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How to define and measure the impacts of plant alien species on ecosystems?

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Abstract

Individuals of alien species cause impacts on ecosystems by influencing the diversity, wealth and spread of native species. However, despite the recognized impacts and risks caused by such species, there is no consensus on common parameters to quantify their impacts. This study aims at discussing the definitions and methods used for measuring the invasive alien species impacts on ecological systems. It was observed that the formula proposed by Parke et al. (1999) is the most cited in scientific studies, nonetheless, it has certain mathematical and relevant data collection limitations, which hinders their use in research. Thus, abundance measures and phytosociological parameters can generate indices, which allow one to estimate the impact caused by alien plant species on native biodiversity. Phytosociology allows the characterization of plant communities through the analysis of quantitative attributes, as the Importance Value Index (IVI) allows the finding of the density, dispersion and size achieved by species. Thus, it is possible to assess the community structure in the presence of an invasive species and whether it promotes changes, occupying a high social contribution value and interfering with native species. Finally, this paper shows how impact assessment can contribute to the conservation of native biodiversity.

Keywords: Biological invasion; biodiversity; impact measures; abundance.

Como definir e medir o impacto de espécies exóticas vegetais nos ecossistemas? Ao influenciar na diversidade, riqueza e distribuição de espécies nativas, as espécies exóticas causam impactos nos ecossistemas. Mesmo com as reconhecidas ameaças causadas por estas espécies, ainda não há consenso sobre parâmetros comuns para quantificar os seus impactos. Objetivou-se discutir as definições e os métodos usados para medições de impactos de espécies exóticas invasoras nos ecossistemas. A fórmula proposta por Parker et al. (1999) é a mais citada em estudos científicos. Porém, apresenta determinadas limitações matemáticas e na coleta de dados correspondentes, o que dificulta o seu uso nas pesquisas. Deste modo, medidas de abundância e parâmetros fitossociológicos podem originar índices que permitem estimar o impacto de uma espécie exótica vegetal. A fitossociologia permite através da análise de atributos quantitativos, a caracterização de comunidades vegetais e a partir do Índice de Valor de Importância (IVI) conhecer a densidade, dispersão e dimensão alcançada por uma espécie. Assim, é possível avaliar a estrutura da comunidade diante da presença de uma espécie invasora e se esta promove mudanças, ocupando um alto valor de contribuição social e interferindo nas espécies nativas. Por fim, apresenta-se como a avaliação de impactos pode contribuir para a conservação da biodiversidade nativa.

Palavras-chaves: Invasão biológica; biodiversidade; medidas de impacto; abundância.

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1. Introduction

Never before in human history has the transport of plant and animal species between different regions and continents been so intense and accelerated as in current time (RICCIARDI et al., 2013). Species that are outside their natural range are called alien, and according to their biological characteristics and those of the introduction environment, they can become invasive. By broadening its expansion in an area, alien species can pose a threat due to the negative impact it can have on society, economy and ecosystems (CBD, 2000).

Biological invasion, a result of the proliferation of alien species, is a serious environmental problem in native communities (FINE, 2002). For that reason, some consider it the second global cause of biodiversity loss, and the main cause in conservation units (GISP, 2007; ZILLER, 2006). Among the effects caused by invasive species are alterations in key ecological processes, such as changes in the physical characteristics of the environment, the exclusion of native species through competition or predation, the spread of diseases, the production of hybrids with native species and, in extreme cases, local extinction (ESPINOLA e JÚLIO-JÚNIOR, 2007).

In recent decades, invasion ecology has advanced substantially in providing understanding of the ecological impacts of invasive alien species (DICK et al., 2017). However, the very concept of impact is not precise and the information already available is hampered by the absence of boundaries (JESCHKE et al., 2014). The lack of a large-scale assessment also limits the ability to generalize and predict when and where the impacts may be more deleterious (DICK et al., 2017; PYŠEK et al., 2012). Consequently, robust quantitative assessments of environmental impacts were held to less than 200 plant alien species, which represents a significant lack of knowledge (HULME et al., 2013), and reinforces the need to develop mathematical concepts and formulas that allow one to characterize and quantify the impacts.

The development of better metrics to quantify and categorize the impacts of invasive alien species may contribute to risk assessment and management (DICK et al., 2014; SIMBERLOFF et al., 2013), and represent a set of tools to prioritize actions of conservation, restoration and appropriate policy responses to invasions (BUCHADAS et al., 2017; JESCHKE et al., 2014), especially in the current context where biological invasions are increasing in severity and geographical extent (RICHARDSON e WILGEN, 2004). Thus, this study aims at understanding how the impacts of alien species have been defined and measured, and discussing aspects that should be considered in the measurements and quantification of impacts and their importance for biodiversity conservation.

