Restoration Success: How Is It Being Measured?

Maria C. Ruiz-Jaen[1,2] and T. Mitchell Aide[2]

Abstract

The criteria of restoration success should be clearly established to evaluate restoration projects. Recently, the Society of Ecological Restoration International (SER) has produced a Primer that includes ecosystem attributes that should be considered when evaluating restoration success. To determine how restoration success has been evaluated in restoration projects, we reviewed articles published in *Restoration Ecology* (Vols. 1[1]–11[4]). Specifically, we addressed the following questions: (1) what measures of ecosystem attributes are assessed and (2) how are these measures used to determine restoration success. No study has measured all the SER Primer attributes, but most studies did include at least one measure in each of three general categories of the ecosystem attributes: diversity, vegetation structure, and ecological processes. Most of the reviewed studies are using multiple measures to evaluate restoration success, but we would encourage future projects to include: (1) at least two variables within each of the three ecosystem attributes that clearly related to ecosystem functioning and (2) at least two reference sites to capture the variation that exist in ecosystems.

Key words: **diversity, ecological processes, ecosystem attributes, replication, restoration success, vegetation structure.**

Introduction

"Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004). The ultimate goal of restoration is to create a self-supporting ecosystem that is resilient to perturbation without further assistance (Urbanska et al. 1997; SER 2004). But how do we know when we have reached that goal? Various authors have suggested that restoration success could be based on vegetation characteristics (Walters 2000; Wilkins et al. 2003), species diversity (van Aarde et al. 1996; Reay & Norton 1999; Passell 2000; McCoy & Mushinsky 2002), or ecosystem processes (Rhoades et al. 1998). Other authors have promoted a more integrated approach that includes many variables to provide a better measure of restoration success (Hobbs & Norton 1996; Neckles et al. 2002; SER 2004).

The Society of Ecological Restoration International (SER) (2004) produced a Primer that provides a list of nine ecosystem attributes as a guideline for measuring restoration success. They suggested that a restored ecosystem should have the following attributes: (1) similar diversity and community structure in comparison with reference sites; (2) presence of indigenous species; (3) presence of functional groups necessary for long-term stability; (4) capacity of the physical environment to sustain reproducing populations; (5) normal functioning; (6) integration with the landscape; (7) elimination of potential threats; (8) resilience to natural disturbances; and (9) self-sustainability. Although measuring these attributes could provide an excellent assessment of restoration success, few studies have the financial resources to monitor all these attributes. Furthermore, estimates of many attributes often require detailed long-term studies, but the monitoring phase of most restoration projects rarely lasts for more than 5 years.

In practice, most studies assessed measures that can be categorized into three major ecosystem attributes. These attributes are (1) diversity; (2) vegetation structure; and (3) ecological processes. Diversity is usually measured by determining richness and abundance of organisms within different trophic levels (Nichols & Nichols 2003; Weiermans & van Aarde 2003). In addition, it is useful to determine the diversity of species within different functional groups because this information provides an indirect measure of ecosystem resilience (Peterson et al. 1998). Vegetation structure is usually determined by measuring vegetation cover (e.g., herbs, shrubs, trees), woody plant density, biomass, or vegetation profiles (Salinas & Guirado 2002; Kruse & Groninger 2003; Wilkins et al. 2003), and these measures are useful for predicting the direction of plant succession. Ecological processes such as nutrient cycling and biological interactions (e.g., mycorrhizae, herbivory) are important because they provide information on the resilience of the restored ecosystem. For example, nutrient cycling determines how much organic and inorganic components are available for organisms to persist in an ecosystem (Davidson et al. 2004; Feldpausch et al. 2004). Nutrient cycling is usually measured indirectly by estimating nutrient availability (Fuhlendorf et al. 2002). The recovery of biological interactions is also critical for the long-term function of

[1] Address correspondence to Maria C. Ruiz-Jaen, email mcruizjaen@gmail.com
[2] Department of Biology, University of Puerto Rico–Rio Piedras, P.O. Box 23360, San Juan, Puerto Rico 00931-3360.

a restored ecosystem. In many systems, poor seed dispersal is a major limiting factor for forest recovery (Holl et al. 2000; Donath et al 2003; White et al. 2004) and is often assessed by measuring seedling density and diversity (Whisenant et al. 1995; Vallauri et al. 2002). The evaluation of diversity, vegetation structure, and ecological processes can reflect the recovery trajectory and self-maintenance of restored ecosystems.

In addition to evaluating these attributes in the restored site, it is necessary to compare them with values from reference sites to estimate the level of restoration success (Passell 2000; Purcell et al. 2002; SER 2004). Reference sites should occur in the same life zone, close to the restoration project, and should be exposed to similar natural disturbances (Hobbs & Harris 2001; SER 2004). Moreover, it is important to consider the variation that occurs among reference sites; thus, more than one reference site should be used for estimating restoration success (Hobbs & Norton 1996; SER 2004). Including reference sites will increase restoration costs, but they are essential for evaluating restoration success.

The goal of this paper is to review how restoration success has been evaluated in restoration projects and compare these results with the SER guidelines. Specifically, we addressed the following questions: (1) what measures of ecosystem attributes are assessed and (2) how are these measures used to determine restoration success. To address these questions, we reviewed all restoration studies published during the first 11 years (1993–2003) of Restoration Ecology.

Methods

We evaluated all articles published in *Restoration Ecology* (Vols. 1[1]–11[4]). We only considered articles that used seeding or planting techniques to assist the restoration process and whose main objective was to restore a site or evaluate restoration success. We categorized the measures assessed in these articles into three categories of ecosystem attributes: diversity, vegetation structure, and ecological processes. Articles with the main objective of comparing different restoration techniques were not included in this review.

