

Article

Functional Connectivity in Future Land-Use Change Scenarios as a Tool for Assessing Priority Conservation Areas for Key Bird Species: A Case Study from the Chaco Serrano

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Abstract

Planning conservation for multiple species while accounting for habitat availability and connectivity under uncertain land-use changes presents a major challenge. This study proposes a protocol to identify strategic conservation areas by assessing the functional connectivity of key bird species under future land-use scenarios in the Chaco Serrano of Córdoba, Argentina. We modeled three land-use scenarios for 2050: business as usual, sustainability, and intensification. Using the Equivalent Connected Area index, we evaluated functional connectivity for *Chlorostilbon lucidus*, *Poliophtila dumicola*, *Dryocopus schulzii*, *Milvago chimango*, and *Saltator aurantirostris* for 1989, 2019, and 2050, incorporating information about habitat specialization and dispersal capacity to reflect differences in ecological responses. All species showed declining connectivity from 1989 to 2019, with further losses expected under future scenarios. Connectivity declines varied by species and were not always proportional to habitat loss, highlighting the complex relationship between land-use change and functional connectivity. Surprisingly, the sustainability scenario led to the greatest losses in connectivity, emphasizing that habitat preservation alone does not ensure connectivity. Using the Integral Connectivity Index, we identified habitat patches critical for maintaining connectivity, particularly those vulnerable under the business as usual scenario. With a spatial prioritization analysis we identified priority conservation areas to support future landscape connectivity. These findings underscore the importance of multispecies, connectivity-based planning and offer a transferable framework applicable to other regions.

Keywords: prospective analysis; equivalent connected area index; integral connectivity index; spatial prioritization analysis; landscape connectivity



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1. Introduction

Land-use change is a major driver of global environmental transformation, with deforestation being one of its most significant consequences [1–3]. Land-use changes

result in the loss, degradation, and fragmentation of natural habitats causing a substantial loss of biodiversity worldwide, manifested through reductions in species abundance and diversity [4–6]. Such changes have negatively impacted ecosystem processes affecting the resilience and resistance of ecosystems to environmental change [7,8].

The widespread and accelerating transformation of ecosystems highlights the urgent need for spatial conservation planning. In this context, protected areas (PAs) are one of the most important tools for biodiversity conservation, as they safeguard ecosystems by protecting habitats, species, and ecological processes from human activities that threaten their integrity [9–12]. Consequently, the expansion of PAs has become a global conservation priority, with international targets calling for the protection of 17% to 30% of terrestrial areas, through ecologically representative, well-connected, and effectively managed networks [13,14].

Connectivity is a key indicator of the ecological impacts of environmental change, and its loss represents a significant threat to biodiversity conservation. PAs are unlikely to meet their conservation objectives without functional linkages that facilitate essential ecological processes such as species migration [15]. Functional connectivity is the degree to which a landscape, including both habitat patches and the surrounding matrix, facilitates or restricts the movement of focal organisms [16]. Therefore, a landscape that is functionally connected for some species may not be so for others. In response to these concerns, the use of connectivity metrics in systematic conservation planning has grown significantly [17]. Approaches based on graph theory are powerful tools for representing landscape patterns and detecting critical changes in connectivity, as well as identifying key landscape elements essential for maintaining overall connectivity [18]. In particular, functional connectivity metrics should be preferred if conservation is focused on key particular species [16].

However, the mere establishment of PAs is not sufficient to ensure long-term ecosystem conservation. Building sustainable and resilient socio-ecological systems requires harmonizing human activities with the conservation of natural ecosystems [19]. Achieving this goal depends on the availability of accurate diagnostic and forward-looking information on land dynamics, which is essential for anticipating potential impacts [20], and for identifying key landscape elements critical for connectivity that may be at risk. One of the most powerful tools for conducting such prospective analyses is the use of future-scenario analysis [21–24]. A future scenario refers to a simplified yet plausible depiction of a potential future, built upon a consistent set of assumptions about key driving forces [25–27]. Future scenarios can be spatialized into maps providing decision makers with strategic tools to implement anticipatory actions in response to projected impacts, such as habitat and biodiversity loss, with the ultimate aim of guiding land systems toward more desirable and sustainable futures [20,28].

Landscapes are becoming increasingly complex as land-use and land-cover (LULC) changes produce spatially and temporally variable patterns that affect land-cover types in distinct ways, conditioning how species are impacted by these alterations. This growing complexity, characterized by diverse land uses and competing demands to meet human needs, biodiversity conservation, and ecological functions, makes balancing conservation and development increasingly challenging. Additionally, key biodiversity areas and the threats they face do not always overlap [29,30]. In this context, spatial prioritization has emerged as a critical tool in conservation planning, helping to address the complexity of identifying key areas for conservation and management, such as the creation or expansion of PAs [31].

Incorporating connectivity goals and accounting for uncertainties related to LULC change in the design of PAs networks represent a significant challenge [32]. Effective habitat networks must consider the ecological requirements of multiple species. In this

context, birds are widely used as bioindicators of environmental change due to their role in essential ecosystem functions such as pollination, pest control, and seed dispersal [33]. As highly mobile organisms capable of moving freely between habitats, and exhibiting a wide range of body sizes, feeding strategies, and behavioral traits, bird communities can respond rapidly to environmental disturbances such as habitat loss and fragmentation [34–36]. However, these responses differ among ecological groups; for example, habitat specialists tend to be more vulnerable to such changes than generalist species [35,37–39].

Many ecosystems are currently undergoing rapid and extensive changes that threaten both their ecological integrity and the biodiversity [6]. The Gran Chaco is a prominent example, recognized as one of the world's most threatened ecoregions and designated as a biodiversity hotspot that harbors numerous endemic species [40–42]. A prolonged history of LULC change has significantly altered the natural-vegetation cover of the Chaco, particularly through the loss, fragmentation, and degradation of its forests [43–46]. These ongoing LULC changes are contributing to the rapid decline of biodiversity in the Chaco region [47,48]. Prospective studies conducted in the region suggest that, if current land-use trends continue, deforestation will persist resulting in the increasing isolation of small, highly fragmented forest patches [20,49], thereby exerting an even greater impact on their biodiversity. Overall, scenario analyses in the Chaco emphasize the urgent need for improved territorial planning and land management strategies [20,50].

Within the Chaco, the Chaco Serrano, a highly important ecosystem for biodiversity conservation, has only been assessed by a few studies [51,52]. Due to its topography, it constitutes a landscape with high physiognomic heterogeneity and a complex pattern of LULC change dynamics that differs from those observed in the plain areas of the Chaco, potentially posing greater challenges for management and conservation [52–55]. The land-use scenarios used in this study reflect plausible trajectories of landscape transformation in the Chaco Serrano, and were designed to align with—or contrast against—existing conservation and land-use planning frameworks in the region. In particular, a sustainability scenario is consistent with the objectives of the provincial native forest law (Ley de Bosques N° 9814), the national Forest Law (Ley N° 26.331), and local efforts to promote sustainable land management and biodiversity conservation in the Sierras de Córdoba. In this context, the main objective of this study is to propose a protocol for the identification of strategic priority areas for conservation by assessing the functional connectivity of key bird species under different land-use change scenarios in the Chaco Serrano of Córdoba, Argentina. Specifically, we aimed to achieve the following: (a) develop land-use change scenarios that represent different land-use alternatives for the year 2050 for the Sierras Chicas of Córdoba, Argentina; (b) assess the past, current, and future functional connectivity of a group of key bird species; and (c) propose a landscape design that optimizes territorial planning by identifying strategic areas that enhance the effectiveness of the current protected area system, taking into account the functional connectivity of key bird species.