2. Definition of impact and the necessary components for its assessment

The impact of invasive species is described by Hulme et al (2013) as "any change, an increase or decrease of an ecological process or standard, which can be perceived as positive, negative or neutral for humans." Similarly, Ricciardi et al (2013) states it as positive or negative, with the possibility of being compared over time and space. For Parker et al (1999) it is summarized as a degree of ecological change produced by an initial invasion. Though, the definition of impact is still problematic due to the scientific and social influences on its perception and the variety of ecological factors that determine the level of impact produced (Lockwood et al., 2007).

One of the controversial aspects that arises due to social influence is the need to consider human values in a definition of impact. If included, two components need to be analyzed, the magnitude of change that can be measured and the value of change given by humans (JESCHKE et al., 2014), and a major challenge arises from that, since there are groups with diverging interests. An example was the introduction of pines in the southern hemisphere, which damaged part of the population by reducing the quality of

the soil and decomposition, while the timber industry benefited from the rapid growth of trees (SIMBERLOFF et al., 2013).

So, there is no consensus among scientists about which human values to include in the definition of impact, as there may be conflicts between environmental effects and non-ecological metrics (RICCIARDI et al., 2013). Another reason is that a strong ecological impact, as the local extinction of a species, is not necessarily related to a socio-economic impact (JESCHKE et al., 2014). For that reason, one can infer that the inclusion of human values in a definition of impact would not be ideal, as it could generate different results, according to the group of people that will be considered in the assessment and for using different metrics.

However, regardless of the concept used for impact assessment, the context of invasion should be analyzed and some factors must be considered, such as the characteristics of invasive species and the introduction environment. This way, it is important to recognize which conditions may favor the invasion and subsequent impacts. Invasive species have high capacity of vegetative and sexual propagation, tolerance to herbivory, great longevity of the period of flowering and fruiting, resistance to pathogens, phenotypic capacity (MATOS e PIVELLO 2009; CHAME, 2007; HOROWITZ et al., 2007), among other aspects that provide them with competitive advantage against native species and favor the process of invasion and consequent impacts. Along these lines, for the assessment of the impact of an invasive species to be possible in the native biota, a thorough understanding of the biology of each species introduced together with the knowledge of native species is necessary (MANCHESTER et al., 2000).

Likewise, the characteristics of the environment where the species is introduced also contribute to the success of the invasion and potential impacts. This is because some communities appear to be highly susceptible to invasion by alien species, for example, fragmented environments with low species diversity, altered by human action and with the absence of natural enemies (VITULE e PRODOCIMO, 2012; SAX et al., 2007; DISLICH et al., 2002). This should be studied especially in degraded environments, since change in environmental conditions, such as increased incidence of fires and/or solar radiation, can provide opportunities for the establishment of generalist and resistant species, many of which are alien (DISLICH et al., 2002). As the presence of alien species coincides in time and space with other modifying agents, such as the expansion of agriculture and cattle raising, and forest fragmentation (ZALBA e ZILLER 2007) it, therefore, hinders the analysis of the contribution regarding each impact (BYRNES, 2002).

Consequently, human disturbances can remove native species, allowing the establishment of invasive species that fill the vacant ecological niches in which they can experience little or no resistance to their establishment (GUREVICH et al., 2009; BYERS, 2002). Anthropogenic changes can create a mismatch between the characteristics of native species and their environment, so that some invasive species are very well, if not better, adapted to the changed environment as to competing native species (Byers 2002), which may favor their establishment and consequent impact. As an example, in the Amazon, several alien species were able to invade forest fragments, which, although relatively rich in species, the effects of their fragmentation increased their susceptibility to invasion (LAURANCE e VASCONCELOS, 2009).

The potential of some species in rapidly colonizing degraded areas is called invasiveness and represents the successful establishment and spread of alien species (RICCIARDI e COHEN, 2007). The invasiveness of a species is due to both its plasticity and the characteristics that provide greater competitive advantage, being it a reflex of its evolution in the source environment, or through the selective pressure in the alien environment. Both the success of the invasion and the impact are dependent upon environmental characteristics and, thus, they may widely vary among regions (RICCIARDI, 2013). If each species may vary their impact in relation to their habitat type, especially when considering

degraded and conserved environments, there may be significant variations in both the direction and the magnitude of the impact among different regions (PYŠEK et al., 2012). This way, the impact of the same species can vary much in space and time (RICCIARDI et al., 2013; HULME et al., 2013; PARKER et al., 1999), according to the environmental conditions in which it was introduced.

