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Native forests within and outside protected areas are key for nine-banded armadillo (*Dasypus novemcinctus*) occupancy in agricultural landscapes

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ABSTRACT

Given the accelerating worldwide expansion of agriculture, biofuel production and managed forest plantations, the future of many tropical mammals depends on understanding why or when some species successfully survive in anthropogenically modified habitats, while others do not. Armadillos are potentially able to adapt to agricultural landscapes and play a key role as ecosystem engineers. However, it is not clear how dependent armadillos are on natural areas in agricultural landscapes and, more specifically, how or if armadillos can use sugar cane or managed forests as alternative habitats. Here, we assessed the relative effects of landscape features, composition and configuration, anthropogenic impacts and degree of protection, as potential predictors of landscape occupancy of the nine-banded armadillo (*Dasypus novemcinctus*). We deployed 203 camera trap stations in three agricultural landscapes of the Brazilian Cerrado, where sugar cane or managed forest cover most (> 50%) of the landscape. We found that cover by native forests and proximity to watercourses strongly and positively affect the occupancy of nine-banded armadillo. In contrast, managed forests mostly composed of *Eucalyptus* spp. had a negative effect on this armadillo's landscape occupancy. We did not detect the effect of sugar cane, although this particular result might be biased due to our sampling design. Overall, our findings indicate that even disturbed native forest strips, particularly those close to watercourses, are important habitats for this armadillo in agricultural matrices, demonstrating the utmost importance of native forests existing both within and outside protected areas. The Brazilian Forest Code protects native vegetation existing in rural private properties in Brazil, but adherence to this law by rural owners is still weak. Therefore, our study supports the strategic role this law plays in conservation in Brazil. Although not endangered by extinction, maintaining the nine-banded armadillo is important for a broader biota because of its putative role as an ecosystem engineer. The effective implementation of the Forest Code is therefore key not only to maintain this armadillos' populations but also to increase ecosystem services in agricultural landscapes.

1. Introduction

With the increasing demand for agriculture commodities and planted forest products, vast proportions of native forests have been converted into monocultures (Millennium Ecosystem Assessment, 2005). In this scenario of rapid changes in land cover and land use, knowledge on how animal populations cope with those disturbances is essential for improving the management of agricultural areas and developing effective conservation policy for wildlife (Gardner et al., 2009; Melo et al., 2013). Understanding why some species can successfully survive in anthropogenically modified habitats, while others cannot, is a key question in ecology, agriculture and conservation biology (Tscharntke et al., 2005; Newbold et al., 2015).

In tropical countries such as Brazil, one-third of the land has already been converted, and agricultural frontiers are still expanding (Sparovek et al., 2010). This is especially true for the state of São Paulo, which became dominated, in the last 40 years, by sugar cane monocultures and, to a lesser degree, by managed tree plantations (i.e., *Eucalyptus* spp. and *Pinus* spp.; Egeskog et al., 2014; CONAB, 2014; ABRAF, 2016). In fact, just 17% of its original vegetation remains today (Kronka et al., 2005; Metzger and Rodrigues, 2008). The resulting agricultural landscapes are mostly mosaics formed by a homogeneous matrix of agroecosystem permeated by remnant patches of native vegetation (Metzger and Rodrigues, 2008). Therefore, wildlife conservation in such human-dominated areas requires considering the productive land use (i.e., cropland; Gheler-Costa et al., 2013; Collins and Fahrig, 2017) from the

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perspective of the species in focus. Positive and negative effects may both occur; however, ecologically flexible species capable of exploiting these highly modified habitats should be more resilient as human expansion continues (e.g., Rodrigues et al., 2017).

The nine-banded armadillo (*Dasypus novemcinctus)* might have the potential to adapt to agricultural landscapes (McDonough et al., 2000; Dotta and Verdade, 2011; Bovo et al., 2018). These are medium-sized mammals (adult body weight: 3–6 kg) with a wide geographic distribution, encompassing most of the Neotropics and the southern tip of the Nearctic (southern United States). The nine-banded armadillo digs burrows for feeding, to raise young, to hide from predators and to buffer against environmental temperatures (McNab, 1980; Eisenberg and Redford, 1999). Given these aspects of their natural history, we can assume that they are directly dependent on soil surface physical and chemical properties. Therefore, changes in soil quality (e.g., changes in soil morphology and physical-chemical properties due to anthropogenic impacts), together with agrichemical exposure resulting from the widespread use of fertilizers, herbicides and pesticides typical of modern agriculture, might negatively affect them. Notwithstanding this, it is not clear how or if these armadillos surviving in agricultural landscapes (Dotta and Verdade, 2011) are dependent on native vegetation, such as forest patches. Further, we do not yet know how or if these armadillos use sugar cane or managed forests as alternative habitats. Although the nine-banded armadillo is relatively well studied in the United States (Superina et al., 2014), there is a dearth of ecological information on this species elsewhere (Eisenberg and Redford, 1999; Superina et al., 2014). There is almost no research focusing on habitat preferences or on the extent to which this armadillo can survive in anthropogenic environments. In fact, less than 20% of the armadillo studies were based on fieldwork conducted on wild populations (Superina et al., 2014; Loughry et al., 2015).