We assume that past and projected LULC changes will affect the functional connectivity of birds in the Chaco Serrano. We hypothesize that a sustainable future scenario, one that integrates conservation measures and land management strategies, will better mitigate losses in functional connectivity of birds compared to a business-as-usual scenario, which reflects the continuation of current pressures on native vegetation.

2. Materials and Methods

2.1. Study Area

The Sierras Chicas of Córdoba, in central Argentina, are located in the southern portion of the Gran Chaco (within the dry Chaco), stretching 250 km in a north–south direction, with an altitudinal range of 400 to 1900 m.a.s.l. and an area of 8400 km² (Figure 1A). Vegetation

is distributed in altitudinal belts [56], with Serrano forests (between 600 and 1300 m.a.s.l.) dominated by *Schinopsis marginata*, *Zanthoxylum coco*, *Condalia buxifolia*, *Vachelia caven*, *Senegalia gillesii*, *Lithraea molleoides*, *Celtis ehrenbergiana*, and *Croton lachnostachys*. Shrubs and early successional forests occur in a transition belt between 1300 and 1700 m.a.s.l., while grasses become dominant as elevation increases above 1500 m.a.s.l. (Figure 1B) [55,57,58]. A long history of LULC change has significantly altered the natural vegetation communities of the Sierras Chicas. Urban expansion, the invasion of exotic woody species (*Ligustrum lucidum* and *Pinus* sp.), wildfires, livestock grazing, and agriculture have been the primary drivers of these changes [52,53,59]. Collectively, these processes have exerted a profound negative impact on biodiversity, particularly on bird communities [60,61].

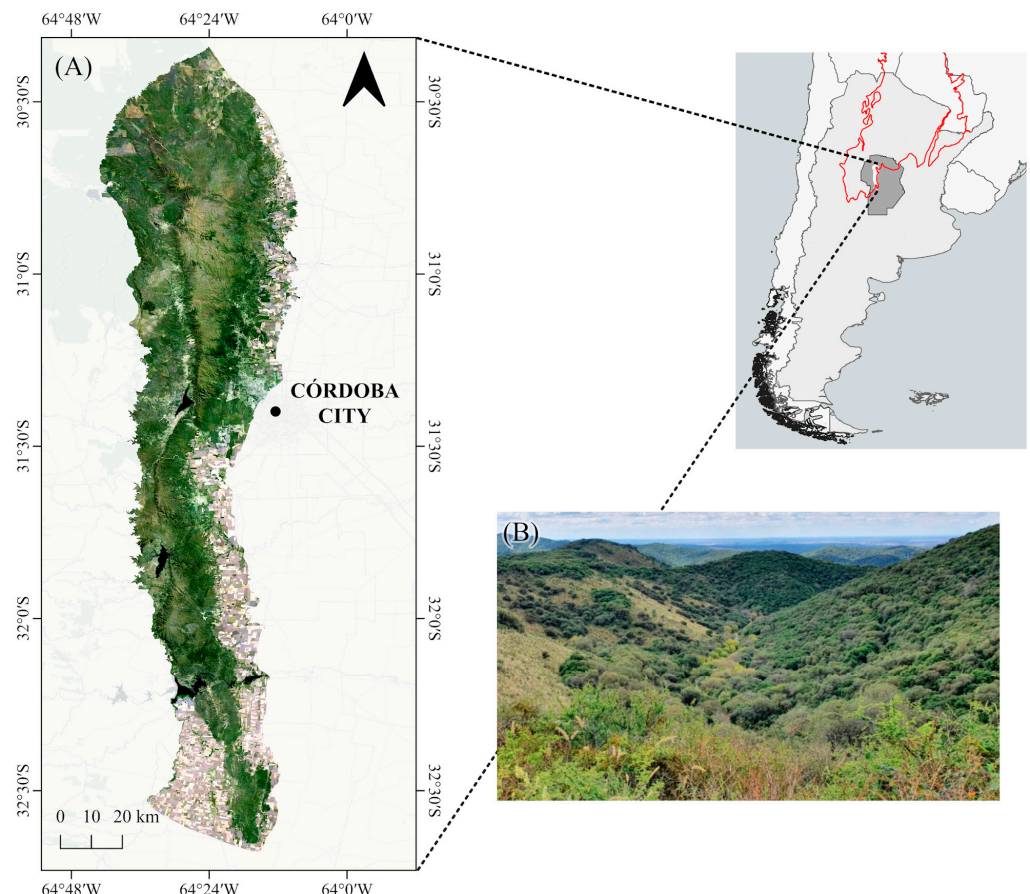


Figure 1. (A) Sierras Chicas of Córdoba, Argentina, study area with a true color composite (bands 4, 3, 2) from Landsat 8 imagery. The South American Gran Chaco limits are depicted in red. (B) Representative vegetation of the Chaco Serrano.

2.2. Future Land-Use Change Scenarios

Three spatially explicit LULC scenarios were modeled for 2050, based on a literature review and two workshops conducted with experts on LULC change in the study area (Figure 2). The 2050 horizon assessed longer-term effects, enabling the analysis of LULC change patterns and their potential ecological impacts [28].

Scenario 1. Business as usual (BAU). This scenario assumes that current LULC change trends will continue unchanged through the projected time horizon. Specifically, it assumes the following: (1) deforestation rates will persist at current levels, with no new restrictions, and even PAs may experience clearing events (as has occurred previously); [62]; (2) urban areas will continue to expand at current rates without spatial planning; and (3) invasive exotic tree species will continue to spread, further displacing native forests.