For each article, we determined the geographic region and classified habitat type (e.g., conifers, grasslands, wetlands), previous land use (e.g., agriculture, deforestation, mining), and restoration technique (e.g., seeding or planting). In addition, we determined which measures of the three ecosystem attributes were assessed. Specifically, measures of diversity included richness or composition of microbes, fungi, plants, invertebrates, and vertebrates, as well as tropic guilds. Measures of vegetation structure included vegetation cover, woody density, vegetation height, basal area, biomass, and litter structure (e.g., number of litter layers, cover, or biomass). Measures of ecological processes included nutrient pools, soil organic matter (e.g., quantity or carbon isotopic composition), and biological interactions (e.g., herbivory, mycorrhizae, pollination, predation, parasitism). In practice, most measures of ecological processes are one-time measurements or indicators of these processes. In addition, we classified the statistical analyses used to determine restoration success. Statistical analyses were classified into four categories: group comparison (e.g., analysis of variance [ANOVA], *t* test, Kruskall–Wallis), ordinations (Detrended Correspondence Analysis [DCA], Canonical Correspondence Analyses [CCA], cluster analysis), indexes (e.g., Shannon–Weiner, Jaccard, Bray Curtis), and linear comparison (e.g., regression, correlation, time trajectories). We also documented the number of restored and reference sites. Replicates were independent sites and not plots or treatments within a site.

Results

Of the 468 articles analyzed, only 68 studies evaluated restoration success after seeding or planting (Table 1). The majority of these studies were carried out in North America (53%), but there were also studies from Australia (19%), Europe (16%), Africa (4%), South America (4%), and Asia (3%; Table 1). Wetlands were the habitat most frequently studied (19%), followed by grassland (16%) and montane forest (13%). Previous land use was mainly mining (36%) or agriculture (18%). The most frequently used restoration technique was planting seedlings (56%), followed by direct seeding (31%), but some studies used both techniques (13%). Two studies (3%) only measured one ecosystem attribute, diversity. Forty studies (59%) measured two ecosystem attributes (28 measured diversity and vegetation structure, 6 measured diversity and ecological processes, and 6 measured vegetation structure and ecological processes). Twenty-six studies (38%) measured three ecosystem attributes.

Diversity

Plant (79%) and arthropod (35%) richness were the most common measures of diversity recovery (Table 1). The majority of the studies measured only one group of organisms (61%). In addition, some of these studies assigned species to functional groups. For example, Kindscher and Tieszen (1998) defined plant guilds in terms of photosynthetic pathways to evaluate succession in prairies after agriculture abandonment. Williams (1993) and Longcore (2003) used arthropod trophic guilds to assess restoration success. Other studies included multiple taxa. For example, van Aarde et al. (1996) evaluated the recovery of a coastal dune in South Africa by measuring seedlings, millipedes, beetles, birds, rodents, and shrews. Nichols and Nichols (2003) measured ants, reptiles, birds, and mammals for the recovery of the jarrah forest after mining in Australia.

Vegetation Structure

Plant cover (62%), density (58%), biomass (39%), and height (39%) were the most common measures of vegetation structure (Table 1). Most studies only included one or two measures of vegetation structure (69%) and 31% included three or more measures. For example, Parrota and Knowles (1999) used crown cover, plant density, tree basal area, canopy height, and litter depth to measure recovery of a tropical moist forest followed mining. Similarly, Clewell (1999) used vegetation cover, density, height, and tree basal area to measure the recovery of riparian forest after mining.

Ecological Processes

Measures of biological interactions (60%) were the most common ecological processes, followed by nutrient pools (47%) and soil organic matter (39%; Table 1). The presence of mycorrhizae was measured in many studies, and was classified as a biological interaction. For example, Moynahan et al. (2002) quantified arbuscular mycorrhizae colonization after liming and revegetation in abandoned metal-contaminated mines. Other biological interactions such as herbivory, dispersal, pollination, predation, or parasitism were mostly measured indirectly. For example, Reay and Norton (1999) indirectly measured bird dispersal by quantifying bird-dispersed seedlings in restored grassland in New Zealand. Some studies included very detailed measures of ecosystem processes. For example, Rhoades et al. (1998) used soil nitrogen, soil organic matter, organic carbon, and litter dynamics to measure the recovery of soil and abiotic conditions of a tropical montane forest in Ecuador.

Statistical Analyses

Restoration success was commonly evaluated by using group comparisons (e.g., ANOVA, *t* test; 56%), ordinations (34%), or linear comparisons (34%; Table 1). For example, McKee and Faulkner (2000) measured the recovery of biogeochemical functions in different types of mangroves in two restoration sites and compared them with two reference sites using ANOVA. Ordination was mostly used in studies that included the recovery of diversity. For example, Watts and Gibbs (2002) used DCA to measure community composition of ground-dwelling beetles in prairies with different vegetation structure in New Zealand. A useful way to evaluate restoration success is by comparing the trajectory of recovery of different variables through time with reference sites. For example, Morgan and Short (2002) considered a measure to have recovered if its value was within the 95% confidence interval in the reference site.

Most studies included more than one restored site (68%), and restoration success was determined by comparing ecosystems attributes with reference sites (70%) and usually with more than one reference sites (67%; Table 1). Studies that were not replicated usually made multiple measurements through time to demonstrate the recovery trajectory (Zedler & Callaway 1999; Craft et al. 2002; Germaine & Germaine 2002).

Discussion

Study Region

The majority of studies published in *Restoration Ecology* were conducted in North America (mainly United States), Australia, and Europe. This geographic bias is not because these areas are necessarily more degraded, but these countries have environmental laws that are often enforced and financial resources to conduct these projects. For example, nearly 60% of the review studies were done to comply with laws (e.g., Clean Water Act, U.S.A.; National Environment Protection Measures Act, Australia). Existing laws usually do not include requirements for comparison with reference sites. If laws do not require replication or reference sites, it is unlikely that they will be incorporated into future projects, given the increase in monitoring costs. Restoration ecologists should incorporate reference sites, more detailed methods of restoration success (e.g., ecosystem attributes), and lobby to include these methods in policy.

