	53.8	54.5
Prunus maritima	54.0	200 (1)	51.0	37.0	87.8	91.9
Prunus serotina	66.7	700 (3)	51.4	37.1	78.9	80.0
Rhus aromatica	43.0	500 (1)	18.8	16.4	80.9	85.4
Rhus copallina	5.0	1000 (2)	0.6	1.2	0	0
Rhus glabra	4.0	1000 (2)	1.6	1.0	25.0	20.0
Rhus typhina	10.0	500 (1)	0.4	4.8	0	0
Robinia pseudoacacia	55.0	500 (1)	0.8	2.0	50.0	20.0
Rubus allegheniensis	4.0	500 (1)	0.4	2.8	0	14.3
Rubus occidentalis	2.0	500 (1)	1.6	0.8	0	50.0
Sambucus canadensis	39.5	2000 (4)	11.8	15.1	2.5	4.0
Viburnum dentatum	0	200 (1)	3.0	0	33.3	0
Mean (+/- 1 SD)	24.3	32.5	14.7	13.5	41.4	40.4
	(25.0)	(63.3)	(19.9)	(16.5)	(16.5)	(32.9)

*Number of accessions (collection locations) in parentheses.

removed during the study period. Because seed eaters, especially small mammals, tend to feed at a given source until it is exhausted, three possible interpretations can explain these results: (1) No small mammal seed predators were present. 2) Seed eaters were present nearby, but were deterred from entering the relatively bare open site (the young grass cover was sparse). (3) Seed eaters were present, but did not detect the seed trays provided. If this were true, the local seed-eating populations were probably at low densities, since these animals are specialized at seeking and finding both buried and unburied seeds.

Despite evidence that seed predation was low, germination rates were relatively poor (Table 2). The main exception was *Sambucus canadensis*, which had moderate germination but very poor survivorship. Our observations indicate that most seedlings of this species were desiccated within weeks after germinating. Germination rates from laboratory tests correlated positively and significantly with those in the field ($R^2 = 0.352$, $p < .05$), but with considerable variance (Table 2). Overall damage to seedlings was minor in either of the two plots, although several species suffered greater apparent herbivore damage in the unfenced plot, and this is apparent in differences in survival rates for these species (Table 2).

We conclude from these safe site studies that a critical limitation to woodland reclamation occurs in the early phases of recruitment, at the seed and seedling stages, and that, given little evidence for seed predation or herbivory, the soil environment may be a primary limiting factor. Artificial seeding can be an effective technique for land reclamation (Chan *et al.* 1977, Archibold 1979), but parallels with natural succession way be weak when regeneration niches are limited. However, direct seeding by artificial means may be less effective than natural recruitment, when seed planting is guided by disperser behavior, and germination success may be enhanced by seed handling, particularly in the case of avian dispersers, (e.g., Krefting and Roe 1949). We turn now to studies that have aimed to promote woodland reclamation by employing natural seed dispersal by birds as a means to stimulate succession.

Proximity and source effects limiting recruitment on derelict lands

In two separate experiments in the New York metropolitan region, we have been testing the potential to stimulate woodland succession by "inoculating" sites with clusters of trees and shrubs, designed to spread and coalesce through recruitment. In addition to internal recruitment, we also studied the arrival of propagules from external sources by natural dispersal, primarily animal dispersal, with the planted clusters serving to attract dispersers. Our experiments draw from theories of invasion and colonization (Moody and Mack 1988, Vitousek *et al.* 1996), which predict that successful colonization of a new species can result from a series of isolated invasions by small satellite populations that eventually coalesce. Satellites form nucleation points (Yarranton and Morrison 1974, Austin 1981), which can lead to more rapid spread than a simple diffusion front (Auld and Coote 1980).

Cluster plantings for woodland reclamation, New Jersey Meadowlands

On a 6 ha section of an abandoned municipal landfill in the New Jersey Meadowlands (Plates 2, 3), we installed sixteen clusters of 21 trees and shrubs of seven native species, most with attributes noted in Table 1. Half of the plots were planted with larger trees and shrubs, to test whether woody plant size would enhance any attractive function. An additional eight plots were marked, but not planted, as controls. Recruitment of woody plants inside and surrounding the experimental plots (Plate 4) was examined for five years, and results were compared on the basis of treatment and recruitment mode (avian, wind, or clonal dispersal). A full description of the experiment can be found in Robinson and Handel (1999).

Plate 2. Site prior to experimental reclamation (March 1990). The 12 ha site is closed municipal landfill near Kearney, New Jersey, USA. The site had been abandoned for > 25 yr. The urban skyline in the background is the city of Newark, New Jersey.

We observed a strong pulse of early natural recruitment, primarily from external sources. Plots with larger plants attracted significantly more recruits at the outset, but this difference diminished over time. Mean annual seed rain densities of woody plants were 528/m^2 in planted plots, and 18/m^2 in unplanted controls plots, but seed rain densities declined away from the planted clusters in a non-linear decay. Differences between plots with clusters of large versus small plants were not statistically significant. The majority of seeds in and around planted plots were from fleshy-fruited species, whereas seeds in controls and at distances beyond 10 m from plot edges were mostly wind-dispersed species. Spread of the planted species themselves was generally weak, although clonal growth contributed substantially to spread on the margins of plots. After five years, the area outside the plots themselves contained approximately 800 woody stems ha^{-1}, 36% from avian dispersal, 10% via clonal spread, and 54% from wind dispersal. However, the bulk of all recruitment was pulsed, as seedlings after the second year increased in mean size but not density. Thus, the attractive function of the experimental plant clusters was effective, but the window of opportunity for establishment of new recruits was limited. A major probable limiting factor was the rapid growth of a dense weedy herbaceous cover (Plate 5).