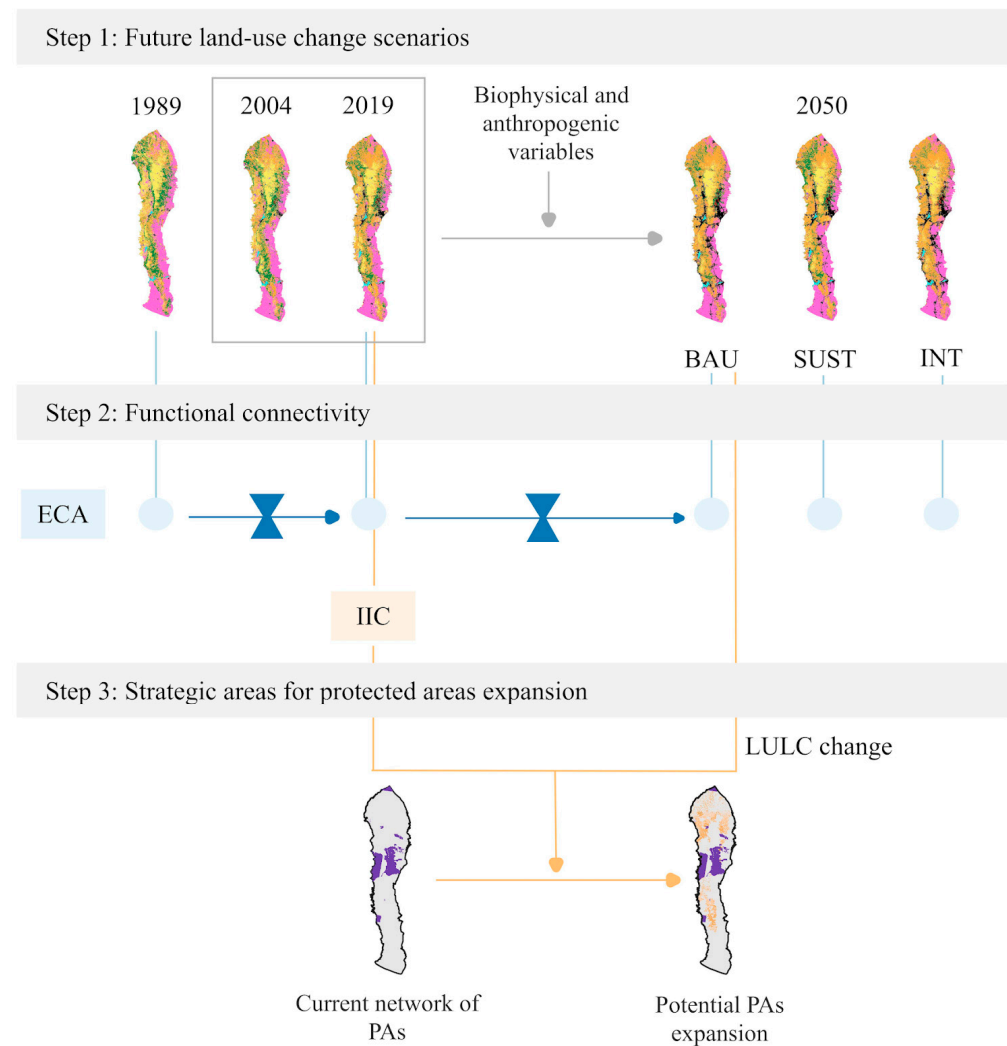


Figure 2. Workflow illustrating the steps to the following: (1) model future land-use change scenarios; (2) analyze the functional connectivity of a selected group of bird species; and (3) identify strategic areas for the expansion of the protected-areas network. BAU: business-as-usual scenario; SUST: sustainability scenario; INT: intensification scenario; ECA: Equivalent Connected Area index; IIC: Integral Index of Connectivity; LULC: land-use/land-cover; PAs: protected areas; X: temporal transition between time periods (e.g., 1989–2019–2050).

Scenario 2. Sustainability (SUST). This scenario envisions a more sustainable relationship between human activities and ecosystem conservation. It assumes the following: (1) all environmental regulations and deforestation-reduction policies are fully implemented and strictly enforced; (2) PAs effectively preserve native forests, preventing their loss and conversion to other land covers; (3) strict urban planning regulations are in place, with urban growth restricted to designated development zones [63]; (4) the expansion of the invasive species *Ligustrum lucidum* is controlled within PAs, and its use as an ornamental plant is prohibited; and (5) a reduction in the frequency of human-started wildfires.

Scenario 3. Intensification (INT). This scenario projects an intensification of the region's current environmental challenges. It assumes the following: (1) an accelerated rate of urban expansion; (2) an increased rate of *Ligustrum lucidum* spread, surpassing that observed between 2004 and 2019 and resembling expansion rates from 1989 to 2004, along with the emergence of new invasion foci; (3) accelerated agricultural frontier expansion; and (4) increased wildfire frequency.

The spatial modeling of these scenarios was conducted using Dinamica EGO V5 software [64], which generates spatially explicit simulations based on historical land-use data.

Land-cover maps from the 2004–2019 period were used (Figure 2) [52], as this timeframe reflects a recent and relatively stable period with regard to LULC dynamics. Land-cover maps include ten LULC classes: water, rock-bare soil, urban, productive land, grasslands, shrublands, native forest, glossy privet forest, pine forest, and acacia forest (further details on the land-cover maps development process, the LULC classes, and the accuracy assessment are provided in [52]). A set of biophysical and anthropogenic variables influencing LULC change in the area was selected for the model (Figure 2–Appendix A). Dinamica EGO analyzes the relationship between historical land-cover changes (from 2004 to 2019) and the physical-environmental and anthropogenic variables used, in order to develop future projections. Once the model is trained, a projection for 2019 was generated using the 2004 land-cover map as input. To validate the model, we compared the simulated 2019 map with the observed land-cover map from 2019 using the “multi-resolution fit” metric implemented in Dinamica EGO [64]. This metric assesses spatial similarity by comparing patterns of land-use change within a moving window (in this case, 5×5 pixels) and returns a similarity index ranging from 0 (no match) to 1 (perfect match). Our validation resulted in a similarity index of 0.505, which meets the minimum threshold suggested by the software’s authors for acceptable model performance. Additional information regarding the scenario modeling can be found in [65] and in Appendix A.

2.3. Bird Species

A group of five native bird species was selected to represent a range of ecological profiles, including habitat preferences and varying sensitivities to land-use change (Table 1). The selection focused on species with distinct functional roles and contrasting habitat requirements within the ecosystem. Additionally, we included species with different conservation statuses and territorial behaviors to assess their potential responses under future land-use scenarios. This approach allows us to explore how diverse functional traits influence species’ vulnerability to landscape change and ensures representation of the broad diversity of bird species found in the Sierras.

Table 1. Bird species [61,66–69].

Species	Functional Role/Habitat Requirement	Reproductive Strategy	Territoriality	Abundance Status	Conservation Status (IUCN)	Sensibility
<i>Chlorostilbon lucidus</i> Glittering-bellied Emerald	Pollinator species found in shrubland habitats and forest understories	Solitary breeder; nests in shrubs or low branches	Low territoriality	Common	Least Concern	Favorable
<i>Poliophtila dumicola</i> Masked Gnatcatcher	Insectivore in forest, forest understory, and shrubland	Builds cup-shaped nests; socially monogamous	Territorial during breeding	Common	Least Concern	Mean
<i>Dryocopus schulzii</i> Black-bodied Woodpecker	Ecosystem engineer in mature forests (creates cavities)	Cavity nester; low reproductive rate	Highly territorial	Rare	Vulnerable	High

Table 1. Cont.

Species	Functional Role/Habitat Requirement	Reproductive Strategy	Territoriality	Abundance Status	Conservation Status (IUCN)	Sensibility
<i>Milvago chimango</i> Chimango Caracara	Opportunistic scavenger in open habitats (grass-land/shrubland)	Opportunistic breeder; nests in trees or structures	Low territoriality	Abundant	Least Concern	Low
<i>Saltator aurantirostris</i> Golden-billed Saltator	Seed disperser in shrubland and forest understory	Builds open-cup nests; monogamous pairs	Territorial	Common	Least Concern	Low

2.4. Functional Connectivity

To assess changes in functional connectivity over the study period, we used the Equivalent Connected Area index (ECA) [70]. The ECA is a network-based metric that quantifies habitat availability and is particularly effective for monitoring variations in functional landscape connectivity [70]. The ECA is measured in area units, which allows for a direct comparison between changes in habitat connectivity and changes in total habitat area. It is defined as the size of a hypothetical, single, continuous habitat patch that would provide the same amount of reachable habitat as the actual configuration of habitat patches and connecting elements in the landscape under study [70,71].

