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Density and fertility of *Byrsonima pachyphylla* A. Juss. (Malpighiaceae) in small fragments of the Brazilian *Cerrado*

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ABSTRACT

Habitat fragmentation is one of the main threats to the biodiversity of the planet. This study was conducted in nine fragments of the Brazilian *cerrado* (savanna) *sensu stricto*. We assessed the effects that fragment size and distance between fragments has on the density and fertility of populations of *Byrsonima pachyphylla* A. Juss. (Malpighiaceae), known in Brazil as "murici". In each of the nine fragments, we evaluated seven individuals. We quantified the *B. pachyphylla* density within a 20-m radius around each individual. Fertility in each fragment was estimated by determining the ratio between the number of flowers and the number of fruits produced. We carried out linear regression analyses between mean *B. pachyphylla* density and fragment size, as well as between mean *B. pachyphylla* fertility and fragment size. The influence of spatial autocorrelation on the fertility of each studied plant was estimated by Moran's I to evaluate the effect of fragment distance on *B. pachyphylla* fertility. Population densities and the proportions of fertile plants were greater in the larger fragments, which were also more preserved. There was spatial autocorrelation only between plants in the same fragment. Neighboring fragments differed significantly in terms of fertility, which is probably related to the degree of preservation of each fragment. Habitat fragmentation has a marked effect on the fertility of plant species in the *cerrado*, and larger fragments are needed in order to maintain their populations and those of associated species.

Key words: Habitat fragmentation, productivity, spatial autocorrelation

Introduction

Habitat fragmentation is one of the most prominent forms of environmental degradation and one of the main threats to world biodiversity (Rathcke & Jules 1993), because it results in extinction of populations and species. The process of habitat fragmentation is the transformation of a large expanse into several patches of small size, isolated from each other by a matrix different from the original. The definition of habitat fragmentation implies four effects: habitat reduction; increase in the number of fragments; decreased fragment size; and increased isolation of the fragments. These four effects are the basis for the quantitative measurement of habitat fragmentation (Fahrig 2003).

The formation of habitat islands, or fragments, results in complicating factors for the maintenance of populations, such as the formation of subpopulations with different degrees of isolation, and the formation of extensive areas of edge habitat, defined as areas of contact between the original habitat and the modified landscape (Ries *et al*. 2004). A greater number of fragments translates to a more advanced stage of fragmentation; and a reduction in the size of the fragments increases the severity of the consequences of habitat loss (Fahrig 2003). In small fragments, the remaining species with small population sizes are vulnerable to extinction by environmental and demographic stochasticity (Ewers & Didham 2006). Such effects can be mitigated if populations are not completely isolated from one another. Species can survive in small areas by combining resources from different areas, which is possible through the ability of these species to disperse between areas (Tscharntke *et al*. 2002). Greater differentiation of the matrix, in relation to the fragment, results in lower permeability of the matrix, and the degree of isolation of a given fragment is therefore determined by the combination of matrix permeability and the dispersal ability of the species (Ewer & Didham 2006).

Fragments that are isolated (far from each other) and within a less permeable matrix are exposed to changes in fauna and flora, leading traditional interactions between species to break down and new interactions to be established. In general, communities that are more complex and comprise species that are more unique are more susceptible

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to habitat degradation and increased isolation (Tscharntke & Brandl 2004). In sensitive ecological interactions, habitat quality can influence the reproductive success of plant species. For example, in the process of pollination, a increase in the distance that pollinators must travel to find plant populations affects the reproductive success of the target plant species and their pollinators (Murcia 1996; Steffan-Dewenter & Tscharntke 1999; Knight *et al.* 2006).

Pollination is the first stage in the reproductive cycle of most plant species. At that stage, any change, such as habitat fragmentation, can have a major effect on the subsequent stages, because the amount of pollen reaching the stigmata can determine the rate of ovule fertilization, with consequent effects on the rate of flower abortion, as well as on the production of fruit and seeds (Krauss *et al.* 2007). The reproductive success of plant species is determined, in part, by pollen limitation. In animal-pollinated species, the amount of pollen that reaches the stigmata of flowers is dependent on the number of pollinators and their efficiency in transporting the pollen to other flowers (Gómez *et al.* 2010). Pollen limitation can also be caused by poor quality of the pollen, which occurs in response to endogamy and reduces the quality of the offspring (Aizen & Harder 2007).

