Combining landscape traits, governance regimes, and threats into an integrative framework for conserving complex landscapes

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Abstract

Biodiversity conservation in heterogeneous landscapes faces the challenge of accounting for the complex interactions between the variation in species responses, existence of multiple habitats, diverse governance regimes, and anthropogenic threats. Yet, the scarcity of integrative studies still limits our understanding of the combined effects of social and ecological factors on biodiversity. We propose a framework for the management of heterogeneous landscapes that explicitly accounts for the interactive effects of governance regimes and anthropogenic threats on key landscape traits that affect biodiversity. We then apply the framework on bird conservation in the Espinhaço mountain range, an heterogeneous landscape composed of cerrado, forest and rupestrian grasslands, in the Southeast of Brazil. The model considered birds that inhabit these three type of environments, whose populations are influenced by habitat area, landscape integral connectivity and connectivity among strictly protected areas via multiple least-cost corridors. We assessed the effects of three governance regimes and three major threats on the aforementioned landscape traits for each bird group. The relative habitat area and integral connectivity for rupestrian grassland's birds are more widely covered by strictly protected areas compared to those inhabiting cerrado and forest. Corridors among strictly protected reserves potentially used by the three bird groups are mostly found inside sustainable-use reserves. Mining and wood-cover loss affects mainly habitat area for forest birds, while fire endangers habitat for rupestrian grassland birds. The integrative framework proposed by our study can be applied elsewhere fostering an heuristic knowledge assisting scientists and practitioners for conserving highly complex landscapes.

1. Introduction

Population, community, and ecosystem studies often focus on very specific parts of social-ecological systems, such as a selected species, a single habitat type, a unique ecological process, one or few environmental governance regimes or certain anthropogenic threat. Mostly, simplification is the only way to understand biodiversity and ecosystems given their inherent complexity. Nevertheless, expanding the range of analysis by including multiple systems' elements, as well as the interaction among them, without losing precision, is wishful. Yet, integrative analyses of conservation that addresses both social and ecological complexity are rare.

One overlooked aspect of simplistic ecological models is landscape heterogeneity, which is defined as the qualitative and quantitative variation in landscape elements (Li and Reynolds 1994; 1995; Fahrig et al. 2011), including the variety and the spatial arrangement of land cover types compositional and configurational heterogeneities, respectively (Li and Reynolds 1995). The idea of islands composed of a single habitat type embedded in a non-habitat environment echoes in much of the ecological literature (Perfecto and Vandermeer 2008). However, landscape heterogeneity increases when more than one habitat type is considered and when habitat patches present a variety of shapes and sizes. Both compositional and configurational heterogeneities influence biotic and abiotic processes important for maintaining functional landscapes, including predation (Kauffman et al. 2007), pest control (Gardiner et al. 2009), pollination (Boscolo et al. 2017), and the movement of individuals (Romero et al. 2009).

Habitat area is traditionally known as the most important factor for conserving biodiversity and when addressing the conservation of heterogeneous landscapes, conservationists have often used the concept of representativeness. Habitat representativeness is defined as how different habitats are under or overrepresented by reserves relative to their area, in another words, the proportion of habitat under protection (Braz and Cavalcanti 2013; Austin and Margules 1986). Nevertheless, ecologists, biologists and environmental scientists are becoming aware that apart from protecting large habitat tracks, certain biological processes must be preserved in order to maintain landscape functionality and stability for species, including humans. Among those ecosystem processes, landscape connectivity has a key role to the long term persistence of populations in patchy landscapes (Taylor et al. 1993). Sub-populations (a population's subset of individuals) connected via dispersal in highly connected landscapes are able to guarantee recolonization after possible local extinction events, a process known as "rescue effect" (Brown and Kodric-Brown 1977). Thus, conservationists should target the protection of landscape features that are important for landscape connectivity, particularly for functional connectivity, defined as how much a given landscape fosters of renders biological flux given its structure and the species responses to it (Metzger 2001).

Functional connectivity is fundamental for conservation and can be addressed in different ways, from regional to local levels, including the entire landscape or by connecting specific places, such as reserves or large habitat patches. Yet, assessing functional connectivity on heterogeneous landscape is challenging. Different land cover classes present diverse influences on species movements across landscapes and those classes most similar to species habitats can assist in the maintenance of the landscape functional connectivity (e.g., agroforests allow the movement of bird species between native forest patches) (Goulart et al. 2015). Among the methods for modeling and understanding functional connectivity, the integral index of connectivity (Saura and Pascual-Hortal 2007; Horta et al. 2018) provides good indicators of how much a given landscape or a habitat patch is important for functional connectivity. Another approach is least-cost corridors, which stands out for identifying routes that may act as ecological corridors between habitat patches (Goulart et al. 2015; Bhakti et al. 2021; Graviola et al. 2021). As to habitat area, the concept of representativeness could be adapted to the understanding of how different governance regimes protect connectivity for biodiversity. This issue could be particularly useful in the understanding and management of heterogeneous and complex landscapes.

Heterogeneous landscapes are also often subjected to diverse governance regimes, from strictly protected, sustainable-use, and the matrix, which increases complexity for conservation scholars and practitioners. We here define matrix as the area that is not under legal protection, which is generally composed of a set of anthropogenic managements, natural and semi-natural areas, although we are aware of the other possible definitions of this term (Forman 1995; Kupfer et al. 2006; Perfecto et al. 2009). These diverse governance regimes have different impacts on nature conservation or degradation, and while many studies have devoted to measuring how much each regime effectively protect habitats, some researchers argue that multiple strategies acting in an integrated form are best (Blackman 2015; Lima et al. 2020). In this sense, the mosaic composed of different governance regimes is a promising option. In Brazil, the Conservation Mosaics is a national policy that combines management of multiple strict conservation reserves (from local to national parks) together with sustainable-use reserves [called Environmental Protection Areas (EPAs)] in association with matrixes' stakeholders. This is an effort to integrate governance networks, at the same time that optimizes and maximizes conservation strategies. Due to the fact that most ecological processes are not restricted to individual conservation units, but act on the entire landscape, the strategy of Conservation Mosaics may be better fitted into ecological scales, and thus more successful in conserving biodiversity and ecosystems at long term (Bergsten et al. 2014).

Apart from those issues, multiple drivers of species loss are rarely considered together in a single framework. Instead, studies focus on isolated threats, such as deforestation (Nolte et al. 2013), fire (Nepstad et al. 2006), exotic eucalypt afforestation, agriculture intensification (Fernandes et al. 2016; Goulart et al. 2016; Goulart et al. 2016) or mining on habitats (Sonter et al. 2017) or species (Pena et al. 2017). All these impacts reduces habitat area and function connectivity for wildlife. Yet, to have a complete picture of the biodiversity threats, there is a need to understand how these impact act synergistically.