To evaluate the contribution of individual patches to overall landscape connectivity, we used the Integral Index of Connectivity (IIC). The IIC is sensitive to both habitat availability and the spatial arrangement of habitat patches, and it allows for the identification of landscape elements that are most critical for maintaining connectivity (dIIC) [18,72].

ECA and IIC consider both the area and the habitat suitability of each habitat patch, as well as the distances between patches. Habitat suitability was determined based on a literature review for each species [61,66–69], assigning a value between 0 and 1 depending on the land-cover type (Table 2). Species-specific distance thresholds were defined using published data and field expertise to determine whether two patches should be considered connected (Table 2).

Table 2. Habitat suitability and distance threshold values assigned to each species across the analyzed land-cover types [61,66–69].

Specie	Habitat Suitability			Distance Threshold (m.)
	Grassland	Shrubland	Native Forest	
<i>Chlorostilbon lucidus</i>	0	1	0.5	500
<i>Polioptila dumicola</i>	0	1	1	500
<i>Dryocopus schulzii</i>	0	0	1	1000
<i>Milvago chimango</i>	1	0.5	0	1800
<i>Saltator aurantirostris</i>	0	1	0.5	200

ECA was calculated for each species for three time points: the past (1989), the present (2019), and under three future scenarios (BAU, SUST, and INT) projected for the year 2050

(Figure 2). The relative change in ECA values (dECA, Equation (1)) was computed for two time intervals (1989–2019 and 2019–2050) and across the three scenarios.

$$dECA = ((ECA_2 - ECA_1) / ECA_1) \times 100, \quad (1)$$

where ECA_1 is the ECA value before the change, and ECA_2 is the ECA value after the change.

These dECA values were then compared to the relative change in habitat area (dA, Equation (2)).

$$dA = ((A_2 - A_1) / A_1) \times 100, \quad (2)$$

where A_1 is the habitat area before the change, and A_2 is the habitat area after the change.

This comparison between dECA and dA enables the assessment of whether changes in habitat area lead to disproportionately higher or lower variations in landscape connectivity [70]. dIIC was calculated for each species for the present (2019) (Figure 2). These calculations considered only areas occupied by grasslands, shrublands, and native forests, and included only patches larger than 4 hectares, due to data processing limitations. Both ECA and dIIC were calculated using the Makhurini package in R [73].

2.5. Strategic Areas for Protected Area Expansion

To identify potential strategic areas for expanding the PAs network while accounting for future changes and the functional connectivity of key bird species, we conducted a spatial prioritization using Zonation 5.0 software (Figure 2) [31,74]. Zonation is a decision-support tool for spatial planning and conservation [31,75]. It integrates spatial data on biodiversity features, such as species distributions or habitat types, along with information on anthropogenic pressures and existing PAs networks, generating a prioritization map that highlights areas based on their importance for biodiversity conservation [31].

We applied the CAZ2 cell-removal rule, which emphasizes areas with high average biodiversity value, while also improving the representation of underrepresented features, those whose distribution does not overlap significantly with other biodiversity attributes, even if this slightly reduces the overall coverage of areas with high average richness [74].

The prioritization focused on areas occupied by grasslands, shrublands, and native forests. The biodiversity features used in the analysis consisted of the five studied bird species, with each species represented by its dIIC values previously calculated for each habitat patch. Higher priority was assigned to those areas within each land-cover type with probability of habitat loss by 2050, based on the BAU scenario (Figure 2). This approach allowed us to simultaneously account for the following: (i) habitat availability for each species, (ii) the importance of each patch for maintaining landscape functional connectivity for each species, and (iii) the risk of patch loss by 2050. A hierarchical mask of the existing PAs network in the Sierras Chicas was included (Appendix B), allowing us to achieve the following: (1) evaluate the effectiveness of the current PAs network in representing the studied species, and (2) identify priority areas, within the top 17% and 30% of the landscape, as aligned with the Aichi Biodiversity Targets and the post-2020 Global Biodiversity Framework [13,14] that are not currently under protection, as potential sites for PAs network expansion.

3. Results

3.1. Future Land-Use Change Scenarios

The three scenarios were generated and spatialized for 2050 (Figure 3). During the model validation process, a match of 50% (0.505) was achieved between the real and simulated maps using a 5×5 pixel window.

Grasslands would decline in all three scenarios. This reduction would be similar in both the BAU and INT scenarios, and slightly lower in the SUST scenario (Figure 3/Appendix C). In all scenarios, the loss of grasslands would be largely compensated for by an increase in shrublands, with smaller portions converted to productive or urban land. Shrublands would expand in all scenarios, with the most pronounced increase occurring under the INT scenario (Figure 3/Appendix C).

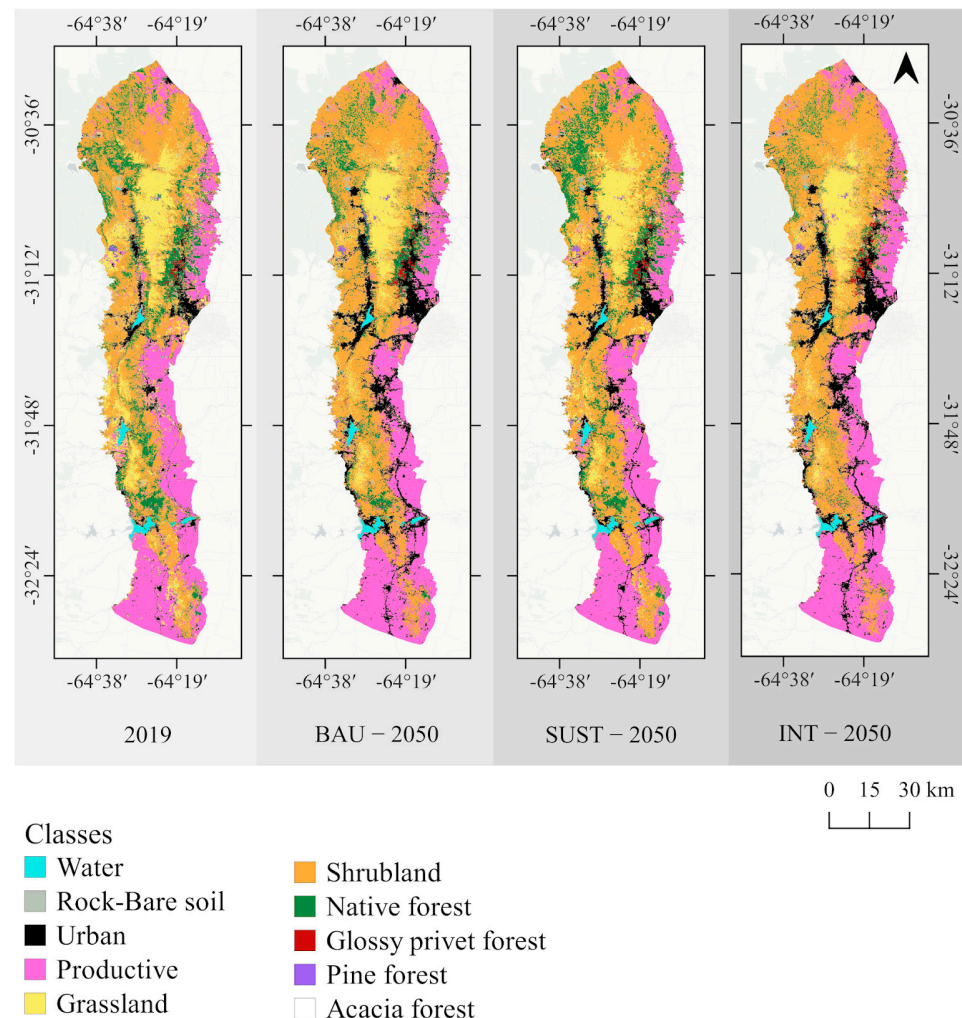


Figure 3. LULC in 2019 and projected LULC for 2050 under business-as-usual scenario (BAU), sustainability scenario (SUST), and intensification scenario (INT). Area occupied by each LULC in each scenario is available in Appendix B.