The reduced sizes of the populations of plant species found in fragmented environments leads to a decrease in cross-pollination and a loss of genetic variability, with a consequent decrease in the production of seeds and fruit, thus increasing the risk of extinction of the population (Jacquemyn *et al.* 2002). In most tropical plants, pollination involves interactions with animals, making this process doubly susceptible to the effect of fragmentation. Fragmentation can lead to changes in the type and number of floral visitors (Aizen & Feinsinger 1994), reducing pollination efficiency by decreasing the quantity or quality of the pollen received by the stigmata of flowers, leading to a lower fruit and seed production (Gómez *et al.* 2010).

In the Cerrado Biome of Brazil, a vast tropical ecoregion of *cerrado* (savanna) vegetation, the process of fragmentation and agricultural expansion has been accelerating, particularly in the states of Goiás and Minas Gerais (Klink & Machado 2005; Carvalho *et al.* 2009). The biome once occupied approximately 25% of the territory of the country (Ribeiro & Walter 1998). However, it has been reduced to less than 20% of its original size, aproximately 6% now being within "conservation units" (protected areas) (Myers *et al.* 2000) and only 2.2% is in fully preserved areas (Klink & Machado 2005). The *cerrado* is composed of various types of vegetation formations, ranging from grasslands to gallery forests (Eiten 1983), featuring high species richness and high endemism of plants and vertebrates (Myers *et al.* 2000).

One tree species that is typical of the Cerrado Biome and has a pollination system that is dependent on interaction with animals is *Byrsonima pachyphylla* A. Juss., popularly known as "murici". The species is pollinated by solitary bees of the tribe Centridini, which are medium to large in size (Alves-dos-Santos *et al.* 2007). In an earlier survey of trees and shrubs in fragments of *cerrado* surrounding the town of Hidrolândia, in the state of Goiás (where the present study was also conducted), we observed this species to be one of the most abundant, with more intense flowering than other tree species, and to occur in all of the fragments surveyed (Melo M.S., personal observation). The aim of the present study was to determine whether the population densities and proportions of fertile individuals of *B. pachyphylla* are greater in larger fragments, as well as whether neighboring fragments are more similar than are distant fragments in terms of *B. pachyphylla* fertility.

Material and methods

Study sites

This study was carried out in 2009, in nine fragments of *cerrado sensu stricto*, a common type of vegetation formation in the Cerrado Biome. Specimens were collected between July and October, which is the period of flowering and fruiting of *Byrsonima pachyphylla*. The environment features a tropical savanna-type formation, with marked seasonality, together with grasslands that have, in different proportions, tree and shrub layers (Ribeiro & Walter, 1998). The fragments studied, all of which are located within the area governed by the municipality of Hidrolândia (Fig. 1), range from 19.5 to 1124.78 ha in size (Tab. 1). The predominant soil types are the Oxisols and Inceptisols. According to the Köppen classification system, the climate of the region is type Aw (tropical rainy, i.e., tropical savanna climate), with wet summers, dry winters, a mean annual temperature of 20.1°C, and mean annual precipitation of 1300-1600 mm (Ribeiro & Walter 2008).

The fragments under study were within a vegetation matrix dominated by cattle pastures, the predominant grass being *Urochloa* sp. (signal or liverseed grass), popularly known in the region as "capim braquiária". Most farms in the area are small and have some cultivated areas for growing sugar cane (which serves to supplement livestock feed in periods of drought) or corn. However, those croplands do not border any of the fragments studied. Some of the fragments are close to the urban areas of the towns Aparecida de Goiânia and Hidrolândia. The landscape is slightly undulating, most of it being at approximately 800 m above sea level, although there are a few mountains.

