Point of View

Nucleation in tropical ecological restoration

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ABSTRACT: Ecological theories of facilitation and nucleation are proposed as a basis for environmental restoration in tropical ecosystems. The main goal of this paper is to present restoration techniques based on the concept of nucleation, in which small nuclei of vegetation are established within a degraded land. The nucleation techniques (artificial shelters for animals, planting of herbaceous shrub life forms, soil and seed bank translocation, seed rain translocation, soil and seed rain translocation's seedling set, artificial perches, planting of native trees in groups, and ecological stepping-stones with functional groups) promote the landscape connectivity on two flows: inward: *receiver connectivity* and outward: *donor connectivity*. The nuclei development represents an alternative for restoration by prioritizing the natural processes of succession. This methodology appears to take long to generate vegetation corresponding to tropical climates, but is fundamental in the formation of communities capable of acting, in the future, as a new functional nuclei within the current fragmented landscape. This strategy also encourages greater integration between the theories and projects of ecological restoration for the development of human resources and to benefit the restoration practitioner.
Key words: facilitation, succession, heterogeneity, landscape connectivity, degraded areas

A Nucleação na restauração ecológica de ecossistemas tropicais

RESUMO: As teorias ecológicas da facilitação e nucleação são propostas como base para a restauração ambiental de ecossistemas tropicais. Nesse "Ponto de Vista" apresentam-se técnicas de restauração fundamentadas no conceito de nucleação, onde pequenos núcleos de vegetação são implantados em uma área degradada. As técnicas de nucleação (abrigos artificiais para animais, plantio de espécies herbáceo-arbustivas, transposição de solo e banco de sementes, transposição de chuva de sementes, blocos de mudas procedentes de transposição de solo e chuva de sementes, poleiros artificiais, plantio de árvores nativas em grupos de Anderson, e trampolins ecológicos com grupos funcionais) promovem a conectividade da paisagem sob dois fluxos: interno: *conectividade recebedora*; e externo: *conectividade doadora*. O desenvolvimento dos núcleos representa uma alternativa de restauração que prioriza os processos de sucessão natural. A restauração através das técnicas de nucleação pode parecer muito lenta para atingir uma vegetação que corresponda ao clima tropical, porém representa uma base para a constituição de comunidades que, no futuro, poderão potencialmente atuar como novos núcleos funcionais dentro da atual paisagem fragmentada. Encoraja-se maior integração entre teorias ecológicas e projetos de restauração para desenvolvimento de recursos humanos e formação de restauradores ecológicos.
Palavras-chave: facilitação, sucessão, heterogeneidade, conectividade da paisagem, áreas degradadas

Introduction

Over the more recent centuries, the human development has drastically changed the structures and functionalities of the Earth's ecosystems. Humans have sought to expand the productivity of the natural elements to satisfy their needs and those of their domestic animals. This has led to the increasing use of agricultural and industrial techniques to augment and enhance the production of food, timber and other resources, thus greatly expanding the human utilization of the earth's productive spaces (Vitousek et al., 1997; Boff, 2000). However, the alarming impact of human development is beginning to signal a need to reconcile productive areas with conservation zones in order to foster a synergy between these drastically fragmented landscapes. To this end, the restoration of degraded areas has become vital to maintain ecological balance and the quality of life on Earth, particularly by improving the connectivity among natural remnants (Dobson et al., 1997; Honnay et al., 2002; Murphy and Lovett-Doust, 2004; Bélisle, 2005; Turner, 2005; Metzger, 2006, van Andel and Aronson, 2006; Cramer et al., 2008).

According to SER - Society for Ecological Restoration International (2004), ecological restoration is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed". It is an intentional activity that initiates or accelerates an ecological pathway - or trajectory through time - pointing towards a condition for being a reference form. Ecological restoration aims at developing an ecosystem that is resilient and self-sustaining about structure, species composition and function, as well as being integrated into a larger landscape and supporting sustainable livelihoods (SER and IUCN, 2004).

Several authors have advocated that the most appropriate way to bring about this restoration is to induce a process of secondary succession as similar as possible to natural processes, forming communities that lend to form stable states over time and space (McIntosh, 1980; Bradshaw, 1983; Dobson et al., 1997; Palmer et al., 1997; Whisenant, 1999; Young, 2000; Young et al., 2001; Reis et al., 2003; Walker and del Moral, 2003).