Due to the various conditions that can determine the impact, its estimate may depend on a temporal and spatial scale, which hinders its quantification. An example cited by Parker et al (1999) is that small-scale studies can improperly control natural variation in space and time; and on large scales it can be confused by spatial gradients or temporal trends, such as pollution or climate change. However, we emphasize that it is possible to control these variables in a multitemporal and multispatial assessment.

Hulme et al (2013) based their research on the publication of Pyšek et al (2012), which prepared the most comprehensive database to date on quantitative studies of alien plants from 287 scientific publications. Hence, they concluded that 80% of the studies used a single species in analyzing the impact, which limits the comparison between different species and other generalizations. In spite of that, most of the invaded environments have more than one alien species and focus on only one, although more abundant, it can make the subtle effects of rare alien species to go unnoticed (HULME et al., 2013). In order to solve this issue, it is possible to assess the impact of various alien species in a community, as it can be explained from the estimate of population parameters.

3. The effects of biological invasion

The impacts caused by invasive species can occur at any level of the biological organization, immediately or years after their introduction, and can persist for a short or long period of time, or it can be so subtle to a point it is not easily perceived. Moreover, the impacts of different species can interact with each other, which gives rise to cascade effects that trigger additional effects along the ecosystem (REASER et al., 2007). A growing number of studies indicate that the invasion of a single alien species can alter the biodiversity, hydrology, nutrient cycling, soil property, fire frequency and trophic interactions (HULME et al., 2013).

The impact on individuals is described by observing a decrease in the reproductive and survival rates of native populations (LOCKWOOD et al., 2007). A decrease in the native reproduction rate can be verified taking the example of the jackfruit *(Artocarpus heterophyllus* Lam.), a recognized invasive species in Brazil. This species highly colonizes forest edge areas, which prevents the regeneration of native species, leading to a reduction of their populations (SIQUEIRA, 2006). These types of impacts can easily be verified by monitoring the population abundance rate, and for that reason, they are the most described in scientific papers and were the first to be studied (HULME et al., 2013). Furthermore, many conventional methods of measuring population parameters can be used to determine the impact of the invasive species, where population can respond with changes in the abundance, spread and structure (age or size). Information on changes in the composition and abundance of native species can be synthesized in various ways and produce a compound measure of impact (PARKER et al., 1999).

The impacts that affect the community are related to the effects on the population, because they lead to changes in its composition, in case invasive species impact more than one native species (LOCKWOOD et al., 2007). Although studies do not exemplify this situation, we point out that the rates of population parameters of various species in a community can contribute to the understanding of alien effects in a community. In this case, the use of phytosociology is suggested as an alternative to measuring these impacts, as detailed below.

The genetic effects caused by invasive species can be identified through hybridization between native and alien species, which can result in the elimination of original genotypes and phenotypes (ZILLER, 2006). However, these types of effects are poorly documented (PARKER et al., 1999), due to difficulties in observing and

measuring them. For the same reason, there are only a few studies focused on impacts on ecosystems (SIMBERLOFF et al., 2013) and among their effects are: changes in key ecological processes and physical characteristics; erosion and sedimentation; change in renewal rates of environmental resources and; changes in the functions of species and biomass distribution. (REASER et al., 2007; ZILLER, 2006). An example of this is the invasion of nitrogen (N) fixing species, such as *Leucena leucocephala* (Lam.) de Wit, as they may change the availability of this resource and the balance of competition between native and alien species, leading to changes in the structure of the community and the ecosystem (LOCKWOOD et al., 2007).

4. How are impacts being measured?

Impacts should be measured in a reliable manner, able to predict future effects under different environmental conditions, as should the resistance patterns of native species (DICK et al., 2014). For this matter, the models must incorporate both the complexity of the community and the complex relationships between invasive and native species (PARKER et al., 1999). The best known mathematical model is proposed by Parker et al (1999), which include three main dimensions that will determine the impact of an invasive species in a geographic scale: range, i.e., the total occupied area (R), abundance (A) and an impact measure per individual, represented by the per capita effect or biomass of the invasive species (E), resulting in the following linear equation: I = R x A x E (RICHARDSON e WILGEN, 2004; REASER et al.,2007; THIELE et al., 2010). One of the arguments of PARKER et al (1999) for the selection of these components is that any biomass, space or power taken by the invasive species is no longer an available resource for native competitors, representing potential impacts.