Effect of fragment size

The density of *Byrsonima pachyphylla* in the nine fragments studied was estimated by counting the number of individuals within a 20-m radius around each of the seven individuals selected in each fragment. We also recorded the diameter at the height of 30 cm above the ground, as

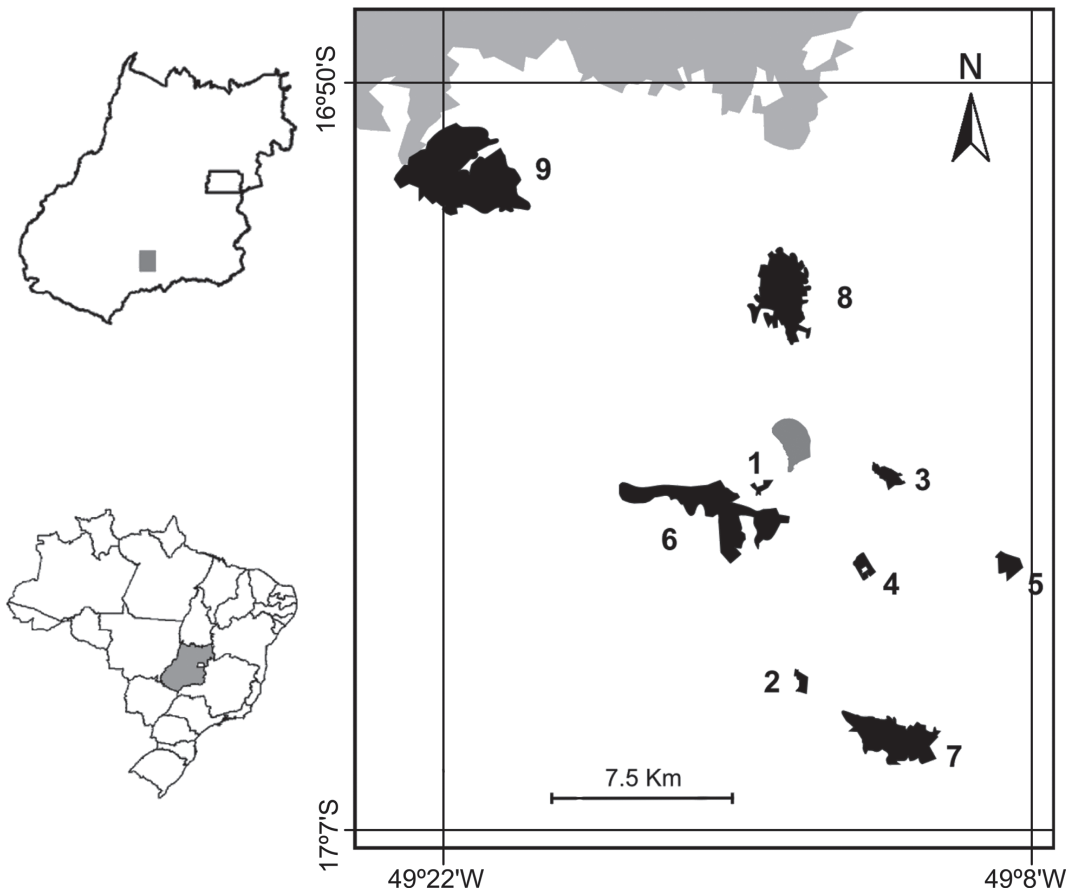

Figure 1. Location of the nine fragments of *cerrado* (savanna) studied. Lower left: map of Brazil with the State of Goiás highlighted; top left: map of the state of Goiás with the study area highlighted; right side: fragments where individuals of *Byrsonima pachyphylla* A. Juss. were studied. Gray areas represent the urban areas of the towns of Aparecida de Goiânia (above) and Hidrolândia (center).

Table 1. Size and geographic coordinates of the fragments of *cerrado* (savanna) studied in the town of Hidrolândia, in the state of Goiás, Brazil.