Facilitation is a positive interaction that can contribute to assembling ecological communities and preserving global biodiversity (Verdú and Valiente-Banuet, 2008). Lockwood (1997), Young (2000) and Temperton (2004) suggested that assembly and succession are the main concepts of restoration ecology. Community assembly refers to the process by which species colonize, interact with other species, and allows for different, path-dependent outcomes. Therefore, restoration should not prioritize a fixed successional trajectory to reach a final product of succession, but rather should aim to induce the process of succession to reach the final product of establishing multiple stable communities (Young et al., 2001). Hence, restoration methodologies should incorporate a variety of ecological perspectives and references in the practice of enabling restoration to be part of a continuous dynamic process, considering several critical constraints imposed by ecosystem dynamics such as catastrophic shifts, thresholds, and alternative stable states (Scheffer et al., 2001; Suding et al., 2004).

A new tendency of restoration practices focuses on models of conservation of biofunctionality and on systemic restoration by redirecting the degraded community toward its integration with the surrounding natural landscape, reflecting its stochastic processes and current resilience capacity (Whisenant, 1999; Reis et al., 2003; García et al., 2000; García and Zamora, 2003; Gómez-Aparicio et al. 2004; Castro et al., 2004; Zamora et al., 2004; Griffith and Toy, 2005; Metzger, 2006; Bechara et al., 2007ab; Reis et al., 2007; Tres and Reis, 2007; Benayas et al., 2008). In this context, the main goal of this "point of vew" is to present restoration techniques based on nucleation. This manuscript advocates restoring degraded tropical lands in which small nuclei of vegetation are established within a degraded area. These nuclei are intended to interact with the natural remnants and vice versa, thus promoting ecological flows (organisms and matter dispersal), resulting in succession that advances towards a state of equilibrium.

Facilitation and restoration ecology

Natural communities present variations in their age structure and mosaic-like spatial distribution (Hartshorn, 1980). This heterogeneity is due to the joint action of abiotic (physicochemical properties of the soil, microtopography and microclimate) and biotic factors (forms of interactions). The different sources of heterogeneity interact to produce a dynamic process for the formation of natural areas, associating environmental heterogeneity with a higher probability of ecological niches. There is a significant correlation between environmental heterogeneity and biodiversity (Rosenzweig, 1995; Stewart et al., 2002; Wilson, 2002).

Biodiversity is reestablished through an ecological flow associated with adjacent natural remnants (Cubina and Aide, 2001). These remnants greatly improve the potential for natural self-regeneration. Many landscapes contain several small natural remnants interspersed in an agricultural matrix, which is permeable for some biological groups (Metzger, 2006). However, one must not overlook the fact that the restoration of many degraded areas, without natural remnants in the landscape, requires human intervention (SER and IUCN, 2004). Environmental restitution through natural regeneration in favorable matrices can lead to the establishment of a high diversity of species and life forms (Uhl et al., 1988; Guariguata et al., 1997; Toriola et al., 1998; Aide et al., 2000). Considering ecological systems from this standpoint, it seems clear that restoration models should focus on establishing a series of processes and contexts of the system as a whole, which will generate a diversity of ecological flows.

Although the majority of conceptual models of community structure are either explicitly or implicitly based on competition, a large body of empirical evidence and theory has accrued supporting positive interactions, such as facilitation, as another important and general phenomenon affecting plant distributions, productivity, diversity, and reproduction (Hunter and Aarssen, 1988; DeAngelis et al., 1986; Brooker et al., 2008; Bulleri et al., 2008). Positive interactions are incredibly diverse and have a well-documented influence on ecosystems. Facilitation is a phenomenon by which one species enhances the survival, growth and vigor of another (Callaway, 1995). However, facilitation can be considered as a successional dynamic that spans more than a single organism's lifespan. Facilitation plays a significant role in structuring plant communities (Bruno et al., 2003). The positive interspecific interactions (Hurlbert, 1971) and connectance (Williams and Martinez, 2000) among the diverse trophic levels are essential to many organisms' life history strategies. Hence, the theoretical framework of modern ecology should be updated by including the concept of facilitation. This is not to say that current theory emphasizing competition or predation is wrong, but that it paints an incomplete, and in some cases misleading picture of our understanding of the structure and organization of ecological systems (Bruno et al., 2003).