This information is relevant, considering the growing scenario of biofuel and managed forest expansion (Egeskog et al., 2014; ABRAF, 2016; Spera et al., 2017). Brazil is one of the world's largest ethanol producers (Monteiro et al., 2012; CONAB, 2014). As a result, sugar cane plantations dominate rural landscapes in some states, particularly São Paulo, where approximately one-third of the Brazilian ethanol production originates (CONAB, 2014; Egeskog et al., 2014). Brazil also ranks as one of the five largest cellulose producers in the world, with devoted areas to managed forest reaching upwards of 7.7 million hectares, most of which are from exotic species, such as *Eucalyptus* spp. and *Pinus* spp. (ABRAF, 2016). The state of São Paulo has the second largest area of managed forests in the country, with 1.19 million hectares (ABRAF, 2016).

Armadillos, as a whole, have important roles in the Neotropical ecosystems, so understanding how agricultural lands affect them is also relevant to a larger biota. Specifically, the nine-banded armadillo is a key prey for top and mesocarnivores (Bueno and Motta-Junior, 2004; Bianchi et al., 2010, 2011; Foster et al., 2010). Their burrowing activity alters vegetation, promotes sediment movement and nutrient cycling, and alters soil fertility and mineralization rates which, in turn, affects forest dynamics and regeneration (Sawyer et al., 2012). Their burrows might act as refuges for other vertebrate species and form suitable habitats for vertebrates and invertebrates, similar to what has been found for other armadillos (Machicote et al., 2004; Desbiez and Kluyber, 2013). Due to these ecological functions, which are similar for all species of armadillos, nine-banded armadillos, and probably other species of armadillo as well, might be recognized as ecosystem engineers (Jones et al., 1994; Machicote et al., 2004; Desbiez and Kluyber, 2013).

Here, we evaluate how agricultural and silvicultural landscapes affect nine-banded armadillos with occupancy modeling using camera trap data from three highly modified landscapes in southeastern Brazil. Specifically, we assessed the relative effects of landscape composition (native forest, sugar cane, and managed forest plantation) and configuration (edge density), as well as anthropogenic impacts (distance from human residences), degree of protection (government protected areas) and natural features (terrain slope and distance from watercourses) as potential predictors of landscape occupancy. Assuming that nine-banded armadillos are sensitive to anthropogenic disturbance (e.g., Ferreguetti et al., 2016), we predict that landscape occupancy is positively affected by areas of remaining natural habitat and negatively affected by distance to water (McDonough et al., 2000) and the amount of anthropogenic land cover types (i.e., sugar cane and forest plantation). Identifying land use patterns that are positively related to armadillos' occupancy would provide options for maintaining and enhancing armadillos' population and ecosystem services in agricultural regions. These options would be particularly valuable in regions where most of the natural habitats have been lost and in situations where taking cropland out of production for conservation is not feasible.

2. Methods

2.1. Study area

Our study area encompassed an area of approximately 132,000 ha in three agricultural landscapes (Fig. 1) within the Cerrado domain (i.e., Brazilian Savannah) of São Paulo State, southeastern Brazil (21°02´ − 21°43´S and 47°54´ − 47°16´W). The main municipalities in this area are Luiz Antonio, São Simão, Altinópolis and Cajuru. The annual temperature varies between 14 °C–28 °C, with a mean annual rainfall of 1470 mm. Rainfall is concentrated in the summer – October to March (CEPAGRI, 2014). Taken together, these three landscapes are characterized by important remnants of natural closed-canopy forest (21%; including a woody savannah ("*cerradão*"), semideciduous, deciduous, and riverine forests), located within and outside of protected areas, and which is surrounded by a heterogeneous matrix made up of *Eucalyptus* spp. (26%), sugar cane plantation (26%), other agricultural crops (13%), waterways (1%), and urban areas (3%).

However, the three study landscapes also have important differences. Landscape A is dominated by a large strictly protected area, the Jataí Ecological Station (JES; 9010 ha), equivalent to a category I protected area from the IUCN (strict nature reserve; IUCN, 2018), and by a smaller reserve (Luiz Antônio Experimental Station – LAES; 1759 ha), equivalent to a category VI protected area from the IUCN (protected area with sustainable use of natural resources; IUCN, 2018). Overall, sugar cane is the predominant land cover type (Table 1). Landscape B is a private property from International Paper (Cara Preta Farm – CPF; 4546 ha) and is predominantly covered with commercial plantations of *Eucalyptus* spp. for paper production. The remaining native forests are protected along rivers and streams (areas of permanent preservation, protected by the Brazilian Forest Code; Brancalion et al., 2016). The third and last landscape (C) is a "mix" between the former two landscapes, with a smaller but still predominant cover by managed forests (*Eucalyptus* spp. and *Pinus* spp.; Table 1). It includes a private farm from International Paper (Dois Corregos Farm – DCF; 2017 ha), a protected area with sustainable use of natural resources (Cajuru State Forest – CSF; 1909 ha) and native forests protected by the Forest Code (Table 1 and Fig. 1).

2.2. Armadillo sampling

We obtained data on armadillos (see Section 3) from camera trapping and track sampling. The camera trapping was based on a total of 203 sampling sites distributed in a grid of 200-ha cells, with cameras placed at the center of each cell. In some cases, we were unable to access the center of the 200-ha cell to place the camera, so we placed them as close as possible. All cameras were spaced ≈ 1.4 km apart. We systematically placed cameras inside JES-LAES (n = 52), CPF (n = 18), and CSF-DCF (n = 19) and randomly placed a similar number of cameras up to 2.6 km from the perimeter of protected areas and areas of permanent preservation (Fig. 1).