Fragment	Size (ha)	Geographic coordinates
1	19.50	16°58'59"S; 49°14'18" W
2	27.09	17°03'23"S; 49°13'28"W
3	53.02	16°58'50"S; 49°11'24"W
4	59.07	16°59'49"S; 49°14'09"W
5	68.06	17°00'50"S; 49°11'51"W
6	297.54	17°00'46"S; 49°08'38"W
7	427.35	17°04'40"S; 49°10'56"W
8	517.61	16°54'27"S; 49°13'51"W
9	1124.78	16°51'54"S; 49°21'53"W

well as the overall height, of *B. pachyphylla* individuals. To determine whether the density and size of *B. pachyphylla* individuals varied depending on the area of the fragments, we performed a linear regression analysis of fragment size in comparison with density, diameter and height. To reduce the asymmetric distribution of the data, the values of the sizes of the fragments were fixed by logarithmic transformation (Krebs 1999).

Fertility was assessed by estimating the number of fruits produced per individual in relation to the number of flowers. To that end, we collected all floral racemes of the seven selected individuals in each of the nine fragments. We counted the floral scars and the number of fruits produced by those 63 trees. The number of fruits was divided by the number of flowers produced and multiplied by 100 in order to arrive at the percentage of fruit produced by each hundred flowers of each individual. The results of this rate were considered the measure of fertility of each individual, and the mean of these values was considered the measure of fertility of each fragment. We conducted linear regression analyses of the fertility rate in function of the size of the fragments in order to determine whether fertility rates were higher in the larger fragments.

For all linear regressions, the assumptions of normality of residuals and variance homoscedasticity in the residuals were tested by visual analysis of a normal plot of residuals and the plot of residual versus independent variables. Given that none of the residual plots showed any kind of structure in the data, it was assumed that in all cases the assumptions of the regression analysis were met.

Effect of inter-fragment distance

To assess the effect that the distance between the fragments had on the fertility of *Byrsonima pachyphylla*, we performed spatial autocorrelation analysis. We used the estimated Moran's I with seven classes of geographical distance between the individuals sampled in the fragments, maintaining a constant number of observation pairs for each class. To assess the significance of the autocorrelogram as a whole, we used Bonferroni correction—α/k—in which α is the significance level (α=0.05), and k is the number of distance classes (seven, in this case). If any distance class shows a significant value (after the Bonferroni correction), we can assume that the autocorrelogram as a whole is significant; that is, *B. pachyphylla* fertility has a spatial structure. To perform the spatial autocorrelation analysis, we used the SAM software package, version 3.0 (Rangel *et al*. 2006), with 10,000 randomizations.

Results and discussion

Effect of fragment size

As can be seen in Fig. 2, the mean density of *Byrsonima pachyphylla* was significantly higher in the larger fragments (r^2=0.6403; *p*=0.0096). However, fragment size was not found to correlate significantly with stem diameter (r^2=0.0378; *p*=0.6161) or height (r^2=0.3243; *p*=0.1095). Several studies have shown the effect of fragmentation on aspects of plant species biology (Donaldson *et al*. 2002; Quesada *et al*. 2004; Aguirre & Dirzo 2008; Dunley *et al*. 2009; Elias *et al*. 2012). The low density of plants in smaller fragments might be attributable to the direct and indirect effects of fragmentation, such as edge effects, frequent fires and trampling/treading by livestock. These effects have a greater impact on young plants, hindering their germination or establishment (Lehouck *et al*. 2009), and, in the long term, the density of the population as a whole decreases, leaving only the previously established individuals.

A simple regression analysis between fertility rates and fragment size (Fig. 3) corroborated the hypothesis that *Byrsonima pachyphylla* individuals are more fertile in larger fragments (r^2=0.6569; *p*=0.0081). The higher fertility rates found for larger fragments are in agreement with the results of other studies, in which larger fragments were found to show greater plant species richness and abundance and the effects of the invasion of exotic species and human activities were found to be less pronounced (Renison *et al*. 2005; Carmo *et al*. 2011). Larger fragments are more functional and structurally similar to undisturbed systems, preserving greater genetic diversity and minimizing the negative effects of population reduction and genetic drift (Keller & Walter 2002; Reed & Frankham 2003). In addition, plants in larger fragments better preserve their network of interactions with other species, especially pollinators (Aizen *et al*. 2008), ensuring that the quantity and quality of pollen are sufficient for reproduction.