The Espinhaço mountain range, located in the Southeast of Brazil, is notable for its biological importance, natural heterogeneity, social complexity, as well as the diversity of threats. The western part of the mountain range is characterized by the Cerrado biome, a savanna-like environment, while the eastern slope is dominated by a semi-deciduous tropical forest, the Atlantic Forest biome (see reviews in Fernandes 2016b). Both of these biomes are considered global hotspots for conservation (Mittermeier et al. 1998). The upper parts of the mountain range are covered by the rupestrian grassland, a mixture of rocky outcrops, bushlands and grasslands, considered a Biosphere Reserve by UNESCO due to its species and ecosystems richness (Miola et al. 2021; Fernandes et al. 2020; 2018). All the three environments forest, cerrado (both are written in minor case letters to distinguish the ecosystem type from the biome, which is written in upper case), and rupestrian grassland, are inhabited by their specific biological community, among which, birds distinguish due to their large diversity and degree of endemism (Vasconcelos 2008; Hoffmann et al. 2020). Parallel to this fact, the governance regimes are also very diverse, and the region is composed of a network of strictly protected and sustainable-use reserves, surrounded by a matrix formed by a variety of land covers and management types (from managed pastures to natural habitat patches).

Within the Espinhaço mountain range lies the Mosaic of Conservation Units of the Espinhaço: Alto Jequitinhonha - Serra do Cabral, hereafter Espinhaço Mosaic (EM) (www.icmbio.gov.br/portal/images/stories/mosaicos/planejamento-espinhaco.pdf). Conservation Mosaic is a model that seeks for integrating management of reserve networks via a participatory basis, in order to conserve biodiversity, ecosystems and foster sustainable development adopted by the Brazilian government since 2010 (http://www.mma.gov.br/areas-protegidas/instrumentos-de-gestao/mosaicos). The EM was built under a participatory basis including the State Forest Institute (IEF), Ministry of Environment, Chico Mendes Institute for Biodiversity Conservation, together with the NGOs Biotropicos Institute and Conservation International (https://www.icmbio.gov.br/portal/images/stories/mosaicos/planejamento-espinhaco.pdf).

As the other parts of the Espinhaço mountain range, the EM is composed of a diversity of vegetation types (mostly forest, cerrado and rupestrian grasslands), all of which inhabited numerous species of endemic and endangered birds. The EM is subjected to multiple governance regimes (from strictly protected reserves, sustainable-use reserves, to the matrix), as well as is under a set of anthropogenic threats, such as afforestation, road development, mining activities, urban expansion, fires (Pena et al. 2017; Fernandes et al. 2018; Fernandes et al. 2016; Sonter et al. 2013). The physical, environmental, biological and social aspects of this region make it a good case study for integrating the analysis of biodiversity conservation in a highly complex landscape.

Given the above mentioned, we propose an analytical framework that contributes to the management of complex landscapes by understanding the interactive effects of anthropogenic threats and governance regimes on landscape traits that are determinant for biodiversity conservation. We then apply the framework to the management of bird conservation in the EM. To this end we selected the main landscape traits that are important for maintaining such diversity (habitat area, integral landscape connectivity, connectivity among strictly protected reserves), main governance regimes (matrix, strictly protected reserves, sustainable-use reserves) and main threats that are known to occur in the region (fire, mining and wood-cover loss).

More specifically, this study aims at assessing the following objectives (Fig. 1):

i. Compare the area representativeness of the different governance regimes in terms of covering habitat area.
ii. Compare the representativeness of the different governance regimes in terms of protecting landscape integral connectivity .
iii. Compare the representativeness of the different governance regimes in terms of protecting connectivity among strictly protected reserves.
iv. Compare the occurrence of different threats on habitat area.
v. Compare the occurrence of different threats on the landscape integral connectivity.
vi. Compare the occurrence of different threats on the connectivity among strictly protected reserves.

2. Methods

2.1. Study area

The EM is a region with outstanding levels of biological richness harboring many endemic species of plants, vertebrates and invertebrates (Barata et al. 2016; Echternacht et al. 2011; Pinho et al. 2017). It is located in the center portion of the state of Minas Gerais, Southeastern Brazil. Our study area was defined by the ten reserves that compose the EM, as well as a 10km-radius buffer surrounding all the reserves, comprising 786.923 thousand hectares.

2.2. Bird species

We selected bird species based on their habitat specificities or ecosystems endemism, that are known to occur on the EM, namely forest, cerrado, and rupestrian grassland's birds. These groups can be understood as models for other species of the habitat-specific communities. Forest birds were those that are endemic of the Atlantic Forest biome and typical of and abundant on forest habitats, namely *Chiroxiphia caudata* (Swallow-tailed Manakin), *Pyriglena leucoptera* (White-shouldered Fire-eye), *Ilicura militaris* (Pin-tailed Manakin) and *Myiothlypis leucoblephara* (White-browed Warbler). The cerrado birds are those species that are typical of the savanna formations, such as *Lepidocolaptes angustirostris* (Narrow-billed Woodcreeper) and *Cyanocorax cristatellus* (Curl-crested Jay). Although these are not strictly endemic from the Cerrado biome (Lopes, 2008), they are very abundant in this ecosystem and are representatives of this biome. Finally, species classified as rupestrian grassland birds are species endemic to the rupestrian and altitude grasslands in areas above 1000 meters (*Asthenes luizae, Embernagra longicauda*, *Augastes scutatus)*.

2.3. Landscape characterization: Land cover map, governance regimes and threats

To characterize our study area, we used the land cover map developed by the Minas Gerais State Forest Institute (FEAM). The mapping process was conducted using Landsat satellite images, with 30 m resolution for the year 2009. Although this map was created more than a decade ago, it was produced by a team of experienced botanists and cartographers using a large set of calibration points, it was subjected to thorough validation, and can be considered the most complete and detailed vegetation map of Minas Gerais State. We combined land cover classes of the original map in accordance with the habitat requirements of the selected bird species. Semi-deciduous stationary sub-montane forest, semi-deciduous stationary montane forest, and deciduous stationary montane forest were combined into a single "forest" class. Grassland and rupestrian grassland were combined into one class named "rupestrian grassland". This category does not include agriculture fields or exotic *brachiaria* pasture formations. Cerrado savanna and Buriti palm groves were combined into "cerrado". Patches smaller than 1 hectare were excluded from the analyses as most selected birds have territories larger than this area (Freitas and Rodrigues, 2012; Fujikawa, 2011; Ribon and Marini, 2016).

We classified the governance regimes into three classes: strictly protected reserves, sustainable-use reserves, and matrix. Strictly protected reserves included parks under different jurisdiction, from municipal level, state, and national parks. According to the International Union for Conservation of Nature (IUCN) these areas are classified in the Category Ia "Strict Nature Reserves". Sustainable-use reserves included areas under state level. These areas can be included under the IUCN Category VI, "Protected area with sustainable use of natural resources". The surrounding area defined by the 10km-radius buffer outside the reserves was classified as "matrix".