The role of nucleation in ecological restoration

Among the various studies on facilitation (García et al., 2000; Bellingham,et al., 2001; Bruno et al., 2003; Franks, 2003; Gómez-Aparicio et al., 2004), the classic theory of Yarranton and Morrison (1974) outlined the nucleation process by describing the spatial dynamics of primary succession (the formation of natural areas) in Canadian dunes. The authors stated that, at first, open grassland with scattered juniper (*Juniperus* spp.) bushes were formed. In the microclimate provided under these bushes, the nuclei of a series of herbaceous colonizing species developed, composed of sedge (*Carex* sp.), grass (*Poa* sp.) and Solomon's seal (*Smilacina* sp.), forming a layer of humus. In this layer rich in organic matter and potassium, chipmunks buried oak (*Quercus* spp.) seeds. Oaks are large trees marking the end of a succession that grew in heterogeneous patches, dominated by juniper bushes and other colonizers, whose populations began to be reduced to oak nuclei. In these nuclei, many other late succession species took root and became attractive to animals, e.g., chokecherry tree (*Prunus* sp.), buffaloberry (*Shepherdia* sp.) and snowberry (*Symphoricarpos* sp.). Therefore, dune vegetation began with a field phase consisting of scattered nuclei of juniper bushes and associated herbaceous species. It then passed on to an intermediate phase with the development of oak nuclei, finally culminating in the formation of long-lived oak forests and their associated understory in areas distant from the sea.

Reis et al. (2003) reconciled the concept of facilitation by nucleation for the practice of ecological restoration, setting nucleation techniques for environmental restoration. These techniques aim at the formation of microhabitats in situations favorable to the opening of a series of stochastic events for natural regeneration, such as the arrival of species and the formation of an interactive network among organisms (Reis et al., 2003). The purpose is to promote ecological drivers, increasing the probability of forming diverse alternative routes of succession. Ephemeral species are essential in this successional process.

Tres and Reis (2007) discussed nucleation from the standpoint of the restoration of fragmented landscapes. These authors considered nucleation a process involving any element, biological or abiotic, that can foster the formation of regeneration niches and colonization of new populations through facilitation, generating new connections in the degraded landscape. In this process, nucleation potentially integrates fragmented landscapes, since it generates *inward* effects (in degraded areas to be restored) and *outward* effects (in areas disconnected by fragmentation) (Reis and Tres, 2007). For the nucleation process to become effective in the landscape and promote connectivity, it is essential for ecological flows to take place in both directions: "from the fragments to the area under restoration" and "from the restored area to the landscape" (Figure 1).

In landscapes with few natural remnants, the closest fragments – even those far from degraded areas - can be the best seed sources for regeneration, representing historical nuclei of the ecological flows. In these areas, because the landscape's mosaic-like pattern is quite heterogeneous, a complex set of natural conditions is developed through the enhancement of these ecological flows originating from the historical remnants into the areas to be restored. Figure 1 represents, schematically,