Pollen limitation is especially important if we consider that, together with resource limitation, it is one of the main factors determining the proportion of flowers that will produce viable seeds (Bierzychudek 1981). According to Aguilar *et al*. (2006), pollen limitation is the main cause of the decrease in the reproductive success of plant species in fragmented habitats. The increased risk of pollination failure is associated with pollen reaching the stigma in an

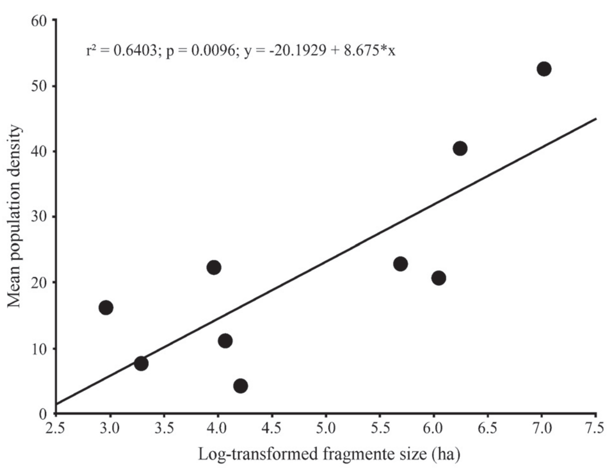

Figure 2. Simple linear regression analysis between the mean population density of *Byrsonima pachyphylla* A. Juss. (number of individuals within a 20-m radius of each selected individual) and the size of the fragments of *cerrado* (savanna) *sensu stricto* in the town of Hidrolândia, in the state of Goiás, Brazil.

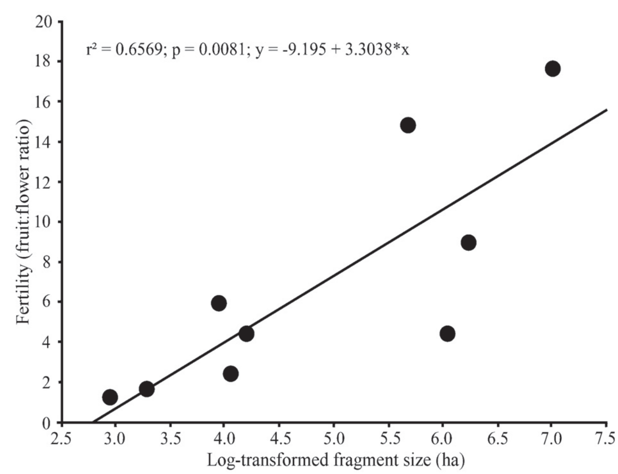

Figure 3. Simple linear regression analysis between the fertility of *Byrsonima pachyphylla* A. Juss. and the size of the fragments of *cerrado sensu stricto* in the town of Hidrolândia, in the state of Goiás, Brazil.

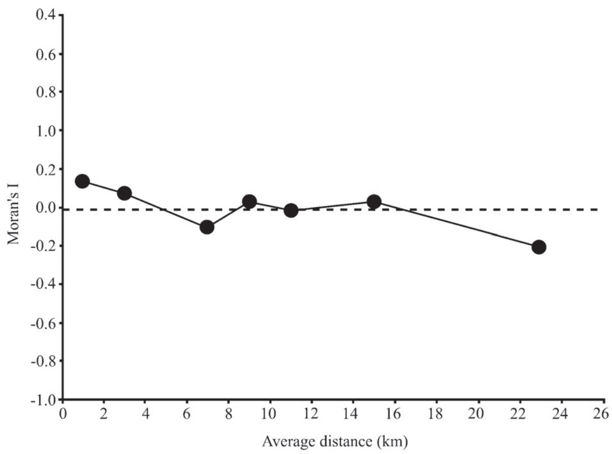

Figure 4. Moran's autocorrelogram (Moran's I) for the fertility of *Byrsonima pachyphylla* A. Juss. in fragments of *cerrado sensu stricto* in the town of Hidrolândia, in the state of Goiás, Brazil.