We considered three types of threats, which are known the be the main drivers of biodiversity loss in the region according to the literature (de Castro Pena et al. 2017; Fernandes et al. 2018): mining, fire and wood-cover loss (Fig. 3). These spatial information have their specificities and different time-scales, which are related to the way these phenomena were assessed (Fig. 3). A map in vector format of the current mined areas in the EM was acquired from the National Department of Mineral Production (DMPN), which includes polygons representing the official records of mining extraction, licensed mines, and artisanal mining (*lavra garimpeira*). We obtained records of fire-outbreaks (a point feature map) from the years 2017–2019 from the National Institute of Space Research (INPE, https://queimadas.dgi.inpe.br). This data set was produced by the project "*Platform of Monitoring and Warning of Forest Fires in the Cerrado*" (ProCerrado INPE) and includes point records obtained from different satellites. We obtained data about wood-cover loss from a time series of wood cover change obtained through the classification of Landsat satellite images from 2000 through 2018 with 30 m resolution (https://earthenginepartners.appspot.com/science-2013-global-forest). In this dataset, wood cover change includes native or cultivated (silviculture) woody vegetation that was lost or gained in each pixel of the Landsat satellite images during the period of interest (Hansen et al. 2013).

2.3.1. Modeling landscape functional connectivity in the EM

2.4.1. Integral Index of Connectivity (dIIC)

We calculated the mean value of the delta of the integral index of connectivity (dIIC) using a binary approach for each habitat type and for each of the bird groups in ten reserves of the EM (Fig. 4). The dIIC is the most recommended index for binary connectivity (Pascual-Hortal and Saura, 2006) and was calculated using the software Conefor Sensinode 2.2 (Saura and Torné, 2009) and given the following formula (1):

$$IIC = \frac{\sum_{j=1}^{n} \sum_{j=1}^{n} \frac{aiaj}{1} + nlij}{AL^2}$$

1

where nl_{ij} is the number of links in the shortest path (topological distance) between patches *i* and *j*, and *a* is the patch attribute (generally the patch area). A_L is the landscape area, and *a* is the patch area. The IIC considers inter-patch distance, patch sizes (assuming the patch itself is a space, in which connectivity exists), and dispersion thresholds (propagules' maximum dispersal distance in a given matrix). The delta IIC (dIIC) is the difference between landscape integral connectivity with and without the target patch. For each cell, we simulated dIIC according to three different dispersal thresholds (propagules' maximum dispersal distance in a given matrix), which was associated to the matrix permeability scenarios, for each of the habitat-specific birds. We selected 100 random points per reserve in which dIIC were sampled. The dispersal threshold was assumed to be 500 meters in a non-habitat matrix, as most species are not long range dispersers and avoid crossing over non-habitat areas (Marini, 2010) (Yabe et al. 2010). To avoid bias in terms of habitat patch area (large habitat patches to have disproportionate large values), dIIC values were divided by the patch area.

2.4.2. Connectivity among reserves through Multiple Least-Cost Corridors (MLCC)

To estimate preferential dispersal routes between habitat patches and reserves of the EM for each bird group, we modeled Multiple Least-Cost Corridors (MLCC) using the software LSCorridors (LSCorr, Ribeiro et al. 2017). This approach is considered more adequate than the traditional least-cost path modelling because it generates multiple possible solutions of paths between pairs of habitat patches and assumes variance on the input parameters, increasing realism, robustness and confidence (Ribeiro et al 2017). LSCorr was already applied in different contexts and for different purposes, from estimating functional connectivity for pollinators (Boscolo et al. 2017) to modelling ecological corridors for people and birds in urban landscapes (Schneiberg et al. 2020, Graviola et al 2021, Bhakti et al 2021).

The MLCC model depends on two basic inputs, a resistance surface, and source and target points. In the resistance surface, each pixel represents the difficulties with which each organism would have to cross each land cover/vegetation type class. The higher the resistance value, the lower will be the permeability of that pixel and thus, lower will be the probability of that pixel to be selected as the most possible route. We obtained information about bird groups movement capacity through expert knowledge. This approach is useful when information about the influences of landscape composition on biodiversity is lacking, which is the reality for most Neotropical bird species. We sent a questionnaire to four experienced ornithologists. All of them hold a PhD in Ecology, Zoology or related fields and have experience in conducting long-term research about birds in the Espinhaço mountain range. Table 1 shows the mean relative resistance value of each land-cover type for each of the three bird groups.

Table 1
Mean friction value (resistance) of each ecosystem types to forest, cerrado and rupestrian grassland's birds.

ECOSSYSTEMS TYPES	BIRD SPECIES		
	forest	cerrado	rupestrian grassland
forest	1.0	2.2	8.2
cerrado	5.6	1.0	7.2
rupestrian grassland	7.9	3.8	0.5
pasture	9.5	4.6	8.3
urban infrastructure	9.8	5.6	8.5
perenial crops	9.0	4.2	9.0
anual crops	9.6	5.2	9.2
water	9.3	8.4	9.3
silviculture	6.9	4.8	10.0

Regarding sources and targets among which bird movement were simulated, we created random points in habitat patches inside the strictly protected reserves. This approach allows the estimation of preferential routes between the reserves considering specificities of each one of the bird groups. The MLCC were modeled using the parameter MP (Measures by Pixel) of LSCorr and the default value (2.0) of the variability parameter. In this approach, for each bird group, LSCorr generates a map with uniformly distributed random values ranging between 0 and 1 and multiply it by the variability to add a degree of stochasticity in the simulations (when the variability is equal to 0, it means no stochasticity is added in the simulations) (Ribeiro et al. 2017). Then, LSCorr adds 1 to each pixel of the resulted map and finally multiply this map by the resistance map (Ribeiro et al. 2017). This final map is used to simulated the MLCC. The LSCorr output is a raster image containing the frequency with which each pixel was selected during the MLCC simulations (Route Selection Frequency Index, RSFI). Groups of pixels with the highest RSFI values represent the best potential routes between the pair of sources and targets. We extracted the RSFI values located in the matrix and within sustainable-use reserves to assess their contribution in conserve connectivity between strictly reserves. We ran 100 iteractions (routes) among every pair of points (source and targets), 4500 corridors for each bird group, totalizing 13500 corridors.

3. Results

3.1. Modelling landscape functional connectivity in the EM

The dIIC analyses reveled that most important patches for landscape connectivity of Cerrado and rupestrian grassland are located at the northern part of the EM, while forest patches that mostly contribute to connectivity is located in the Southern parts (Fig. 4, left hand side). Most least-cost corridors for rupestrian grassland birds connect northern and southern passes through southwestern parts of the EM, while forest corridors are mostly located at the southeast (Fig. 4, right hand side). The description of the intercrossed results are fully described below.

3.2 Governance X habitat area (objective I)

Most of the studied area is composed by the matrix, while a smaller portion is composed of strictly protected or sustainable-use reserves (Fig. 6A). The cerrado's relative area in the matrix is larger than forest and rupestrian grassland, respectively. Greater proportion of forest is found in sustainable-use reserves, compared to rupestrian grassland and particularly cerrado, which has less than 5% of its area under this governance regime. Rupestrian grasslands are underrepresented by sustainable-use reserves, covering less than 10% of this habitat area. Among the ecosystems types, rupestrian grassland has greater proportional area in strictly protected reserves. This is an expected pattern as most the reserves in this region were stablished to protect the rupestrian grasslands.