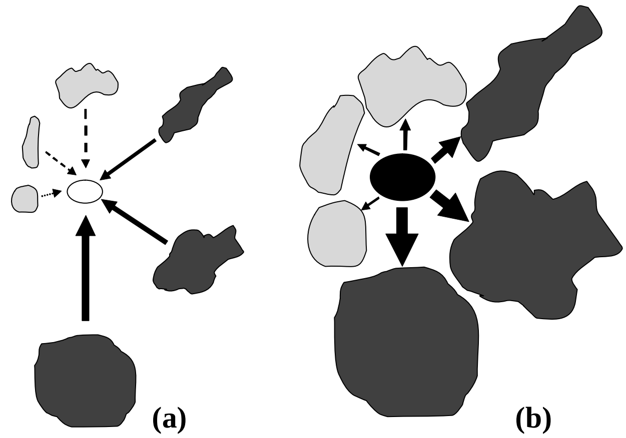

Figure 1 - Connectivity feedback dynamics between the landscape and an area in the process of restoration. **(a)** *Receiver connectivity*: the direction of the ecological flows is from the source's natural remnants to the area being restored (white ellipse); **(b)** *Donor connectivity*: the area under restoration becomes a larger nucleus (black ellipse) inserted in the landscape context, with the ecological flows reacting to the natural remnants which increase in size and reduce distance to the restoring area. Gray shades represent successional stages of the remnants dispersed in a matrix with variable permeability. Arrows of different thicknesses represent the different degrees of connectivity between the remnants and the area undergoing restoration (the thicker arrows represent more intense ecological flows). Distances decrease from (a) to (b). Adapted from Tres and Reis (2007).

the nucleation process as a facilitator for restoring connectivity, considering variable parameters of the landscape such as scale, size and degree of isolation between remnants, intensities of ecological flows and matrix permeability (Merriam and Lanoue, 1990; Dunn et al., 1991; Wiens et al., 1997; Antongiovanni and Metzger, 2005; Ewers and Didham, 2006).

The nucleating process works as a feedback mechanism. Two dynamics can be imagined, one receiver and the other donor. First, in the landscape, natural areas such as fragments are considered the last nuclei of diversity. The idea is to look for several elements (soil, seeds, microorganisms, fungi, bacteria, etc.) inside these fragments and move them into the degraded areas. The combination of these elements allows for the creation of a new condition in the degraded area, starting with the formation of a small nucleus of diversity (Manders and Richardson, 1992; Blundon et al., 1993; Franks, 2003). Over time, these nuclei tend to spread out and coalesce, gaining strength by establishing connections with the natural units of the landscape (natural remnants, ecological corridors). This is the first route of connectivity: the *receiver connectivity* that occurs between natural fragments and the degraded area. In a subsequent stage, this nucleus formed in the degraded area becomes a differentiated element, with new diversity and functionality in the landscape. From this point onward, the nucleus begins to yield a return to the landscape as it spreads out and gains strength and the feedback it produces is the connectivity between the area under restoration and the fragments surrounding it (Verdú and García-Fayos, 1996). This is the second route of connectivity: the *donor connectivity* between the restored area and the fragments of the landscape. At this point, a web of connections is restored, which is essential for promoting connectivity among the units of the landscape as an intricate whole.

The receiver and donor routes are intersectional in time and space, for even spatially isolated nuclei may be connected by ecological flows depending on the permeability of the matrix. The intended ecological flows promoted by nucleation tend to reproduce coalescence patches (in time and space) as the dynamic process of succession described by Yarranton and Morrison (1974). Based on these receiver and donor perspectives, restoration through nucleation is characterized by several techniques that are not implemented in a whole area but always in the nuclei, occupying around 10% of the area. Nucleation thus speeds up natural succession, enabling the mechanisms of reestablishment used by nature itself to be expressed. The nucleation techniques are implemented jointly rather than separately, restoring the spatial and temporal heterogeneity. The greater higher the diversity of forms and functions of nuclei the greater the effectiveness of the technique set. According to Reis et al. (2003), Bechara (2006), Bechara et al. (2007a), Reis et al. (2007) and Reis and Tres (2007a), Reis and Tres (2007b) nucleation techniques include:

Artificial shelters - Piles of brush or firewood decomposed by microorganisms and insects, which attract birds that come to feed on them. Lizards and rodents hide in the piles, and are preyed upon by snakes. These piles act as natural shelter for animals (Beisiegel, 2006). Over time, the piles of organic matter are entirely decomposed, forming layers of humus and restoring the biota of the soil (Bayer and Mielniczuk, 1999).

Planting of herbaceous shrub life forms - Plantings of ground-covering ruderal species in mixed or single species nuclei that flower and bear fruit within a few months, attracting a variety of animals that are pollinators, seed dispersers and consumers (Bechara et al., 2007b). Since they are short cycle plants, they soon serve as food for the decomposers, recycling organic matter into the soil.