Diversity

Although plants are the most measured group, some studies of diversity included data on fauna. Invertebrates are often included because they represent many different functional groups (e.g., pollinators and decomposers; Holl 1995; Majer 1997; Longcore 2003) and because they play a critical role in nutrient cycling (Tian et al. 1997). Vertebrates were included when wildlife recovery was the major motivation of the restoration project (George & Zack 2001; Morrison 2002; Nichols & Nichols 2003). Furthermore, vertebrates are more frequently studied than plants or invertebrates in conservation biology projects, reflecting differences in motives and funding sources (Clark & May 2002). Although debates will continue on what groups will provide the best measure of restoration success (MacMahon & Holl 2001), it is important to consider more than one group of organisms and preferably groups in different trophic levels (Parmenter & MacMahon 1992; Nichols & Nichols 2003).

Vegetation Structure

All studies evaluated at least the recovery of vegetation structure or diversity after restoration (Table 1), in part, because laws requiring restoration always include vegetation monitoring (Allen 1992). Another reason why vegetation characteristics are always included is that it is assumed that the recovery of fauna and ecological processes will follow the establishment of vegetation (Toth et al. 1995; Young 2000). For example, there is a strong

Table 1. Characteristics of 68 restoration studies published in *Restoration Ecology* between 1993 and 2003.

				Diversity					*Vegetation Structure*					*Ecological Processes*			*Statistical analysis*				*Replication*		
GeoRe	*Habitat*	*PreUse*	*Techn*	*Plant*	*Arth*	*Bird*	*Othr*	*Guild*	*Cover*	*Density*	*BioM*	*Height*	*Litter*	*BioInt*	*NutPo*	*SOM*	*GC*	*Ord*	*LC*	*Ind*	*Rest*	*Refe*	*Authors*
One ecosystem attribute																							
NA	Grass	Agr	Sdl	X														X	X	X	13	2	Sluis (2002)
NA	Ripar	Culve	Sdl	X	X																1	1 (1)	Purcell et al. (2002)
Two ecosystem attributes																							
AUS	Dunes	Transp	Sdl	X	X				X	X							X	X			5	5	Webb et al. (2000)
EUR	MonF	Mine	Sdl	X	X							X									6	1	Tajovsky (2001)
AFR	Dunes	Mine	Sd	X	X	X	X	X	X			X						X			3	1	Weiermans and van Aarde (2003)
AFR	Dunes	Mine	Sd	X	X	X	X	X		X		X								X	6	2	van Aarde et al. (1996)
NA	Conif	Agr	Sdl	X	X			X	X	X	X		X					X			1	2	Willet (2001)
NA	DryF	Transp	Sd/Sdl	X	X			X	X	X		X					X	X	X	X	4	7 (4)	Longcore (2003)
EUR	Grass	Mine	Sd	X	X			X		X							X			X	5		Cullen and Wheater (1993)
EUR	Grass	Transp	Sd	X					X												16		Andres et al. (1996)
NA	Wetld	Mil	Sd	X					X									X			2	6	Parikh and Gale (1998)
NA	Ripar	Defo	Sd	X		X			X			X					X				5		Kus (1998)
NA	DryF	Dam	Sd/Sdl	X			X		X	X							X			X	1	1	Patten (1997)
NA	Decid	Defo	Sdl	X					X		X						X				1		Larson (1996)
NA	Wetld	Transp	Sdl	X					X		X							X			2	3	Forbes (1993)
NA	MonF	Agr	Sdl	X					X	X		X					X		X		8		Kruse and Groninger (2003)
NA	Wetld	Mine	Sd/Sdl	X					X	X							X		X		6	6	Cooper and MacDonald (2000)
AUS	Grass	Agr	Sd	X					X	X		X	X				X	X	X	X	5	2 (2)	Wilkins et al. (2003)
EUR	Ripar	Defo	Sdl	X					X	X							X			X	2	2	Salinas and Guirado (2002)
AUS	WetTep	Dam	Sdl	X						X	X						X				2	1	Smale et al. (2001)
EUR	Grass	Agr	Sd	X							X								X		1		Kleijn (2003)
ASIA	Wetld	Defo	Sdl	X						X	X	X					X				29	5	Walters (2000)
SA	WetTro	Mine	Sd/Sdl	X						X	X	X	X				X			X	3	1 (1)	Parrota and Knowles (1999)
AUS	DryF	Mine	Sd	X						X							X				1		Ward et al. (1996)
AUS	DryF	Mine	Sd	X				X	X	X							X		X	X	4	1 (2)	Grant and Loneragan (2003)
AUS	Grass	Pastu	Sd/Sdl		X				X	X							X				1		O'Dwyer and Attiwill (2000)
AUS	DryF	Mine	Sd/Sdl		X			X	X			X	X					X			6	2	Andersen (1993)
AUS	Grass	Mine	Sd		X			X	X			X	X					X		X	7	3	Bisevac and Majer (1999)
ASIA	WetTro	Mine	Sdl			X						X					X			X	8	7 (4)	Passell (2000)
AUS	Prairie	Agr	Sdl		X			X	X	X		X	X					X		X	3	1	Watts and Gibbs (2002)
NA	Conif	Agr	Sdl	X	X									X			X				1	1	Meyer and Sisk (2001)
NA	Grass	Defo	Sd	X	X									X			X		X		10	11	Leong and Bailey (2000)
NA	MonF	Mine	Sdl	X	X									X					X		18	5	Holl (1995)
AUS	WetTro	Mine	Sd	X	X		X									X			X		17	18	Andersen and Sparling (1997)

Table 1. (Continued)