Native forests would undergo a substantial reduction in all scenarios. Between 2019 and 2050, the BAU scenario would result in a loss of 64,000 hectares of native forest (59% of the 2019 native forests extent). The SUST scenario would see a smaller loss of approximately 45,000 hectares (42%), while the INT scenario would lead to a loss of 81,000 hectares (74%) (Figure 3/Appendix C).

All three scenarios showed a significant increase in urban areas. In the BAU scenario, urban expansion is projected to reach 62,000 hectares between 2019 and 2050. In contrast, the SUST scenario anticipates a more moderate increase, with growth occurring in a more compact form and restricted to areas specifically designated for urban development. The INT scenario projects the greatest expansion in urban areas among the three scenarios (Figure 3/Appendix B). Productive land would show relatively little variation in extent across the three scenarios. In both the BAU and SUST scenarios, a decrease in

productive areas is expected, whereas the INT scenario would result in a slight increase (Figure 3/Appendix C).

3.2. Functional Connectivity

Functional connectivity varied among the five species, across the three time points, and under the three modeled scenarios. All five species experienced a decline in functional connectivity between 1989 and 2019, with *Dryocopus schulzii* exhibiting the greatest loss (−34%) and *Polioptila dumicola* the smallest (−7%) (Figure 4). For *Dryocopus schulzii*, the relative change in equivalent connected area was similar to the relative change in native forest area (dECA $\cong$ dA). In *Milvago chimango*, dECA < dA for grasslands. In *Chlorostilbon lucidus*, *Polioptila dumicola*, and *Saltator aurantirostris*, dECA values were negative, despite positive dA values for shrublands and negative dA values for native forests and grasslands (Figure 4/Appendix D).

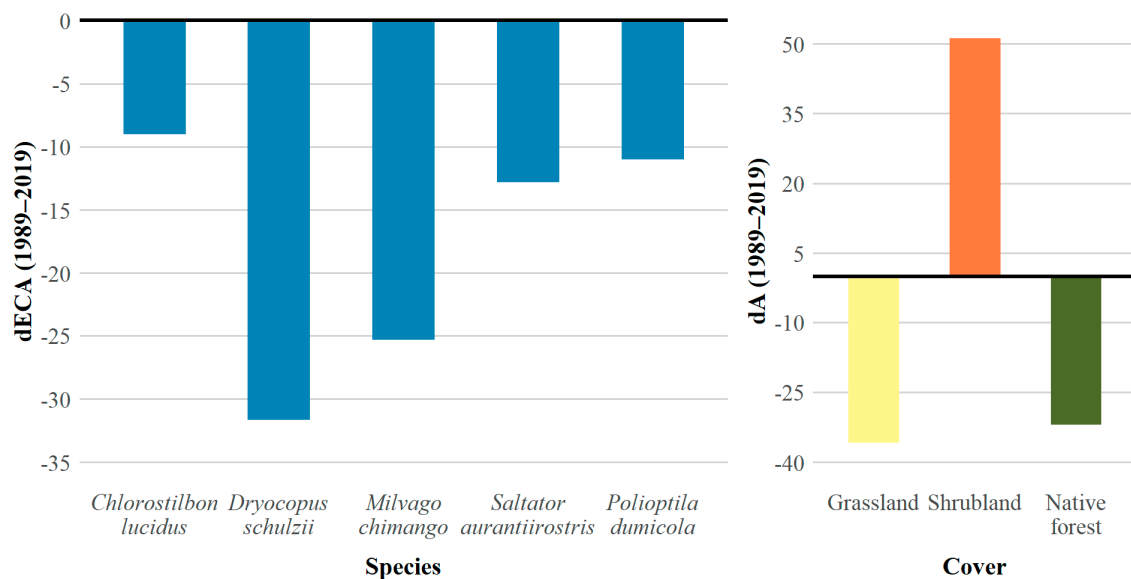


Figure 4. Relative change in equivalent connected area (dECA) and relative change in habitat area (dA) between 1989 and 2019, for the five bird species and the three native-vegetation covers (expressed as percentages). dECA and dA values are available in Appendix D.

Between 2019 and 2050, most species are projected to continue losing functional connectivity under all three scenarios (Figure 5). For all five species, the greatest losses are expected under the SUST scenario. *Dryocopus schulzii* is projected to remain the most affected species, experiencing the highest connectivity losses. In contrast, *Polioptila dumicola* is expected to show a slight gain in functional connectivity under the BAU and INT scenarios (Figure 5). Over this period, the relative change in habitat area (dA) is projected to remain negative for native forests and grasslands and positive for shrublands across all scenarios (Figure 5).

The dIIC values for each habitat patch varied among the studied species. While some species, like *Chlorostilbon lucidus*, *Polioptila dumicola*, and *Saltator aurantirostris* shared a similar pattern of high-importance patches for maintaining landscape functional connectivity, others species like *Dryocopus schulzii* and *Milvago chimango* exhibited distinct patterns, with different sets of patches contributing most significantly to functional connectivity (Figure 6)

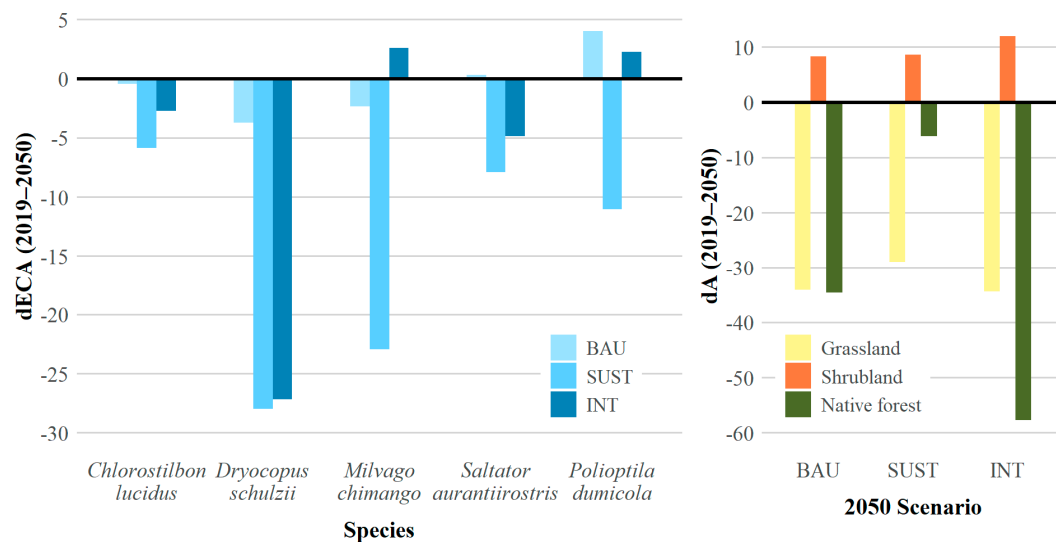


Figure 5. Relative change in equivalent connected area (dECA) and relative change in habitat area (dA) between 2019 and 2050 (in BAU, SUST, and INT scenario), for the five bird species and the three native vegetation covers. dECA and dA values are available in Appendix D.