Soil translocation - Removal of small amounts of topsoil from the closest remnant natural areas for translocation in nuclei in the degraded area. This facilitates the recovery of the regional seed bank and the biota of the litter and soil. This technique, here distributed spatially in nuclei, has been used previously by other authors (Sturgess and Atkinson, 1993; Rodrigues and Gandolfi, 2000), albeit over an entire area, which requires degradation of the source area. In one square meter-nuclei from 13 to 29 plants were recruited from 26 to 54 native species (15-22% trees, 12-16% shrubs, 45-65% herbs and 5-8% lianas (Bechara et al., 2007a).

Seed rain translocation - seeds that fall each month on seed traps installed in the nearest remnant native communities are planted in nuclei and can be either germinated in nurseries or planted directly in the degraded areas. Seedlings of all plant life forms are produced: lianas, herbs, shrubs, trees and epiphytes. This monthly periodicity allows for the establishing of plants that will produce fruit every month, supporting the animals in the degraded area throughout the entire year (Reis et al., 1999). A total of 455 plants of 39 native species (9% trees, 4% shrubs, 31% herbs, 36% lianas, 1% epiphytes and 19% indeterminate were produced in a nursery over a period of five months. The seeds originated from 30 seed traps one square meter in size (Bechara et al., 2007a).

Soil and seed rain translocation seedling set - the soil and seed rain collected in remnants fragments are taken to a nursery for producing seedlings. But here, the containers used are trays for raising seedlings that are distributed in plots in the field. This can supplement the traditionally-collected seeds as one more way of reintroducing biodiversity.

Artificial perches - Wood poles 5 to 10 m high to serve as perches for birds and bats, which bring large quantities of seeds from the remnant natural areas in the region. The perches serve, visually in the landscape, as beacons for resting, foraging and latrine sites, resulting in the nuclear deposition of high diversity seed rain, which also represents a feeding place for granivorous animals. Several authors have previously reported the effect of artificial perches on restoration (McDonnel and Stiles, 1983; Guevara et al., 1986; McClanahan and Wolfe, 1993; Whittaker and Jones, 1994; Holl, 1998, 1999; Galindo-Gonzales et al., 2000; Shiels and Walker, 2003).

Planting of native trees in groups - Planting is not done over the entire area, but in dense patches of five to thirteen seedlings, generally staggered 0.5 m apart, widely spaced in the area (Anderson, 1953), forming scattered islands of diversity. Shade species, fast-growing and medium longevity, are used.

Ecological stepping-stones with functional groups - Introduction of small refuges for fauna inside an agricultural matrix. In the case of tree plantations, these refuges are introduced in line with the planted rows, in clumps consisting of 16 native tree seedlings having a facilitating function, at a rate of one nucleus per hectare. The introduction of elements with well-defined functions should give rise to changes in the landscape, especially by increasing the permeability of the matrix for the ecological flows in the mid and long term, since they tend to reduce the effective distance of species' dispersion, and therefore favoring the connectivity of the units of the landscape. Each of the nucleation techniques has functional effects and features, which synergistically promote succession, energy flows, regional biodiversity in the degraded area, and connectivity among the different units of the fragmented landscape. For example, the seeds dispersed below an artificial perch can be used locally as a center for animal feeding and, when dispersed secondarily, can find their regenerating niche under a pile of brush in decomposition or even in neighboring areas. Therefore, the biomonitoring of nucleation techniques should be performed by evaluating all the biological groups and their different functions in the area to be restored.

The nucleation techniques proposed here are alternatives for environmental restoration, based on the prioritizing of the natural processes of facilitation. This methodology appears to take an extended length to generate tropical vegetation, but it represents a key for the formation of communities that will be able, in the future, to act as new functional nuclei within the current fragmented landscape.

Final considerations

Developing technologies for the restoration of degraded areas and creating facilitation patches within the larger landscape that enable ecological flows are essential to reconcile the needs of the human species and the conservation of natural ecosystems. Paraphrasing Young et al. (2001), "ecological restoration projects are an experimental ecologist's dream".

Even though a great deal is known about terrestrial ecosystems, there is a gap between theory and applied practice in the areas that are undergoing the process of environmental restoration. This paper calls for restorers to be more observant in the areas where they are working, and searching for solutions within that same environment in which the degraded areas are inserted while at the same time, stimulating the natural processes of restoration of degraded ecosystems. We also call for greater integration between the theories and the design of projects for ecological restoration. This will help to develop human resources and will benefit the restoration practitioner.

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