NA	Decid	Pastu	Sdl	X		X								X			X				1	1	Germaine and Germaine (2002)
EUR	Alpine	Defo	Sdl	X										X			X				1		Urbanska and Fattorini (2000)
SA	MonF	Pastu	Sdl						X	X	X	X	X		X	X			X		1		Rhoades et al. (1998)
NA	Wetld	Dre/Dis	Sdl						X	X	X				X	X	X				2	1	Sheridan et al. (1998)
NA	Decid	Mine	Sdl						X		X	X		X	X	X	X		X		4		Helm (1994)
EUR	Grass	PowS	Sd						X						X		X	X			2		Shaw (1996)
NA	Wetld	Mine	Sdl								X				X	X	X		X		1	1	Craft et al. (2002)
NA	Wetld	Transp	Sdl								X				X	X			X		1	1	Zedler and Callaway (1999)
Three ecosystem attributes																							
NA	Wetld	Pastu	Sdl	X	X		X		X					X						X	1	1	Tanner et al. (2002)
AUS	DryF	Mine	Sdl	X	X	X	X	X		X		X		X				X	X	X	2	2	Nichols and Nichols (2003)
AUS	WetTro	Transp	Sdl	X	X			X		X			X	X			X				3	2	Jansen (1997)
NA	DryF	Pastu	Sdl	X					X	X	X	X		X	X	X					1		Whisenant et al. (1995)
NA	Wetld	Defo	Sdl	X						X	X	X	X	X	X						2	2	McKee and Faulkner (2000)
NA	Wetld	Mine	Sd/Sdl	X					X	X	X	X			X	X					1	27	Clewell (1999)
AFR	Dunes	Mine	Sdl	X						X					X	X	X			X	4	2, 1	van Aarde et al. (1998)
EUR	Grass	Mine	Sd	X					X		X				X		X	X		X	1		Chapman and Younger (1995)
NA	Decid	Agr	Sdl	X		X			X	X		X		X			X	X		X	13, 7		Twedt et al. (2002)
NA	Conif	Agr	Sdl	X		X			X	X	X		X	X				X			28	5	Houseman and Anderson (2002)
EUR	Conif	Ero	Sdl	X			X			X		X		X			X				85		Vallauri et al. (2002)
SA	MonF	Transp	Sd	X			X			X				X			X				15		Rosales et al. (1997)
NA	Wetld	Agr	Sdl	X						X	X			X			X	X	X		3	6	Shear et al. (1996)
NA	Wetld	Transp	Sdl	X					X	X						X		X	X		6	11	Morgan and Short (2002)
NA	Conif	Mil	Sd/Sdl	X					X		X	X		X			X				1	1	Fimbel and Kuser (1993)
NA	Prairie	Agr	Sd	X				X	X	X					X	X	X	X			2	2	Kindscher and Tieszen (1998)
NA	Prairie	Agr	Sd	X				X							X	X			X		4	1	Fuhlendorf et al. (2002)
NA	MonF	Mine	Sd	X				X	X		X				X	X	X			X	2	1	Chambers et al. (1994)
AUS	MonF	Pastu	Sdl		X				X				X	X				X	X	X	3	2 (1)	Reay and Norton (1999)
NA	Wetld	Mine	Sdl		X	X		X	X					X				X	X	X	18		Mulyani and DuBowy (1993)
NA	Ripar	Defo	Sdl		X			X	X			X		X			X				1	1	Williams (1993)
EUR	MonF	Mine	Sdl				X			X	X				X	X		X	X		6	1 (1)	Pizl (2001)
NA	MonF	Mine	Sd/Sdl				X						X		X	X			X		1		Allen (1993)
NA	Prairie	Mine	Sd				X				X			X	X		X				1		Corbett et al. (1996)
NA	Conif	Mine	Sd				X		X					X	X			X	X		1	1	Moynahan et al. (2002)
EUR	Grass	Pastu	Sdl				X			X	X			X			X				3	4 (1)	Greipsson and El-Mayas (2000)
			Total	49	22	9	13	16	37	34	23	23	12	23	18	15	38	23	23	20			

Geographic region (GeoRe): AFR = Africa; AUS = Australia; EUR = Europe; NA = North America; SA = South America.
Habitat: Decid = deciduous forest; Conif = coniferous forest; DryF = dry or coastal forest; Grass = grassland or savana; MonF = montane forest; Ripar = riparian forest; Wetld = wetlands or mangroves; WetTep = wet temperate; WetTro = wet tropics.
Previous use (PreUse): Agr = agriculture; Culve = culverts construction; Defo = deforestation; Dre/Dis = dredging and discharges; Mil = military practices; Nat = natural disturbance; Pastu = pastures; PowS = power stations; Transp = transportation development.
Restoration Technique (Techn): Sd = seeds; sdl = seedlings; Sd/Sdl = seeds and seedlings.
Diversity: Arth = arthropods; Othr = microbes, fungi, earthworms, reptiles, small mammals, or fish; Guild = guilds or trophic levels.
Vegetation structure: cover = plant cover; Density = plant Density; BioM = plant biomass or basal area; Litter = litter layers, cover, biomass, or production.
Ecological processes: BioInt (biological interactions) = herbivory, mycorrhizae, pollination, predation, seed dispersal, parasitism, or competition; NutPo = nutrient pools; SOM = soil organic matter or carbon isotopic composition.
Statistical analyses: group comparison (GC) = ANOVA, Kruskall–Wallis, *t* test, Mann–Whitney, chi-square, or Fisher exact test. Ordination (Ord) = CCA, DCA, nonmetric multidimensional scaling (NMS), principal components scaling (PCA), cluster analysis, dendrograms, or multi-response permutation procedures (MRPP). Indexes (Ind): Diversity indexes or similarity indexes. Linear comparison (LC) = Correlation, General Linear Models, regression, time trajectories.
Replication: Rest = number of restored sites; Ref = number of reference sites. The number in parenthesis represent control sites (e.g., prerestored conditions or areas of natural regeneration).

correlation between vegetation structure (e.g., height, foliage layers, and basal area) and the recovery of birds (Tilghman 1987; George & Zack 2001). Similarly, development of structural complexity enhanced seed dispersal and nutrient availability (Robinson & Handel 1993; Bradshaw 1997; Rhoades et al. 1998). Another reason for including plants as measures of restoration success is that measures associated with vegetation structure are easy and rapid to measure, and usually there is little seasonal variation in these measures. In contrast, to measure the recovery of the bird community in a site, it is important to take into consideration the seasonal variability of a site (Martin & Karr 1986; Lefebvre & Poulin 1996; Holmes & Sherry 2001). Similarly, measurements of productivity or decomposition will require at least a year of monitoring because of their seasonal variation.

Ecological Processes

Ecological processes were not measured as frequently as measures of diversity or vegetation structure. Studies that include ecological processes usually evaluated presence of mycorrhizae or nutrient pools. Most studies measured mycorrhizae colonization because they can significantly affect plant growth and patterns of succession after a disturbance (Haselwandter 1997). Including measurement of mycorrhizae and nutrient cycling (e.g., decomposition, mineralization, immobilization, or soil organic matter turnover) will improve the evaluation of restoration studies.