The dashed line indicates the value of Moran's I expected in the absence of spatial autocorrelation (I=−0.012). No values were statistically significantafter Bonferroni correction (α=0.05).

insufficient quantity, when stigma is not receptive, or as a mixture containing pollen from other species (Wilcock & Neiland 2002). These situations are associated with sparse populations featuring only a few individuals, all genetically similar to each other (Gargano *et al*. 2009). This could explain the fact that we found *Byrsonima pachyphylla* fertility to be lower in the smaller of the fragments analyzed, where the populations are likely to be smaller and less dense.

Effect of inter-fragment distance

We observed significant spatial autocorrelations, even after Bonferroni correction, only in the first distance class and in the seventh (last) distance class (Fig. 4). The expected value of Moran's I, under the null hypothesis (absence of a spatial autocorrelation), was I=−0.0120. As shown in Tab. 2, the spatial autocorrelation for the fertility of plants was positive for the first class (I=0.1330; p=0.0040) and negative for the seventh class (I=−0.2090; p<0.0010). The first class included only plants within the same fragment, whereas the seventh class included only plants that were ≥ 17 km from each other. Legendre & Legendre (1998) stated that positive values the last distance classes in an autocorrelogram should not be considered because they are due to large spatial range and formed by pairs of points bordering the surface. Based on that statement, the significant value at the last distance class found here is assumed to be an artifact of the data analysis, as discussed by Legendre & Legendre (1998), and therefore without biological significance. The plants within the same fragment (those represented by the first distance class) are subject to similar environmental conditions and are exposed to the same community of pollinators, which favors similar values of fertility. *Byrsonima pachyphylla* is pollinated by bees of the tribe Centridini, which are generally medium to large in size and, according Tscharntke *et al*. (2002), show a linear relationship between body size and distance traveled to forage. Long flights for pollination of plants throughout a given fragment promote similar fertility rates of *B. pachyphylla* within that fragment. However, bee visits to plants in other fragments are probably rare to nonexistent, because solitary bees are most affected by habitat loss and it is possible to observe a decrease in their populations in small-scale fragmentation due to their specific need for foraging (Steffan-Dewenter *et al*. 2002). This explains the autocorrelation for fertility found among *B. pachyphylla* individuals within the same fragment and the lack of such a correlation between individuals in different fragments.

Our results raise the possibility of fragments forming independent islands, isolated by a matrix that is mainly impermeable to the displacement of pollinators, as described in the Material and methods section. Small populations of plants have fewer reproductive individuals, which reduces resource availability for pollinators (Frazén & Nilsson 2009). According to Cunningham (2000), pollinators might not visit small, isolated plant populations, leading

Table 2. Moran's I for the seven classes of distances between individuals of *Byrsonima pachyphylla* A. Juss.

Class	n of pairs	Minimum distance (km)	Maximum distance (km)	Moran's I	p
1	522	0.00	0.95	0.133	0.004*
2	521	0.96	6.28	0.069	0.069
3	527	6.29	7.73	-0.108	0.015
4	519	7.74	10.36	0.029	0.375
5	522	10.37	13.12	-0.014	0.628
6	522	13.13	17.27	0.023	0.380
7	521	17.28	29.59	-0.209	<0.001*

*Statistically significant (α=0.05) after Bonferroni correction.

to the reproductive failure of those populations. Therefore, a small fragment in close proximity with a large fragment might not have the same fertility as the larger fragment, because there are great difficulties in maintaining the fertility of plants with low population densities found in small fragments.

In the present study, we identified no relationship between the size of *Byrsonima pachyphylla* plants and their fertility. However, we found that fragment size correlated positively with *B. pachyphylla* fertility, probably because larger fragments have better environmental conditions and maintain a more efficient pollinator fauna. The positive spatial autocorrelation was restricted to plants within the same fragment, which is a strong indication that the matrix is mainly impermeable, limiting the foraging of these pollinators to within each fragment. This results in marked differences between neighboring fragments, in terms of plant fertility, if the fragments differ in size. These results underscore the need to maintain environmentally protected areas large enough not only for the maintenance of populations of specific plants but also for their network of associated species—notably pollinator species—which tend to disperse little between the protected areas.

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