The positive aspect of this equation is that it produces a standardized metric that may be compared across different species and locations (RICCIARDI et al., 2013) and it also includes the main components of regional impacts - it provides basic arithmetic and establishes standards regarding measurement units (Thiele et al., 2010). However, a major limitation for its practical use is due to the fact that the three components used (R, A and E) are not independent and can be correlated, making the linear equation inadequate (THIELE et al., 2010; REASER et al., 2007). Thus, the effects per individual or per unit of biomass may vary with the abundance of the invasive species itself or with the type of habitat invaded, which requires a large sample of local species invaded for a thorough assessment (THIELE et al., 2010). Another limitation arises as many studies use only one of these three components of the equation, as they are parts of a whole. Thereby, species may vary in their degree of impact due to the many combinations among these three factors (PARKER et al., 1999).

Despite criticism and limitations that prevent the application of the formula of Parker et al (1999), his main contribution was identifying the environmental variables that determine the severity of the impact (LOCKWOOD et al., 2007), which allows one to recognize the components that can be observed in an assessment and guide the establishment of a standardized metric. Due to logistical difficulties regarding data collection and the relationship between the three components considered by Parker, data derived from abundance, however, can be used as a viable alternative to estimate the potential impact of an alien species on the plant community.

4.1 Abundance as an impact measure

Abundance is the number of individuals of a species on a site or sample (MORO e MARTINS, 2011). Even if the impact is not related to abundance only, as proposed by Parker et al (1999), it is currently the most viable option for a measurement (BRADLEY, 2013; RICCIARDI et al., 2013). The use of abundance measures as a criterion to measure impact is supported by the fact that a substantial change in the composition or abundance of many species is likely to induce changes in at least some ecosystem processes, by interfering with the sizes of the populations (SIMBERLOFF, 2011). The

increase in the mango *(Mangifera indica* L.*)* population in semi-arid areas of the Brazilian northeast, which caused its fruit to become food for animals, reducing the consumption of native fruits and consequent dispersion of those species (LEÃO et al., 2011), is an example of change in the size of populations. Thus, the abundance of invasive plants correlates with impact (BRADLEY, 2013), because the advantage of monopolizing more space in the community than that occupied by a dominant native species is directly related to the impact of the invasion (HEJDA et al., 2009).

Therefore, monitoring the abundance of invasive species provides information on the likely expansion in the area (VELDTMAN et al., 2010) and, consequently, occupation at the expense of native species, a viable alternative for measuring impacts. Invasive species can also decrease the abundance of most members of a community for having greater competitive ability or having impacts that affect different species in different ways, resulting in key changes in the community's composition. The sort order for abundant species can indicate changes, facilitating their quantification and other statistical tests (PARKER et al., 1999). Despite this fact, one of the main difficulties in determining the invasive potential from abundance is the logistical difficulty in collecting data, and a method that can assist in this activity is the "species area-curve," indicating the sample sufficiency based on the cumulative number of samples. Therefore, with this methodological strategy, one can characterize plant communities, and also collect abundance data, providing information on small and large scale spread (VELDTMAN et al., 2010).

In estimating impacts from information on abundance, on the other hand, it should be recognized that the results are dependent upon the observed scale. The sample used can provide an incomplete picture of the spread of abundances in the investigated community (MAGURRAN, 2013). Moreover, invasions advance more quickly when the species is introduced at various places than when in a limited area only (MACK et al., 2000). In order to address this situation, as in any study, as highlighted by Thiele et al (2010) a comprehensive assessment may require a large sample of invaded sites, which must be strictly random, or a thorough search in a pre-defined area, so that the sampling sites are representative for the invasive species.

4.2 Other forms of measurement used

Other measuring methods can be used to assess impact. The first one is based on the comparison of several ecological variables in invaded and non-invaded sites (VILÀ et al., 2011). For this matter, we suggest the installation of plots in areas with invasive species and without invasive species, also called control areas. The study of Hejda et al (2009), for example, used this method to measure impact using the calculation of similarity between the plots and Shannon's Diversity Index (H'), so as to represent the effects of invasive species in the environment.