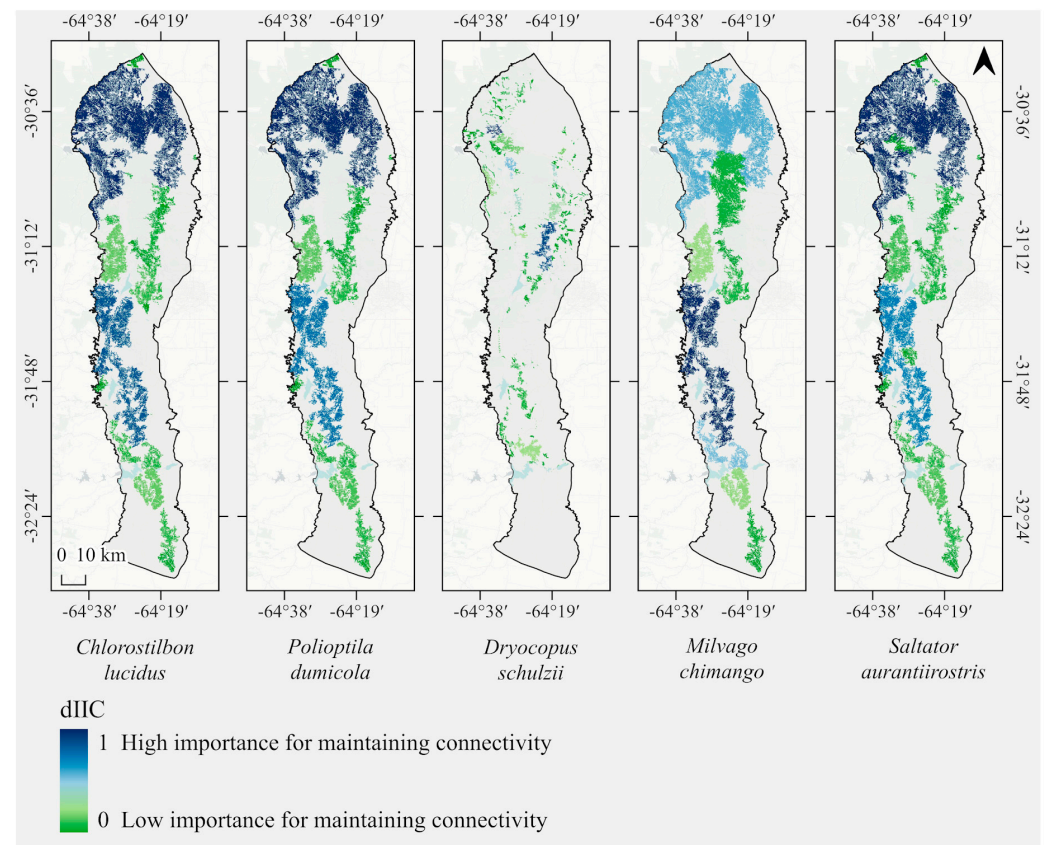


Figure 6. dIIC values for the five bird species in 2019.

3.3. Strategic Areas for Protected Area Expansion

Based on the existing network of PAs within the study region, pixels with high priority values were identified as potential sites for PAs network expansion, aiming to achieve 17% (color: dark orange) and 30% (color: dark orange + light orange) coverage of the study area's surface (Figure 7A). Although the high-priority pixels are spatially dispersed, several zones with a notable concentration of such pixels, herein referred to as high-priority patches, can be identified.

The performance curves illustrate the effectiveness of the spatial prioritization in capturing the habitat of each target species (Figure 7B). Among the species analyzed, *Dryocopus schulzii* exhibited the highest level of representation under the current prioritization. In contrast, the remaining species displayed lower, but relatively similar, levels of representation. Currently, the existing PAs system, which covers 14% of the study area (black dashed line), includes 39% of *Dryocopus schulzii*'s habitat and only 6–9% of the habitat of the other species. If the network were expanded to cover 17% of the region (red dashed line), the representation of *Dryocopus schulzii*'s habitat would increase to 49%, and that of the other species to approximately 12%. Further expansion to 30% (blue dashed line) would increase the representation of *Dryocopus schulzii*'s habitat to 84%, while the other species would reach representation levels between 45% and 47% (Figure 7B).