A different kind of limitation was apparently due to source effects. In the first place, spatial patterns of seed arrival and seedling recruitment reflected a strong directional proximity component. This was evident in the large variance in cumulative, externally-derived seed rain densities in planted plots, which ranged from 30 to over 5,000 m^{-2}. For both wind- and bird-dispersed recruits, densities were much higher in proximity to the

Plate 3. Site preparation and planting one of sixteen clusters of native trees and shrubs (May 1991). The elevated structure in the left background is the New Jersey Turnpike.

Plate 4. Experimental planted cluster (large plant treatment) after two years' growth. The trees in the center are *Acer rubrum*, and the flowering shrub at left is *Viburnum dentatum*.

Plate 5. Experimental planted cluster (small plant treatment) after five years' growth. Note the tall, dense surrounding herbaceous vegetation.

nearest putative sources (Robinson and Handel 1999). In the second place, the species pool of external recruits was small, and quickly exhausted. Most of the new woody plant species that colonized from external sources (19/21) had arrived after two years, including virtually all (16/17) of the species found in woodland remnants within 500 m of the site. Among all colonizing species, five contributed over 90% of all recruits.

Cluster plantings for woodland reclamation, Staten Island landfill

In a separate experimental reclamation study, we planted 20 clusters of native woody plants on a steep, west-facing slope of a closed section of the Fresh Kills Landfill, Staten Island, New York (Plates 6,7). The clusters varied in size from seven to seventy plants, five clusters in each size category. Distance from a cluster to the nearest native woodland (the assumed source of external recruitment) varied from approximately 200 m to 600 m.

Plate 6. Site preparation for an experimental woody plant cluster (September 1992). In the background (down slope) is a 1.5 ha native forest remnant, the nearest source pool for externally-derived seeds of woody plants.

Plate 7. Experimental plant cluster after five years' growth. The location is mid-slope, approximately 150 m from the highway in the background. The planted trees are *Celtis occidentalis*, and the shrubs are *Amelanchier canadensis, Prunus maritima, Rhus copallina, Rosa nitida, Rubus allegheniensis*, and *Vaccinium corymbosum*.

Seed rain within plots was high, averaging over 220 m^{-2} in the first year studied, but negligible outside the clusters. Although cluster size did not affect the density of seed rain from external sources, proximity to the putative source (Plate 6) was a significant explanatory variable, with over 30% of seeds landing in the four nearest clusters.

A more interesting finding resulted from the unexpected loss of about half of the nearby remnant forest to a construction project during the second year of sampling. Seed rain fell by more than half and remained at lower levels the third year of study, suggesting that the reduction in source pools (of either seeds or seed dispersers, or both) led to commensurate losses in recruitment (Table 3). Alternate explanations cannot be ruled out, however two other pieces of evidence support a relationship between source area and seed rain. First, the number of seed species did not decline, indicating that seed movement itself continued in a qualitatively similar way. Second, a further reduction was observed in correlation with a dry growing season, indicating that the background threshold seed rain had been altered. As with our experiments in the New Jersey Meadowlands, these results emphasize the importance of natural source pools for land reclamation and habitat restoration.

Table 3. Cumulative annual seed rain (total seeds counted and seed species counted) inside the 20 experimental plant clusters over three years

Year	Seeds collected	Species collected	Notes
1994	14,400	26	
1995	5,500	33	Approx. half of source forest removed
1996	4,400	22	Drought year

DISCUSSION

The growing need for ecological restoration and other forms of land reclamation cannot be met by traditional methods of landscaping and reforestation (Woodwell 1992, Dobson *et al.* 1997, Ehrenfeld and Toth 1997). Neither can we expect natural succession to promote recovery of many degraded lands, because limits to succession are often overwhelming (Woodwell 1992), including restricted dispersal (Da Silva *et al.* 1996, Wunderle 1997, Duncan and Chapman 1999), herbivory and seed predation (Gill and Marks 1991, Handel 1997), soil deficits (Archibold 1979, Bradshaw 1983, 1984, 1992, Woodwell 1992), competition from weeds (Bradshaw 1989, Buckley and Knight 1989, Glass 1989, Berger 1993), and lack of natural source pools of colonists (Ray and Brown 1994, Parker 1997, Bastin and Thomas 1999).

Despite these well-recognized limitations, natural successional processes must be counted on to achieve large-scale and durable programs in woodland reclamation and habitat restoration in many parts of the world. Scientific studies that test the limits of natural succession will therefore be required. The growing ecological literature linking avian dispersal to succession (e.g., Finegan 1984, McDonnell 1986) and reforestation (e.g., Guevara *et al.* 1996, McClanahan and Wolfe 1987, Da Silva *et al.* 1996, Wunderle 1997) can guide many restoration and reclamation efforts (Ash *et al.* 1994, Robinson and Handel 1999). Among our findings, perhaps the most telling is the evidence of critical links between reforestation and the remnant natural landscape (see also Turner and Corlett 1996, van Aarde *et al.* 1997). Without nearby source pools that are sufficiently robust to supply colonists, an extremely valuable tool of ecological restoration - natural succession - will be lost. In other words, land reclamation and habitat restoration are inescapably dependent on the traditional conservation of natural areas.

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