Ecological processes are rarely measured because they are slower to recover in comparison with diversity or vegetation structure (Chambers et al. 1994; Kindscher & Tieszen 1998; Morgan & Short 2002). For example, the recovery of soils after mining requires long-term monitoring (e.g., more than 15 years) to achieve values similar to those of reference sites (Allen 1993; Chambers et al. 1994; Craft et al. 2002). In addition, ecological processes require multiple measurements, which can increase the time and cost of a project (Chambers et al. 1992; Herrick 2000). For these reasons, most studies only make one-time measurements or use indicators of ecological processes.

Statistical Analyses

The analyses used to evaluate restoration success depended on the project design. For example, experimental projects used ANOVA to test differences among restoration techniques. In contrast, descriptive projects mainly used ordinations or diversity indexes to compare restoration sites with reference sites. Ordinations or similarity indices can be more useful in describing species composition in community ecology because these analyses compared species composition, not just richness (McCune & Grace 2002). Another approach for analyzing restoration success is using recovery trajectories (Chambers et al. 1994; Craft et al. 2002; Morgan & Short 2002; Nichols & Nichols 2003). This approach graphically shows changes in variables through time in restored sites in comparison with values of reference sites. For example, Craft et al. (2002) showed trajectories of the belowground biomass in created brackish water marshes by measuring plant biomass in both restored and reference sites every 2 years over a 12-year period. This approach provides a good measure of restoration success, but studies should also consider interannual variation and nonlinear responses (see Zedler & Callaway 1999, for more details). In addition, most studies compared restoration success with one or more reference sites to capture the dynamics and variability in natural systems.

How Do These Results Compare with the SER Primer on Ecological Restoration?

In practice, no study has measured all the SER Primer attributes, but most studies did include the general categories of the attributes evaluated in this review: diversity, vegetation structure, and ecological processes. These three attributes incorporate several of the attributes listed in the Primer, but three Primer attributes are rarely measured in restoration projects. These attributes include the capacity of the physical environment to sustain reproducing populations, the integration with the landscape, and self-sustainability. These attributes require either data collection outside the study area or long-term evaluation. For example, various authors have argued the importance of integrating landscape characteristics (Naveh 1994, 1998; Aronson & Le Floc'h 1996; Radeloff et al. 2000), but the additional burden appears to limit the incorporation of a landscape attribute. Similarly, few studies measure reproducing population or evaluate self-sustainability of ecosystems because these are long-term attributes that can rarely be measured in the time frame of most restoration projects.

Ideally, all projects would follow the SER Primer guidelines and include information on the nine attributes, but a more realistic goal is to promote the measurement of at least diversity, vegetation structure, and ecological processes. These three attributes are essential for the long-term persistence of an ecosystem (Elmqvist et al. 2003; Dorren et al. 2004), but the specific measures of these attributes will vary depending on the ecosystem and the goals of a restoration project. Nevertheless, at least two variables within each of the three ecosystem attributes that clearly related to ecosystem functioning should be included to evaluate restoration success. In addition, the criteria to evaluate restoration success should be based on a comparison with more than one reference site to provide the temporal and spatial dynamics of ecosystems.

Acknowledgments

This study was funded by NASA-IRA and a graduate fellowship from the Dean's Office of Graduate and Research Studies of the University of Puerto Rico. The comments of Miguel Acevedo, Jeanne Chambers, Viki Cramer, Richard Hobbs, Neftali Ríos, Elsie Rivera-Ocasio, and two anonymous reviewers improved the manuscript.

LITERATURE CITED

Allen, E. B. 1992. Evaluating community-level processes to determine reclamation success. Pages 47–58 in J.C. Chambers, and G. L. Wade, editors. Evaluating reclamation success: the ecological considerations. General Technical Report NE 164, Northeastern Forest Experimental Station, United States Department of Agriculture Forest Service, Radnor, Pennsylvania.

Allen, M. F. 1993. Microbial and phosphate dynamics in a restored shrub steppe in southwestern Wyoming. Restoration Ecology **1:** 196–205.

Andersen, A. N. 1993. Ants as indicators of restoration success at a uranium mine in tropical Australia. Restoration Ecology **1:**156–167.

Andersen, A. N., and G. P. Sparling. 1997. Ants as indicators of restoration success: relationship with soil microbial biomass in the Australian seasonal tropics. Restoration Ecology **5:**109–114.

Andres, P., V. Zapater, and M. Pamplona. 1996. Stabilization of motorway slopes with herbaceous cover, Catalonia, Spain. Restoration Ecology **4:**51–60.

Aronson, J., and E. Le Floc'h. 1996. Vital landscape attributes: missing tools for restoration ecology. Restoration Ecology **4:**377–387.

Bisevac, L., and J. D. Majer. 1999. Comparative study of ant communities of rehabilitated mineral sand mines and heathland, western Australia. Restoration Ecology **7:**117–126.

Bradshaw, A. D. 1997. The importance of soil ecology in restoration science. Pages 33–64 in K. M. Urbanska, N. R. Webb, and P. J. Edwards, editors. Restoration ecology and sustainable development. University Press, Cambridge, United Kingdom.

Chambers, J. C., R. W. Brown, and B. D. Williams. 1994. An evaluation of reclamation success on Idaho's phosphate mines. Restoration Ecology **2:**4–16.

Chambers, J. C., J. A. MacMahon, and G. L. Wade. 1992. Differences in successional processes among biomes: importance in obtaining and evaluating reclamation success. Pages 59–72 in J. C. Chambers, and G. L. Wade, editors. Evaluating reclamation success: the ecological considerations. General Technical Report NE 164, Northeastern Forest Experimental Station, United States Department of Agriculture Forest Service, Radnor, Pennsylvania.

Chapman, R., and A. Younger. 1995. The establishment and maintenance of a species-rich grassland on a reclaimed opencast coal site. Restoration Ecology **3:**39–50.