3.3. Governance X landscape integral connectivity (dIIC) (objective II)

A greater proportion of habitat patches that are important for the conservation of landscape integral connectivity of rupestrian grasslands birds is found in strictly protected reserves, followed by sustainable-use reserves and matrix (Fig. 5). A similar pattern is found for forest, with no remarkable differences between sustainable-use reserves and matrix. However, most important patches for the conservation of the landscape connectivity of the cerrado birds is found in the matrix.

3.4 Governance X connectivity among reserves (MLCC) (objective III)

The pixels selected as the best potential routes produced by the MLCC simulations among the strictly protected reserves reached higher values (RSF) in sustainable-use reserves for the three bird groups compared to the matrix (Fig. 5). Additionally, MLCC simulated for forest and rupestrian grasslands birds reached higher RSFI values than those simulated for the cerrado birds in sustainable-use reserves.

3.5 Threats X habitat area (IV)

The number of fire outbreaks was much larger on rupestrian grassland than the number recorded in the cerrado or forest areas (Fig. 6). A larger proportional area of forest habitat was impacted by mining compared to rupestrian grassland and cerrado, respectively. Wood-cover loss affected larger proportional area of forest compared to cerrado.

3.6 Threats X integral index of connectivity (dIIC) (V)

The relative impact of fire on landscape connectivity measured as the sum of the delta values of integral index of connectivity (dIIC) on burned points (fire outbreaks) per habitat area was about an order of magnitude greater on rupestrian grasslands compared to cerrado and forest habitats. A similar pattern was found for mining impacts, for which the sum of the dIIC on mined areas per habitat area was larger on rupestrian grassland, while it was insignificant on forest and cerrado. Integral connectivity of forest, on the other hand, was more impacted by wood-cover loss, and the sum of dIIC of pixels that suffered wood-cover loss was more than twice the value found for cerrado (Fig. 7).

3.7 Threats x connectivity among reserves (MLCC) (VI)

The sum of the accumulated frequency (RSF) of burned pixels crossed by simulated MLCC among strictly protected reserves divided by habitat area was larger on forest, compared to cerrado and rupestrian grassland, respectively (Fig. 7). Mining affected disproportionally connectivity among the strictly protected reserves for forest birds, compared to those that inhabit cerrado or rupestrian grassland. The accumulated RSF that suffered wood-cover loss per habitat area was larger on forest compared to cerrado.

4. Discussion

A large proportion of the matrix of the Espinhaço Mosaic is still composed by forest, cerrado, and rupestrian grassland. Among the habitat types, rupestrian grassland has more proportional area under strict protection compared to the other two habitat (objective I). Therefore, future implementation of strictly protected reserves should be oriented to include especially forested and cerrado areas, conserving bird species typical of these habitats. Nevertheless, cerrado is underrepresented by sustainable-use reserves, which can be seen elsewhere (see (Fernandes, 2016), while forests and rupestrian grasslands have larger areas under this governance regime. These results can guide future landscape planning interventions by balancing the proportion of each habitat under different government regimes, enhancing the EM´s ability in conserving a functioning landscape for all the bird community.

Strictly protected reserves cover patches that are important for the conservation of landscape integral connectivity (objective II) of forest and rupestrian grasslands birds. On the one hand, most patches that are important for conserving the landscape integral connectivity for cerrado birds are found on the landscape matrix. These results are in accordance with the habitat distribution across the EM landscape. Since most of the area is covered by rupestrian grassland, its patches presented high dIIC values. Therefore, even under several threats such as mining, afforestation, and fire (Castro Pena et al 2017, Fernandes et at., 2018, 2020), the rupestrian grassland of the EM still is highly connected, which ensures the conservation of bird populations that use this habitat. Nevertheless, this analyses does not consider the effects of climate change, which is known to greatly reduce habitat area as well as connectivity for these species (Hoffmann et al. 2020). Most of the cerrado patches with high dIIC values are found are in the matrix, hence future actions should focus not only on increasing cerrado representativeness under protection, but also in preserving patches with high landscape integral connectivity indicators in the context of the Espinhaço mountain range.

In terms of the connectivity among strictly protected reserves, we observed that most of the best potential routes of simulated MLCC (higher RSF values) crossed sustainable-use reserves when compared to the matrix (objective III). Since most of the routes crossed sustainable-use reserves, the EM may be capable of protecting the ability of bird populations to move through habitat patches, especially those patches under strictly protected regimes. This is again particularly important in face of climate change, which could displace birds population that inhabit the rupestrian grasslands (Hoffman et al. 2020). Given the distribution shifts of most species, maintaining and increasing functional connectivity is even more urgent.

Threats are not evenly distributed among ecosystems types. Fire outbreaks occurred more than an order of magnitude more frequent in the rupestrian grassland compared to forest and cerrado, affecting mostly birds that depend on this former habitat (objective IV). It is likely that, in spite of higher tolerance to fire, the rupestrian grassland vegetation is more susceptible to burnings due to the grassy vegetation which acts as fire fuel. Also, people tend to ignite fire on rupestrian grassland where the vegetation enable cattle raising and as a retaliation for still unpaid properties during reserve creation (Fernandes et al. 2018). Also, some strictly protected reserves, such as the Sempre Vivas National Park, is using prescribed fires for preventing large scale and destructive burnings.

Mining affected relative habitat area of the three habitats, particularly forest. Wood-cover loss mostly affected forest habitats compared to cerrado. This may be an indication that deforestation is more oriented towards forest areas, in comparison to cerrado, possibly due to the more profitable timber resources of the Atlantic Forest areas (da Cunha et al. 2021). All these trends presented a spatial bias on impacts on the different habitat types. Thus, decision makers can use these results to target specific impacts where they are more frequent and intense.

We also noticed a spatial bias on the impacts of fire, mining and wood-cover loss on functional connectivity. The impacts of mining and fire are greater on the integral landscape connectivity of rupestrian grasslands birds compared to those that inhabit the other habitats (objective V). On the other hand, wood-cover loss had greater impact on the integral connectivity of forest birds patches compared to those of the cerrado. Therefore, local and regional governance schemes, including law enforcement, environmental education, strengthening institutional capacity and increasing surveillance should focus on preventing illegal fire and mining on the rupestrian grassland, and timber harvesting on forests.

Regarding the connectivity among strictly protected reserves, the best potential routes simulated for forest bird species are threatened by wood-cover loss, fire, and mining. Interestingly, and different from what we observed in the dIIC results, the best potential routes simulated for forest species mostly crossed areas impacted by fire even with the reduced area of forest impacted by this threat. Therefore, although deforestation is a threat to landscape connectivity of forest birds, as pointed out by the dIIC analyses, important forest corridors that connects bird population inhabiting strictly protected reserves are mostly impacted by fire. As most routes among strictly reserves are located on sustainable-use reserves, this governance regime should increase protection of these forest corridors from fire. Therefore, efforts should be placed in protecting these corridors, safeguarding bird populations at long run.