In a second method, phytosociology, which is the study of the characteristics, relationships and spread of plant communities, stands out through the description and quantitative attributes (MORO e MARTINS, 2011), making it a tool for the study of biological invasions. A phytosociological survey results in a table that informs on the community structure, through the number of sampled individuals, of absolute and relative measurements of density, frequency and dominance and of the importance value index - IVI (MORO e MARTINS, 2011). From the IVI, which represents the sum of the three relative variables, it is possible to indicate which species have greater social contribution to the community. Therefore, if an alien species has a high IVI value, compared to native species, one can infer that it is causing some kind of impact, since it occupies an important social position, which before the invasion, was occupied by a native species.

Another advantage of using phytosociology is that it allows one to integrate other components, as well as abundance, into an impact measure, which allows a broader community vision. Furthermore, it is possible to compare sites or samples, which would facilitate the understanding of the impact of alien species in

different environments or even to different species within the same study area. The work of Andrade et al (2011) used phytosociology to assess community structure when comparing areas with presence and absence of *Prosopis juliflora* DC (mesquite) in Caatinga. The results indicated that the invaded communities showed lower diversity and evenness values, while invasive species showed a high IVI (Importance Value Index) value, which revealed the aggressive character of the species, whose frequency, size and number of individuals prevailed over the other species.

Another example of using phytosociology was developed by Santana e Encinas (2008), which researched the impact of alien species in areas close to household waste dumping yards. The sampling plots of the study were allocated in areas close to waste dumping yards and in control areas, so that the calculated values could be compared and assess where impact was greatest. For this matter, they used an equation called Alien Species Environmental Impact Index (IIAE) based on the coefficients of Reaser et al (2007), in which the results range from 1 to -1, being values close to -1 when the area has no native plants and to 1 when it has no alien plants.

$$IIAE = - \frac{(Palien - Pnatives)subarea}{\frac{Ptotal}{narea}}$$

Where: IIAE = environmental impact index of alien species in the studied subarea or plot; Palien = IVI value of alien plants in the sampling plot or point; Pnative = IVI value of native plants in the sampling plot or point; Ptotal = total IVI (IVI = 300); n area = number of sampling plots or points.

The advantages of using the IIAE index are the ease in collecting the necessary data and identifying the social position of the alien species within the community. Phytosociology, therefore, is a tool that deserves attention for studying impacts, as the ability to rank the species in order of social importance reflects the effects of alien species, since the decrease in the importance of native species is one of the main effects of biological invasion (PARKER et al., 1999). This technique may also allow monitoring of the expansion of alien species by installing permanent plots and constant data collection, which helps to conserve native biodiversity.

5. The importance of understanding the impacts for biodiversity conservation

Awareness of the impacts of invasive species assists in the conservation of biodiversity. It is important to recognize which species can cause major impacts and develop actions for their early detection and control and/or eradication measures. For that, a study of the ISSG (The Invasive Species Specialist Group) presents the "100 worst invasive alien species in the world". The species were selected based on two criteria: "the severe impact they may cause on biological diversity and/or human activities and their illustration on important issues involving biological invasions" (LOWE et al., 2000).

The ability to predict and measure the impacts of invasive species should be considered a strategic measure for biodiversity conservation. The opportunity to recognize the species responsible for major impacts in advance can help identify and prioritize management actions, since at the time the impact is perceived, irreversible changes may have already occurred and remedial actions can be very expensive or even impossible (SIMBERLOFF et al., 2013). In general, the best opportunities for the eradication of the species is when their populations are small in number and are not yet in the process of dispersion and invasion (ZILLER, 2010).

Thus, those species whose impacts are more durable and permanent should be considered a priority in management strategies, seeking to prevent their spread, preferably still in the initial stage, or if possible, their eradication (PARKER et al., 1999). Hence, recognizing the impacts of alien species should be an increasingly present conservation strategy, especially in the management plans of conservation units, as only by identifying species that cause impact may appropriate management action be taken.

6. Conclusions

The biological invasion process is quite complex and studying their impacts should consider this condition. Thus, in light of the options presented for measuring impacts, Parker's Formula identifies the components that should be analyzed for measuring impact - the total occupied area, the abundance and a measure per individual, such as biomass. However, it has limitations, since the components used can be relate to one another and the linear equation becomes inadequate. One way to overcome these limitations is using phytosociology, which, from its Importance Value Index, can estimate the impact of an alien species in the plant community and it can even rank the species with greater social contribution, being more comprehensive than just using abundance, as recommended by some studies. Furthermore, phytosociology can facilitate long term monitoring, enabling the tracking of alien species in the community and assessing the management techniques in use.

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