Clark, J. A., and R. M. May. 2002. Taxonomic bias in conservation research. Science **297:**191–192.

Clewell, A. F. 1999. Restoration of riverine forest at Hall Branch on phosphate-mined land, Florida. Restoration Ecology **7:**1–14.

Cooper, D. J., and L. H. MacDonald. 2000. Restoring the vegetation of the peatlands in the southern rocky mountains of Colorado, U.S.A. Restoration Ecology **8:**103–111.

Corbett, E. A., R. C. Anderson, and C. S. Rodgers. 1996. Prairie revegetation of a stripmine in Illinois: fifteen years after establishment. Restoration Ecology **4:**346–354.

Craft, C., S. Broome, and C. Campbell. 2002. Fifteen years of vegetation and soil development after brackish-water marsh creation. Restoration Ecology **10:**248–258.

Cullen, W. R., and C. P. Wheater. 1993. The flora and invertebrate fauna of a relocated grassland at Thrislington Plantation, County Durham, England. Restoration Ecology **1:**130–137.

Davidson, E. A., C. J. R. de Carvalho, I. C. G. Vieira, R. D. Figueiredo, P. Moutinho, F. Y. Ishida, M. T. P. dos Santos, J. B. Guerrero, K. Kalif, and R. T. Saba. 2004. Nitrogen and phosphorus limitation of biomass growth in a tropical secondary forest. Ecological Applications **14:**S150–S163.

Donath, T. W., N. Holzel, and A. Otte. 2003. The impact of site conditions and seed dispersal on restoration success in alluvial meadows. Applied Vegetation Science **6:**13–22.

Dorren, L. K. A., F. Berger, A. C. Imeson, B. Maier, and F. Rey. 2004. Integrity, stability, and management of protection forests in the European Alps. Forest Ecology and Management **195:**165–176.

Elmqvist, T., C.. Folke, M. Nystrom, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg. 2003. Response diversity, ecosystem change, and resilience. Frontiers in Ecology and the Environment **1:**488–494.

Feldpausch, T. R., M. A. Rondon, E. C. M. Fernandes, S. J. Riha, and E. Wandelli. 2004. Carbon and nutrient accumulation in secondary forests regenerating on pastures in central Amazonia. Ecological Applications **14:**S164–S176.

Fimbel, R. A., and J. E. Kuser. 1993. Restoring the pygmy pine forests of New Jersey's pine barrens. Restoration Ecology **1:**117–129.

Forbes, B. C. 1993. Small-scale wetland restoration in the high Artic: a long-term perspective. Restoration Ecology **1:**59–68.

Fuhlendorf, S. D., H. Zhang, T. R. Tunnell, D. M. Engle, and A. F. Cross. 2002. Effects of grazing on restoration of southern mixed prairie soils. Restoration Ecology **10:**401–407.

George, T. L., and S. Zack. 2001. Spatial and temporal considerations in restoring habitat for wildlife. Restoration Ecology **9:**272–279.

Germaine, H. L., and S. S. Germaine. 2002. Forest restoration treatment effects on the nesting success of western bluebirds (*Sialia mexicana*). Restoration Ecology **10:**362–367.

Grant, C. D., and W. A. Loneragan. 2003. Using dominance-diversity curve to assess completion criteria after bauxite mining rehabilitation in western Australia. Restoration Ecology **11:**103–115.

Greipsson, S., and H. El-Mayas. 2000. Arbuscular mycorrhizae of *Leymus arenarius* on coastal sands and reclamation sites in Iceland and response to inoculation. Restoration Ecology **8:**144–150.

Haselwandter, K. 1997. Soil micro-organisms, mycorrhiza, and restoration ecology. Pages 65–80 in K. M. Urbanska, N. R. Webb, and P. J. Edwards, editors. Restoration ecology and sustainable development. University Press, Cambridge, United Kingdom.

Helm, D. J. 1994. Establishment of moose browse on four growth media on a proposed mine site in south central Alaska. Restoration Ecology **2:**164–179.

Herrick, J. E. 2000. Soil quality: indicator of sustainable land management? Applied Soil Ecology **15:**75–83.

Hobbs, R. J., and J. A. Harris. 2001. Restoration ecology: repairing the earth's ecosystems in the new millennium. Restoration Ecology **9:**239–246.

Hobbs, R. J., and D. A. Norton. 1996. Towards a conceptual framework for restoration ecology. Restoration Ecology **4:**93–110.

Holl, K. D. 1995. Nectar resources and their influence on butterfly communities on reclaimed coal surface mines. Restoration Ecology **3:**76–85.

Holl, K. D., M. E. Loik, E. H. V. Lin, and I. A. Samuels. 2000. Tropical montane forest restoration in Costa Rica: overcoming barriers to dispersal and establishment. Restoration Ecology **8:**339–349.

Holmes, R. T., and T. W. Sherry. 2001. Thirty-year bird population trends in an unfragmented temperate deciduous forest: importance of habitat change. The Auk **118:**589–609.

Houseman, G. R., and R. C. Anderson. 2002. Effects of jack pine plantation management on barrens flora and potential Kirkland's warbler nest habitat. Restoration Ecology **10:**27–36.

Jansen, A. 1997. Terrestrial invertebrate community structure as an indicator of the success of a tropical rainforest restoration project. Restoration Ecology **5:**115–124.

Kindscher, K., and L. L. Tieszen. 1998. Floristic and soil organic matter changes after five and thirty-five years of native tallgrass prairie restoration. Restoration Ecology **6:**181–196.

Kleijn, D. 2003. Can establishment characteristics explain the poor colonization success of late successional grassland species on ex-arable land? Restoration Ecology **11:**131–138.

Kruse, B. S., and J. W. Groninger. 2003. Vegetative characteristics of recently reforested bottomlands in the lower Cache River watershed, Illinois, U.S.A. Restoration Ecology **11:**273–280.

Kus, B. E. 1998. Use of restored riparian habitat by the endangered Least Bell's Vireo (*Vireo bellii pusillus*). Restoration Ecology **6:**75–82.