5. Conclusions

Given the fact that species, habitats and ecosystems are being destroyed at fast pace, conservation scientists are urged to build models that fosters solutions for protecting nature in real landscapes, assuming their physical, biological, and social heterogeneity and complexity. As an effort to partially fill this gap and contribute to make management tasks more effective, we proposed a framework for integrating the analyses of the influences of different landscape traits, governance regimes and threats for the conservation of distinct bird groups. Although this framework was applied to the Espinhaço Mosaic, it could be used in any other heterogeneous and complex landscapes. By overlapping landscape traits, governance regimes and threats, a heuristic knowledge concerning the efficiency of the Espinhaço Mosaic in preserving its biodiversity can be achieved. By integrating such knowledge, biologists, ecologists, environmental scientists and decision makers can obtain a complete picture of the complex and multiple forces acting in favor or against biodiversity conservation in heterogeneous landscapes, optimizing planning and management. Conservation Mosaics, such as the one proposed by the Brazilian law, are important for landscape conservation for integrating decision making and stakeholders which act in governance networks. However, this conservation strategies will only fulfill their goal in protecting biodiversity if taking into account habitats' representativeness under different government regimes and by controlling the main threats that can lead to the loss of habitat and landscape connectivity.

Declarations

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Authors' contribution: All authors contributed to the study conception and design. Fernando Figueiredo Goulart prepared the data, conducted the part of the analyses and wrote the manuscript.

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Figures

Fig. 1

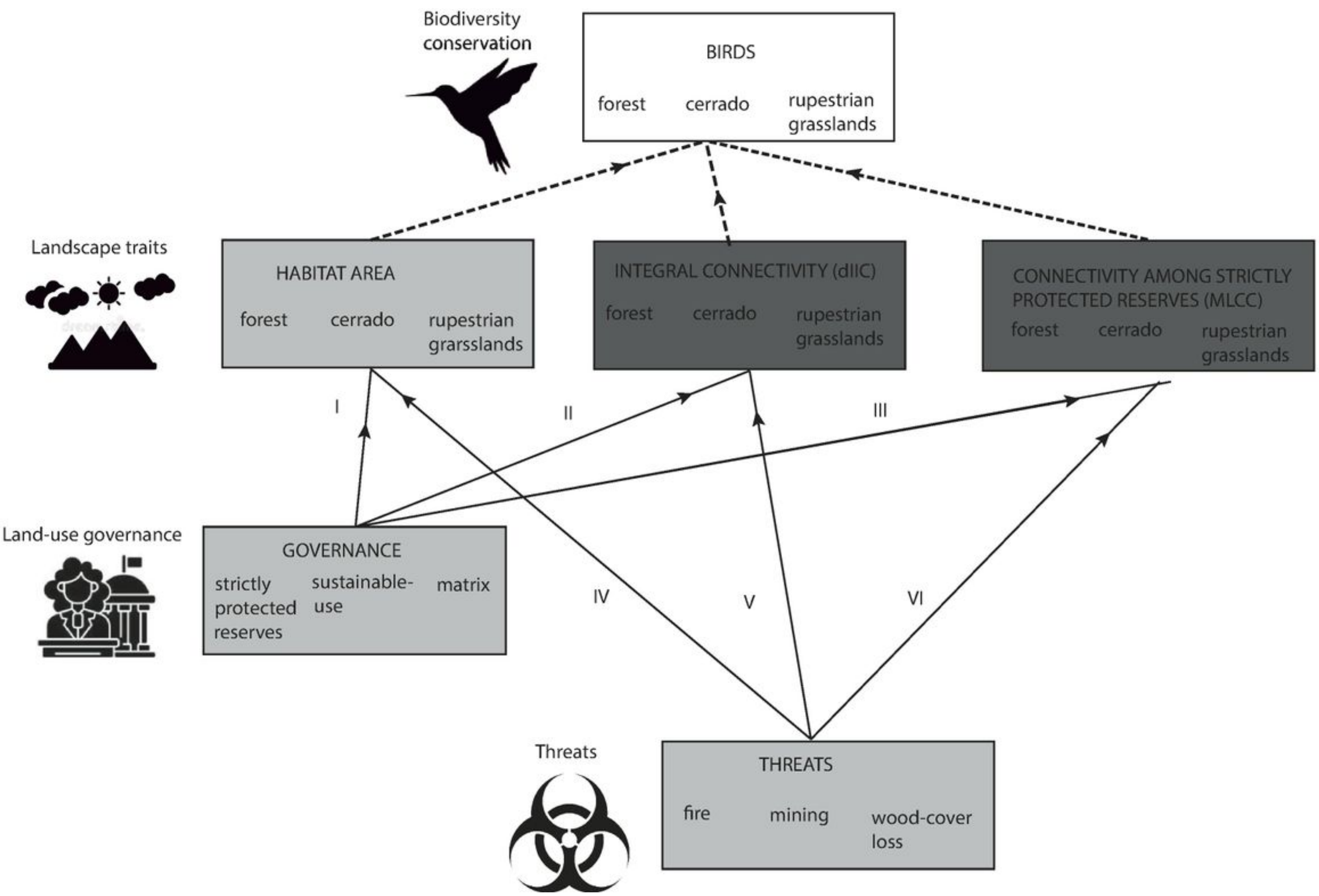

Figure 1

Diagram of the proposed framework. Dashed lines represent presumed links and solid lines represent analyzed relationships. At the top, conservation of forest, cerrado, and rupestrian grasslands birds that are induced by landscape traits. Landscape traits are analyzed in terms of habitat specific area and functional connectivity, including landscape integral connectivity and multiple least-cost path among strict reserves. Additionally, main governance regimes and major biodiversity threats are also considered (mining, fire and wood-cover loss). The following influences were analyzed: the effect of land use governance on habitat area (I), integral index of connectivity – IIC (II), connectivity among strictly protected reserves via multiple least-cost corridors -MLCC (III); and the influence of threats on habitat area (IV), IIC (V), MLCC (VI). White boxes refer to non-spatial and secondary information, light gray boxes are secondary spatialized data (maps), while dark gray boxes concern the results spatially explicit models.