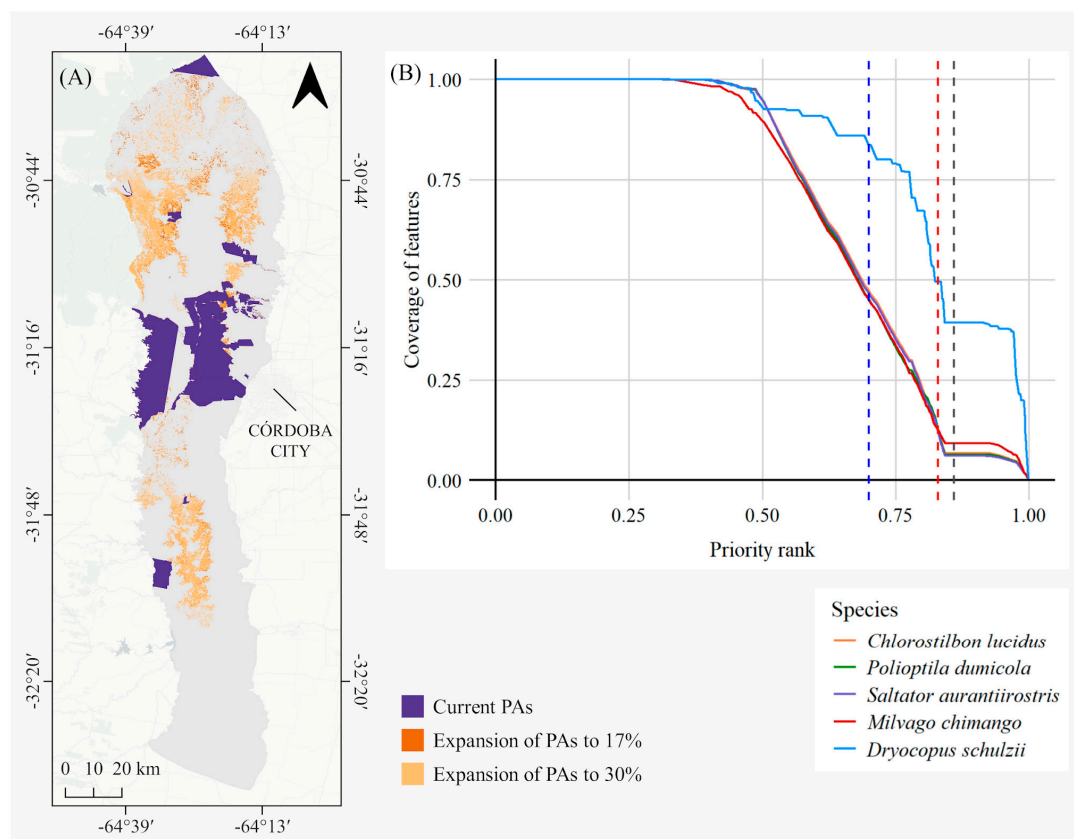


Figure 7. (A) Potential areas for the expansion of the protected area (PAs) network. Dark orange pixels represent priority areas for expanding the network to achieve 17% coverage of the Sierras Chicas region. The combined area of dark and light orange pixels corresponds to the target of 30% coverage. (B) Performance curves for the bird species. The vertical black dashed line indicates the current proportion (14%) of each attribute included within the existing PAs network. The red (17%) and blue (30%) dashed lines indicate the expected levels of representation under expanded protection scenarios.

4. Discussion

The methodology employed enabled the projection of future LULC changes in the Sierras Chicas, as well as the assessment of past, present, and future functional connectivity for the bird species analyzed. The results allowed the identification of key landscape patches with high ecological relevance for maintaining the connectivity of the target species, which are also at high risk of future loss. These areas are proposed as priorities for the expansion of the PAs network or the implementation of complementary conservation strategies. This approach integrates LULC change dynamics with the habitat requirements of local indicator

species, facilitating the identification of priority conservation zones. The methodology is transferable and can be applied in other regions where landscape transformation threatens ecological connectivity, allowing for proactive and precise conservation planning.

Systematic conservation planning often focuses on preserving either species' distribution ranges or landscape connectivity, but rarely addresses both simultaneously [76]. In the Sierras Chicas, the results of functional connectivity assessments under the different future scenarios highlight the importance of incorporating functional connectivity as a central component of conservation planning. As observed in other regions [77], the studied species exhibited different responses to historical and projected LULC changes, with connectivity patterns that did not always match expectations. This was particularly evident in the sustainability scenario, which (contrary to what we expected) resulted in the greatest decline in functional connectivity for all species among the three scenarios analyzed. This finding emphasizes the need for conservation planning approaches that go beyond habitat availability alone and consider how landscape spatial configuration affects connectivity between habitat patches, ultimately influencing species persistence in the face of land-use change and climate change [78,79].

Between 1989 and 2019, all species experienced a decline in their functional connectivity. This is consistent with the trend of declining functional connectivity observed in other regions and species in recent years [77,80,81]. *Dryocopus schulzii* and *Milvago chimango*, both species highly dependent on native forests and grasslands which were the most impacted land-cover types, were the most affected. In *Dryocopus schulzii*, a species closely associated with forests, the relative variation in available habitat area was similar to the variation in equivalent connected area, indicating that the loss of connectivity was proportional to habitat loss [70]. In contrast, for *Milvago chimango* (a generalist species, though primarily associated with grasslands) the relative habitat loss was greater than the relative decrease in connectivity, suggesting greater resilience in terms of functional connectivity [70,81]. In the case of *Chlorostilbon lucidus*, *Poliophtila dumicola*, and *Saltator aurantirostris*, species primarily associated with shrublands but also using forests and grasslands, delta equivalent connected area values were lower but consistently negative. This suggests that, despite the increase in shrubland cover during the study period, the loss and fragmentation of native forests and grasslands negatively affected their functional connectivity. These findings reinforce the importance of adopting an integrated landscape perspective in conservation efforts, rather than focusing actions in isolation on individual land-cover types [82,83].

The projected scenarios help identify areas with a high probability of change, particularly the loss of habitat patches [84]. In the Sierras Chicas, there has been a consistent trend of deforestation and LULC change since the 1970 s, seriously threatening the persistence of native forests and grasslands [52,53,62], and current management and conservation policies are insufficient to ensure their long-term sustainability. The three analyzed scenarios consistently projected continued loss of native vegetation cover. In both the business as usual and intensification scenarios, forest and grassland loss continues at a high rate. In the sustainability scenario, forest loss slowed down, but grassland loss remains high. This suggests that reversing the degradation of the Serrano ecosystem will require more ambitious and diversified policies.

Contrary to expectations, by 2050, the greatest losses in functional connectivity are projected under the sustainability scenario. This indicates that although this scenario may reduce the rate of native cover loss, it does not necessarily ensure the functional connectivity of the species. In fact, the distribution of conserved patches tends to be more isolated, reducing their functional value for species movement. This highlights that preserving habitat area alone is not sufficient to maintain connectivity, especially when newly conserved or restored areas are not strategically located. As observed during the historical period

(1989–2019), *Dryocopus schulzii* remains the most affected species (in all scenarios), reflecting its strong dependence on native forest, projected to be the most heavily lost land-cover type in the region. The variability in species responses across scenarios highlights the complexity of the relationship between LULC and functional connectivity, particularly for species that use multiple habitat types with varying suitability [77,85,86]. Although the sustainability scenario scope was on natural-vegetation cover conservation in the face of anthropogenic pressures, it did not explicitly address functional connectivity, emphasizing the need to incorporate this aspect into future planning. Likewise, the high interspecific variability observed reinforces the importance of adopting conservation approaches based on a suite of indicator species [87]. Using a diverse set of species captures a broader range of ecological responses and facilitates the identification of key conservation areas that benefit a larger number of species [88].

Currently, the existing PAs network covers only a small proportion of the habitat of *Milvago chimango*, *Polioptila dumicola*, *Saltator aurantiirostris*, and *Chlorostilbon lucidus*, leaving critical areas unprotected and vulnerable to landscape transformation. Many of these priority areas lie outside the formal PAs system and face a high probability of loss in the short to medium term. This situation is further compounded by the fact that most PAs in Córdoba exist only “on paper”, that is, they do not meet basic implementation standards [89]. Together, these factors highlight the high conservation risk faced by these species in the Sierras Chicas, a region with a long history of LULC change [52,53,62].

Although a complete redesign of the PAs system is unfeasible, its strategic expansion based on spatial prioritization can significantly enhance its effectiveness [90]. Currently, only 14% of the Sierras Chicas is under some form of protection, well below international targets such as the Aichi Biodiversity Targets and the Post-2020 Global Biodiversity Framework [13,14]. Expanding the network to cover 30% of the territory would significantly improve the representativeness of the studied species, with a relatively moderate investment.

In addition to expanding the PAs network and building on the previously mentioned concept of the importance of planning conservation from an integrated landscape perspective, it is essential to improve the quality of the surrounding matrix, which acts as a buffer zone and facilitates ecological connectivity [82,91–93]. The identification of corridors or wildlife passages that connect patches of natural vegetation can build upon the prioritization analyses developed in this study. In this context, the IIC is a valuable tool for assessing the potential contribution of new patches to landscape connectivity and informing restoration actions [18].