Larson, D. W. 1996. Brown's: an early gravel pit forest restoration project, Ontario, Canada. Restoration Ecology **4:**11–18.

Lefebvre, G., and B. Poulin. 1996. Seasonal abundance of migrant birds and food resources in Panamanian mangrove forests. Wilson Bulletin **108:**748–759.

Leong, J. M., and E. L. Bailey. 2000. The incidence of a generalist thrips herbivore among natural and translocated patches of an endangered vernal pool plant, *Blennosperma bakeri*. Restoration Ecology **8:**127–134.

Longcore, T. 2003. Terrestrial arthropods as indicators of ecological restoration success in coastal sage scrub (California, U.S.A.). Restoration Ecology **11:**397–409.

MacMahon, J. A., and K. D. Holl. 2001. Ecological Restoration: a key to conservation biology's future. Pages 245–270 in M. E. Soulé, and G. H. Orians, editors. Conservation biology: research priorities for the next decade. Island Press, Washington, D.C.

Majer, J. D. 1997. Invertebrates assist the restoration process: an Australian perspective. Pages 212–237 in K. M. Urbanska, N. R. Webb, and P. J. Edwards, editors. Restoration ecology and sustainable development. University Press, Cambridge, United Kingdom.

Martin, T. E., and J. R. Karr. 1986. Temporal dynamics of neotropical birds with special reference to frugivores in second-growth woods. Wilson Bulletin **98:**38–60.

McCoy, E. D., and H. R. Mushinsky. 2002. Measuring the success of wildlife community restoration. Ecological Applications **12:**1861–1871.

McCune, B., and J. B. Grace. 2002. Analysis of ecological communities. MjM Software Design, Gleneden Beach, Oregon.

McKee, K. L., and P. L. Faulkner. 2000. Restoration of biogeochemical function in Mangrove forest. Restoration Ecology **8:**247–259.

Meyer, C. L., and T. D. Sisk. 2001. Butterfly response to microclimatic conditions following Ponderosa Pine restoration. Restoration Ecology **9:**453–461.

Morgan, P. A., and F. T. Short. 2002. Using functional trajectories to track constructed salt marsh development in the Great Bay Estuary, Maine/New Hampshire, U.S.A. Restoration Ecology **10:**461–473.

Morrison, M. L. 2002. Wildlife restoration: techniques for habitat analysis and animal monitoring. Island Press, Washington, D.C.

Moynahan, O. S., C. A. Zabinski, and J. E. Gannon. 2002. Microbial community structure and carbon-utilization diversity in a mine tailings revegetation study. Restoration Ecology **10:**77–87.

Mulyani, Y. A., and P. J. DuBowy. 1993. Avian use of wetlands in reclaimed minelands in Southwestern Indiana. Restoration Ecology **1:**142–155.

Naveh, Z. 1994. From biodiversity to ecodiversity: a landscape ecological approach to conservation and restoration. Restoration Ecology **2:**180–189.

Naveh, Z. 1998. Ecological and cultural landscape restoration and the cultural evolution towards a post-industrial symbiosis between human society and nature. Restoration Ecology **6:**135–143.

Neckles, H. A., M. Dionne, D. M. Burdick, C. T. Roman, R. Buchsbaum, and E. Hutchins. 2002. A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales. Restoration Ecology **10:**556–563.

Nichols, O. G., and F. M. Nichols. 2003. Long-term trends in faunal recolonization after bauxite mining in the jarrah forest of southwestern Australia. Restoration Ecology **11:**261–272.

O'Dwyer, C., and P. M. Attiwill. 2000. Restoration of native grassland as habitat for the golden sun moth *Synemon plana* Walker (Lepidoptera: Castniidae) at Mount Piper, Australia. Restoration Ecology **8:**170–174.

Parikh, A., and N. Gale. 1998. Vegetation monitoring of created dune Swale wetlands, Vanderberg Air Force Base, California. Restoration Ecology **6:**83–93.

Parmenter, R. R., and J. A. MacMahon. 1992. Faunal community development on disturbed lands: an indicator of reclamation success. Pages 73–89 in J. C. Chambers, and G. L. Wade, editors. Evaluating reclamation success: the ecological considerations. General Technical Report NE 164, Northeastern Forest Experimental Station, United States Department of Agriculture Forest Service, Radnor, Pennsylvania.

Parrota, J. A., and O. H. Knowles. 1999. Restoration of tropical moist forests on bauxite-mined lands in Brazilian Amazon. Restoration Ecology **7:**103–116.

Passell, H. D. 2000. Recovery of bird species in minimally restored Indonesian thin strips mines. Restoration Ecology **8:**112–118.

Patten, M. A. 1997. Reestablishment of a rodent community in restored desert scrub. Restoration Ecology **5:**156–161.

Peterson, G., C. R. Allen, and C. S. Holling. 1998. Ecological resilience, biodiversity, and scale. Ecosystems **1:**6–18.

Pizl, V. 2001. Earthworm succession in afforested colliery spoil heaps in the Sokolov Region, Czech Republic. Restoration Ecology **9:**359–364.

Purcell, A. H., C. Friedrich, and V. H. Resh. 2002. An assessment of a small urban stream restoration project in northern California. Restoration Ecology **10:**685–694.

Radeloff, V. C., D. J. Mladenoff, and M. S. Boyce. 2000. A historical perspective and future outlook on landscape scale restoration in the Northwest Wisconsin Pine Barrens. Restoration Ecology **8:**119–126.

Reay, S. D., and D. A. Norton. 1999. Assessing the success of restoration plantings in a temperate New Zealand forest. Restoration Ecology **7:**298–308.

Rhoades, C. C., G. E. Eckert, and D. C. Coleman. 1998. Effect of pastures trees on soil nitrogen and organic matter: implications for tropical montane forest restoration. Restoration Ecology **6:**262–270.

Robinson, G. R., and S. N. Handel. 1993. Forest restoration on a closed landfill: rapid addition of a new species by bird dispersal. Conservation Biology **7:**271–278.

Rosales, J., G. Cuenca, N. Ramírez, and Z. De Andrade. 1997. Native colonizing species and degraded land restoration in La Gran Sabana, Venezuela. Restoration Ecology **5:**147–155.