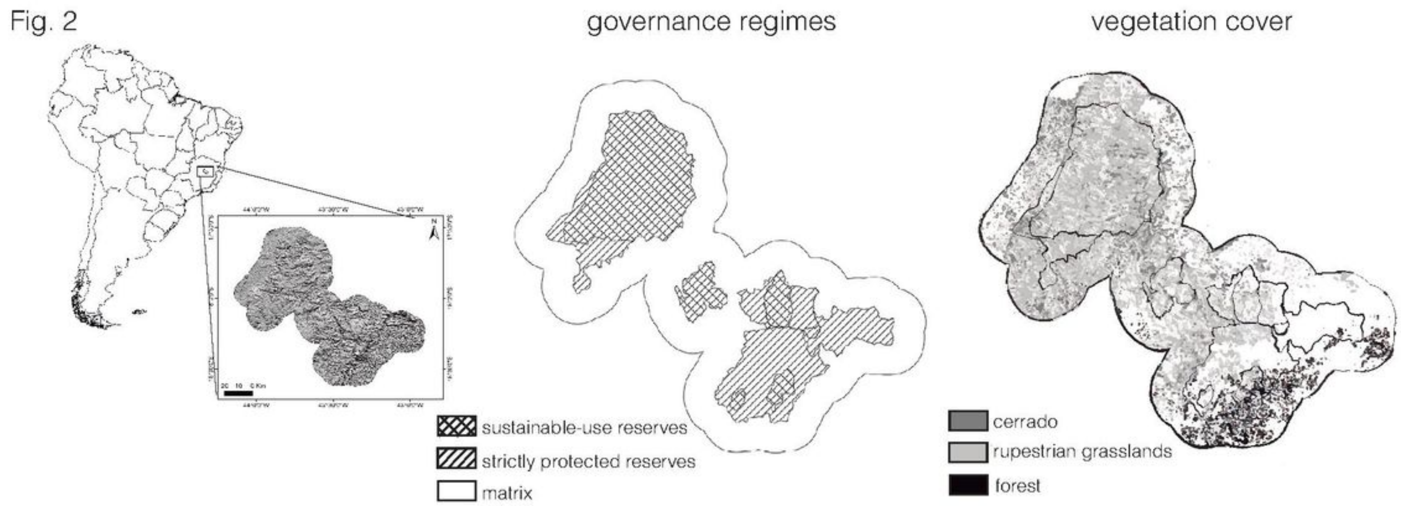

Figure 2

Maps showing the location of the study area, governance regimes and vegetation cover

Fig. 3

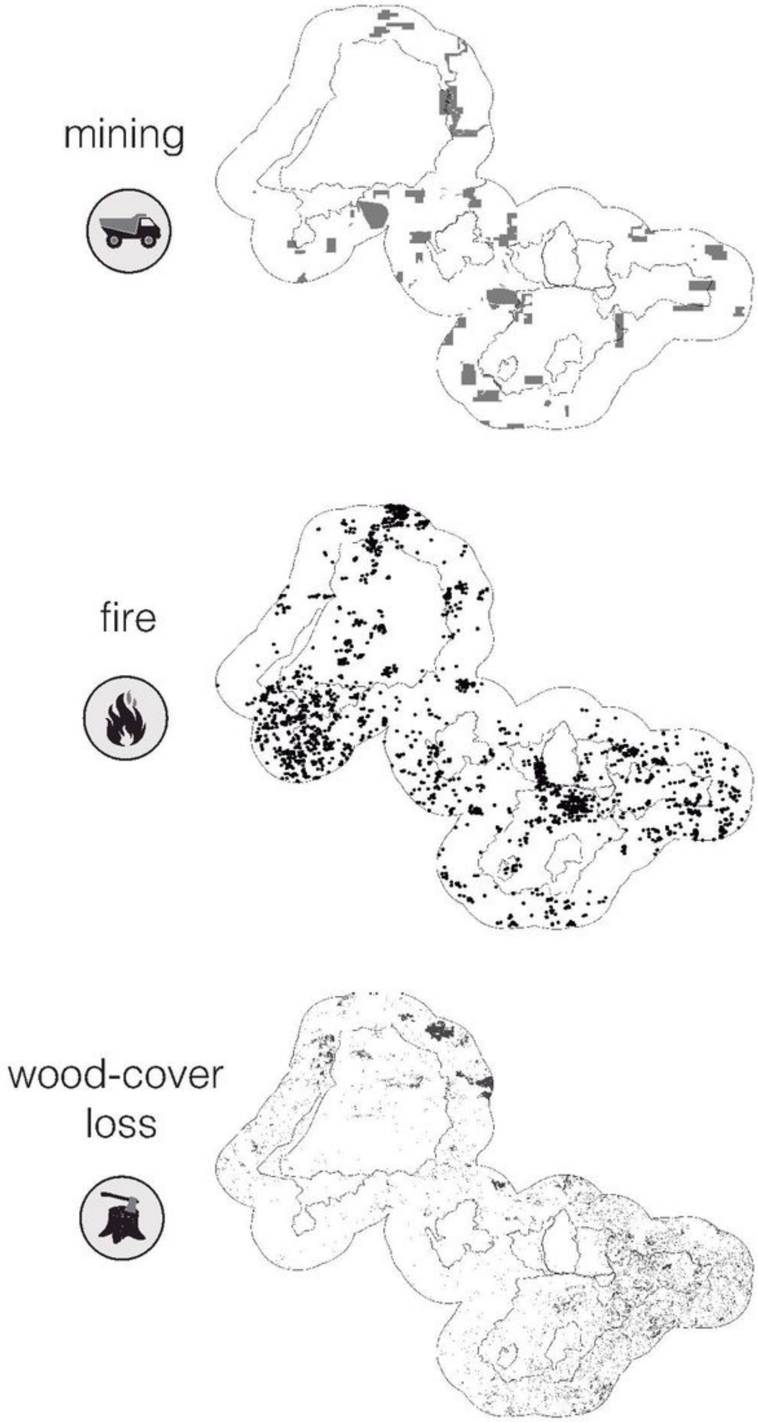

Figure 3

Mined areas (2018), fire out-breaks (2017-2019) and wood-cover loss (2000-2018) in the Espinhaço Mosaic (Brazil).

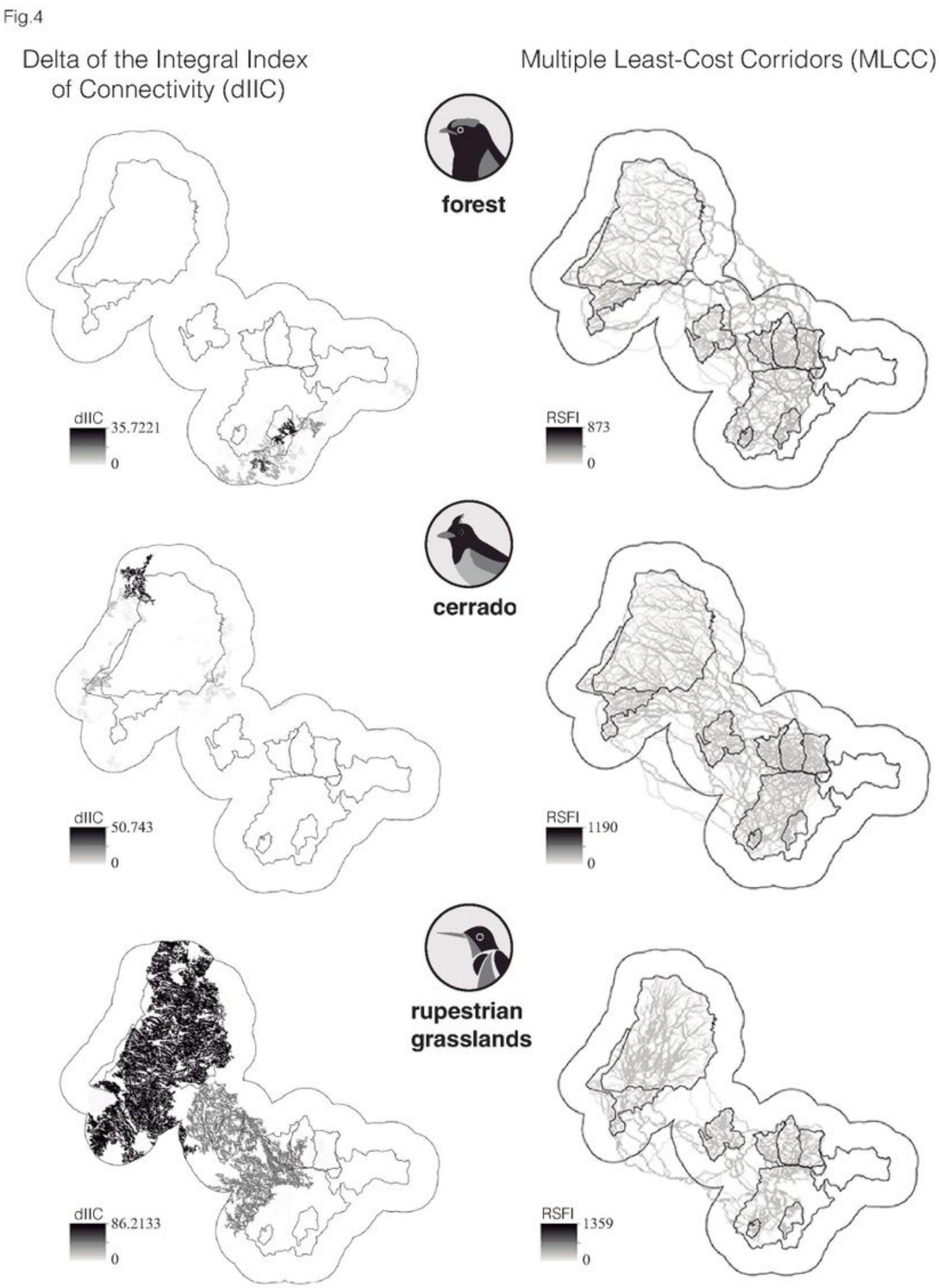

Figure 4

The delta of the integral index of connectivity (dIIC) for forest, cerrado and rupestrian grassland birds across the Espinhaço Mosaic (left-hand side). Route Selection Frequency Index map demonstrating the frequency with which each pixel was selected during the MLCC simulations among strictly protected reserves (right-hand side).

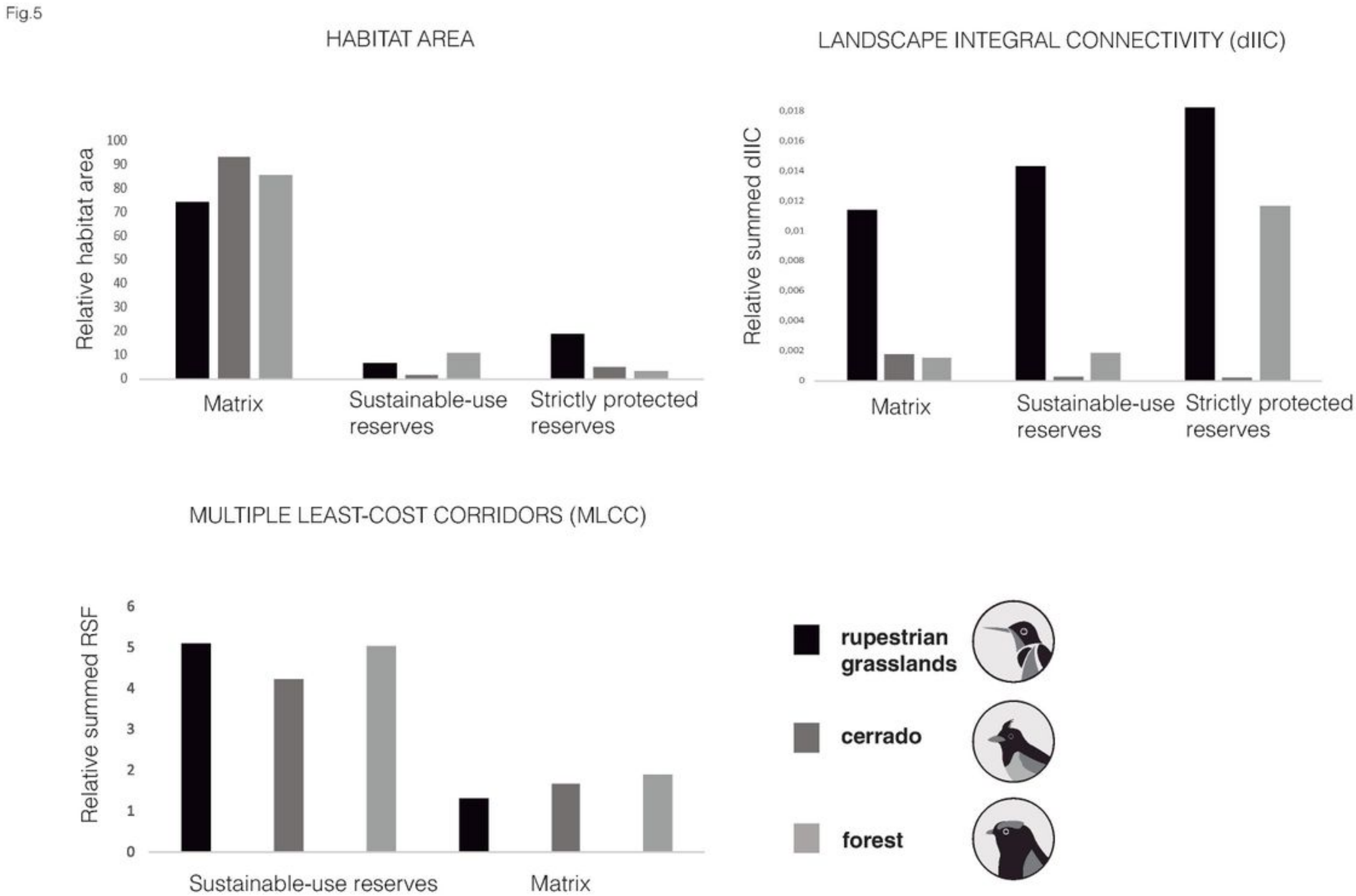

Figure 5

Relative habitat area under the three governance regimes, relative summed integral index of connectivity (dIIC) and relative sum of the accumulated RSF frequency for birds inhabiting three bird groups.