Salinas, M. J., and J. Guirado. 2002. Riparian plant restoration in summer-dry riverbeds of southeastern Spain. Restoration Ecology **10:**695–702.

SER (Society for Ecological Restoration International Science & Policy Working Group. 2004. The SER International Primer on Ecological Restoration (available from http//www.ser.org) accessed in July 2005. Society for Ecological Restoration International, Tucson, Arizona.

Shaw, P. J. A. 1996. Role of seed bank substrates in the revegetation of fly ash and gypsum in the United Kingdom. Restoration Ecology **4:**61–70.

Shear, T. H., T. J. Lent, and S. Fraver. 1996. Comparison of restored and mature bottomland hardwood forests of southwestern Kentucky. Restoration Ecology **4:**111–123.

Sheridan, P., G. McMahan, K. Hammerstrom, and W. Pulich. 1998. Factors affecting restoration of *Halodule wrightii* to Galveston Bay, Texas. Restoration Ecology **6:**144–158.

Sluis, W. J. 2002. Patterns of species richness and composition in a re-created grassland. Restoration Ecology **10:**677–684.

Smale, M. C., P. T. Whaley, and P. N. Smale. 2001. Ecological restoration of native forest at Aratiatia, North Island, New Zealand. Restoration Ecology **9:**28–37.

Tajovsky, K. 2001. Colonization of colliery soil heaps by millipedes (Diplopoda) and terrestrial isopods (Oniscidea) in the Sokolov Region, Czech Republic. Restoration Ecology **9:**365–369.

Tanner, C. D., J. R. Cordell, J. Rubey, and L. Tear. 2002. Restoration of freshwater intertidal habitat functions at Spencer Island, Everett, Washington. Restoration Ecology **10:**564–576.

Tian, G., L.. Brussaard, B. T. Kang, and M. J. Swift. 1997. Soil fauna-mediated decomposition of plant residues under constrained environment and residue quality conditions. Pages 125–134 in G. Cadish, and K. E. Giller, editors. Driven by nature: plant litter quality and decomposition. CAB International, Wallingford, Oxon.

Tilghman, N. G. 1987. Characteristics of urban woodlands affecting breeding bird diversity and abundance. Landscape and Urban Planning **14:**481–495.

Toth, L. A., D. A. Arrington, M. A. Brady, and D. A. Muszick. 1995. Conceptual evaluation of factors potentially affecting restoration of habitat structure within the channelized Kissimmee River ecosystem. Restoration Ecology **3:**160–180.

Twedt, D. J., R. R. Wilson, J. L. Henne-Kerr, and D. A. Grosshuesch. 2002. Avian response to bottomland hardwood reforestation: the first ten years. Restoration Ecology **10:**645–655.

Urbanska, K. M., and M. Fattorini. 2000. Seed rain in high-altitude restoration plots in Switzerland. Restoration Ecology **8:**74–79.

Urbanska, K. M., N. R. Webb, and P. J. Edwards. 1997. Why restoration? Pages 3–7 in K. M. Urbanska, N. R. Webb, and P. J. Edwards, editors. Restoration ecology and sustainable development. University Press, Cambridge, United Kingdom.

Vallauri, D. R., J. Aronson, and M. Barbero. 2002. An analysis of forest restoration 120 years after reforestation on bandlands in the southwestern Alps. Restoration Ecology **10:**16–26.

van Aarde, R. J., S. M. Ferreira, J. J. Kritzinger, P. J. van Dyk, M. Vogt, and T. D. Wassenaar. 1996. An evaluation of habitat rehabilitation on coastal dune forest in northern KwaZulu-Natal, South Africa. Restoration Ecology **4:**334–345.

van Aarde, R. J., A. M. Smith, and A. S. Claassens. 1998. Soil characteristics of rehabilitating and unmined coastal dunes at Richards Bay, KwaZulu-Natal, South Africa. Restoration Ecology **6:**102–110.

Walters, B. B. 2000. Local mangrove planting in the Philippines: are fisherfolk and fishpond owners effective restorationists? Restoration Ecology **8:**237–246.

Ward, S. C., J. M. Koch, and G. L. Ainsworth. 1996. The effect of timing of rehabilitation procedures on the establishment of a jarrah forest after bauxite mining. Restoration Ecology **4:**19–24.

Watts, C. H., and G. W. Gibbs. 2002. Revegetation and its effect on the ground-dwelling beetle fauna of Matiu-Somes Island, New Zealand. Restoration Ecology **10:**96–106.

Webb, C. E., I. Oliver, and A. J. Pik. 2000. Does coastal foredune stabilization with *Ammophila arenaria* restore plant and arthropod communities in southeastern Australia? Restoration Ecology **8:**283–288.

Weiermans, J., and R. J. van Aarde. 2003. Roads as ecological edges for rehabilitating coastal dune assemblages in northern KwaZulu-Natal, South Africa. Restoration Ecology **11:**43–49.

Whisenant, S. G., T. L. Thurow, and S. J. Maranz. 1995. Initiating autogenic restoration on shallow semiarid sites. Restoration Ecology **3:**61–67.

White, E., N. Tucker, N. Meyers, and J. Wilson. 2004. Seed dispersal to revegetated isolated rainforest patches in North Queensland. Forest Ecology and Management **192:**409–426.

Wilkins, S., D. A. Keith, and P. Adam. 2003. Measuring success: evaluating the restoration of a grassy eucalypt woodland on the Cumberland Plain, Sydney, Australia. Restoration Ecology **11:**489–503.

Willet, T. R. 2001. Spiders and the other arthropods as indicators in old-growth versus logged redwood stands. Restoration Ecology **9:** 410–420.

Williams, K. S. 1993. Use of terrestrial arthropods to evaluate restored riparian woodlands. Restoration Ecology **1:**107–116.

Young, T. P. 2000. Restoration ecology and conservation biology. Biological Conservation **92:**73–83.

Zedler, J. B., and J. C. Callaway. 1999. Tracking wetland restoration: do mitigation sites follow desired trajectories? Restoration Ecology **7:**69–73.