Fig. 6

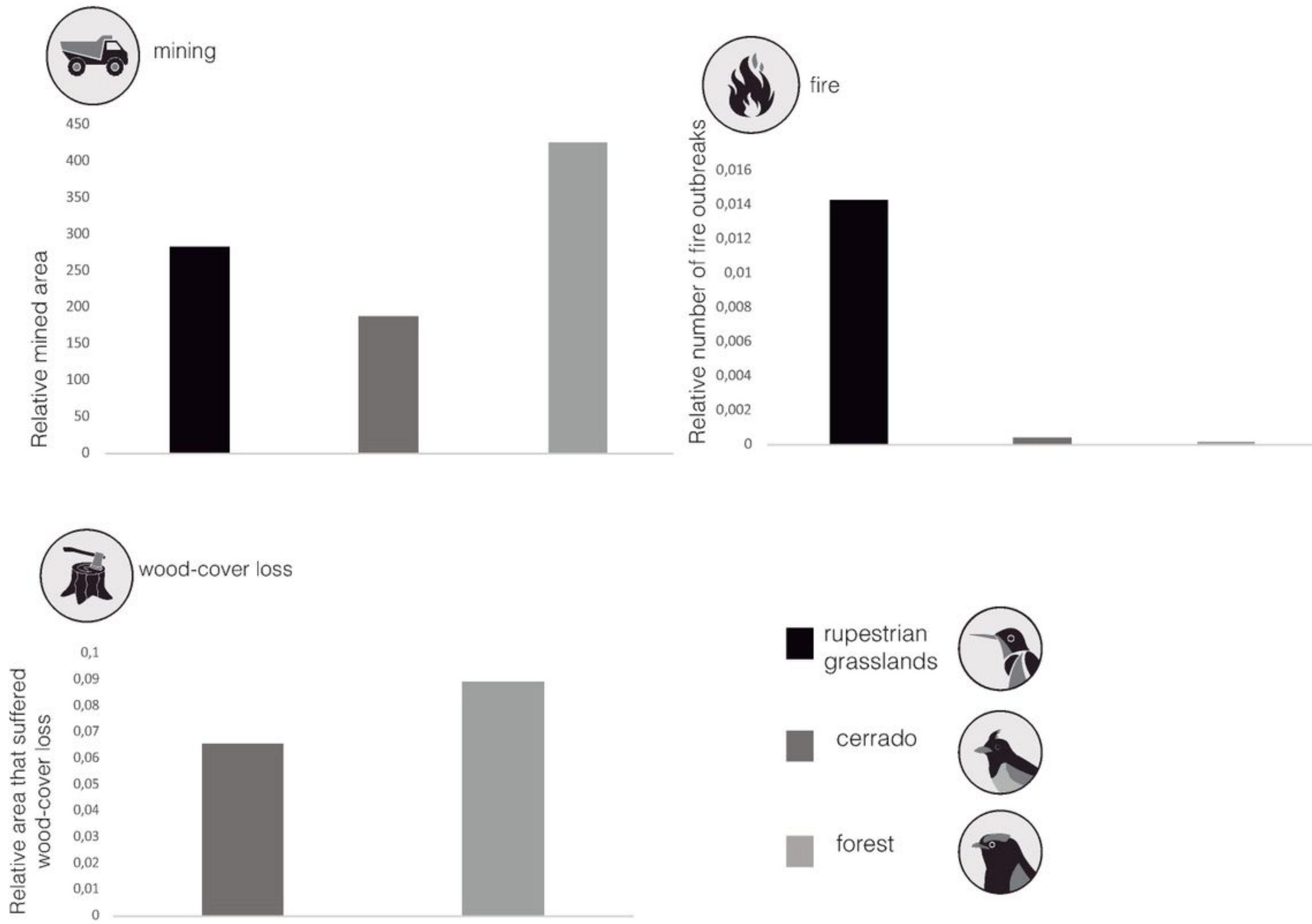

Figure 6

Effects of fire, mining and wood-cover loss on three bird groups (forest, cerrado, and rupestrian grasslands birds) across the Espinhaço Mosaic (Brazil).

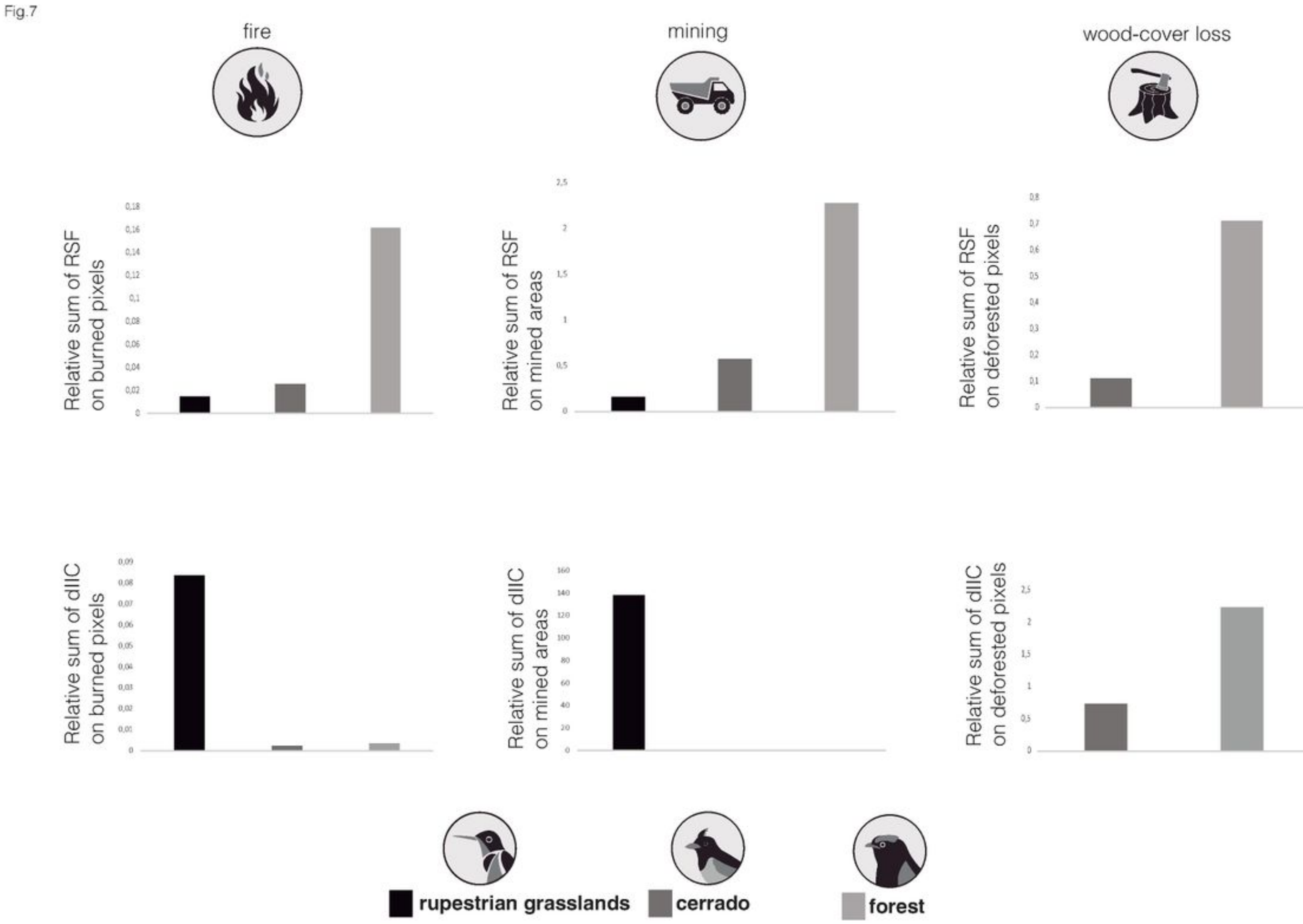

Figure 7

Effects of fire, mining and wood-cover loss on the connectivity among strictly protected reserves (MLCC) and on the integral index of connectivity (dIIC) for bird groups (rupestrian grassland, cerrado and forest birds) inhabiting the Espinhaço Mosaic.