Since each species has different distributions and ecological requirements, the habitat patches that are critical for maintaining landscape connectivity varied among the species analyzed [94]. Therefore, the spatial prioritization carried out in this study reflects the specific needs of this particular group of species. Designing an integrated and complementary PAs network requires incorporating representative information from a diverse set of species, thereby strengthening the network’s resilience and conservation effectiveness [90,95,96].

The proposed expansion of the protected area network must be understood within the context of ongoing and intensifying land-use pressures, particularly urbanization and agricultural expansion, which are dominant drivers of habitat loss and fragmentation in the Sierras Chicas. These pressures can undermine the long-term effectiveness of protected areas by isolating habitat patches and degrading the surrounding matrix, thereby reducing functional connectivity. Consequently, conservation planning should not only prioritize the identification and protection of key habitat patches but also incorporate land-use management strategies that address agricultural practices and urban development. Integrating connectivity-based spatial prioritization with land-use zoning, sustainable agriculture, and urban planning policies will be critical to mitigate negative impacts and ensure the persis-

tence of biodiversity in this rapidly changing landscape. Furthermore, enhancing ecological corridors and buffer zones around protected areas can facilitate species movement and resilience to land-use pressures.

5. Conclusions

Conservation efforts often focus on protecting habitat for flagship species, while rarely accounting for their connectivity needs [76,97]. It is essential to include connectivity as a key indicator in conservation planning, using a broad set of indicator species to capture diverse habitat requirements [15,78,79,88]. Although the lack of data on species movement and ecological needs poses limitations [16], the methodology proposed here allows for the generation of useful insights using accessible data, and it can be refined as more information becomes available. On the other hand, scenario modeling and the use of indices such as the IIC provide a means to test different alternatives according to future potential risks, anticipate species responses to environmental change, and guide restoration actions with greater confidence in their positive effects on functional connectivity [18,28]. In our case, the unexpectedly lower connectivity loss under the BAU scenario may result from the persistence of large forest patches in areas less affected by land-use pressures, which act as key structural elements in the landscape. In contrast, the sustainability scenario, despite promoting vegetation recovery, may lead to more fragmented configurations if restoration occurs in isolated or suboptimal areas. These findings underscore the importance of integrating spatial configuration—not just habitat extent—into conservation strategies.

In the current context of the Sierras Chicas, characterized by strong LULC change trends, a lack of spatial planning and weak governmental regulation means that the business-as-usual scenario appears likely to materialize [52,53,62], with significant consequences for biodiversity connectivity. In light of this situation, broader measures are required that not only preserve existing fragments but also promote the restoration of degraded areas and support the regeneration of natural cover and species connectivity.

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Abbreviations

The following abbreviations are used in this manuscript:

LULC	Land-Use/Land-Cover
PAs	Protected areas
BAU	Business-as-usual scenario
SUST	Sustainability scenario
INT	Intensification scenario
IUCN	International Union for Conservation of Nature
ECA	Equivalent Connected Area index
IIC	Integral Index of Connectivity
dECA	Relative change in equivalent connected area
dA	Relative change in habitat area

Appendix A. Future Land-Use Change Scenario Modeling

Because the dynamics of LULC change vary within the study area, the area was divided into three subregions for scenario modeling:

- **Urban Zone:** a 300 m buffer surrounding the main urban areas. This distance was chosen because it approximates the extent of urban expansion between 2004 and 2019.
- **Non-Urban Zone:** the area outside the main urban settlements and their buffer zones.
- **Northwest Zone:** a native forest area located in the northern part of the study area, away from extensive urbanization and invasions of exotic tree species.

For scenario development, LULC maps from 2004 and 2019 were used, along with a set of physical-environmental and anthropogenic variables (Table A1). The land-cover maps employed correspond to those produced by [52]. These maps include ten LULC classes: water, rock-bare soil, urban, productive land, grasslands, shrublands, native forest, glossy privet forest, pine forest, and acacia forest. Further details on the map development process, the classified LULC categories, and the accuracy assessment are provided in [52].

Table A1. Physical-environmental and anthropogenic variables used for scenario modeling.

Variable	Description	Source
Physical-environmental		
Altitude (m.a.s.l.)	Mean value for the period 1940–2000	DEM NASA SRTM version 3.0 [98]
Slope (degrees)		Derived from the digital elevation model
Orientation (degrees)		
Temperature (°C)	Mean value for the period 1940–2000	WorldClim BIO12 [99]
Annual precipitation (mm)		
Aridity	Martonne aridity index	Atlas Climático digital de la República Argentina [100]
Distance to water (m)	Distance to watercourse or waterbody	Administración Provincial de Recursos Hídricos
Native forest patch area (ha)	The pixel value represents the area of the native forest patch it is part of	[52]

Table A1. Cont.

Variable	Description	Source
Distance to grassland (m)	Distance from each raster pixel to the corresponding class, cover type, or feature of interest	[52]
Distance to shrubland (m)		
Distance to native forest (m)		
Distance to glossy privet forest (m)		
Distance to pine forest (m)		
Antropic		
Fire frequency	Fire frequency between 2004 and 2018	[101]
Population density (Hab/km ²)	Population density derived from the 2001 and 2010 national census data	[102]
Distance to roads (m)	Distance to primary, secondary, and tertiary roads	Mapas Córdoba–IDECOR
Distance to urban areas (m)	Distance from each raster pixel to the corresponding class, cover type, or feature of interest	[52]
Distance to productive areas (m)		

The magnitude and direction of LULC changes between 2004 and 2019 were quantified using Markov transition matrices, which indicate the proportion of a given land-cover type at time T_1 that transitions to another type at time T_2 . The following transitions were modeled:

Productive >> Urban
 Productive >> Shrubland
 Grassland >> Urban
 Grassland >> Productive
 Grassland >> Shrubland
 Grassland >> Native Forest
 Shrubland >> Urban
 Shrubland >> Productive
 Shrubland >> Native Forest
 Native Forest >> Urban
 Native Forest >> Productive
 Native Forest >> Grassland
 Native Forest >> Shrubland
 Native Forest >> Glossy privet Forest
 Native Forest >> Pine Forest
 Glossy privet Forest >> Urban

Dynamica EGO analyzes the relationship between historical land-cover changes (from 2004 to 2019) and the physical-environmental and anthropogenic variables used, in order to develop future projections. Once the model is trained, a projection is generated using the 2004 land-cover map, and the simulated 2019 map is validated by comparing it to the actual 2019 map using a similarity metric. Finally, a 3×3 pixel majority filter was applied to the simulated maps to reduce noise and eliminate spurious pixels. One limitation of the model is its reliance on LULC maps, which contain inherent uncertainties that may be propagated or even amplified during the simulation process. Additionally, LULC transition rates are assumed to remain constant over the entire study period, which may not adequately capture the temporal dynamics of actual land-cover and land-use changes [103]. Addressing this limitation would require dividing the simulation period into distinct temporal stages. Both

aspects underscore the importance of having prior knowledge of the study area to inform appropriate modeling decisions.

Additional information regarding the scenario modeling can be found in [65].

Appendix B

Table A2. Protected Area Network of the Sierras Chicas.

	Name
National PAs	La Calera Ascochinga
Provincial PAs	Reserva forestal natural Uritorco Reserva forestal natural Sierras de Punilla Reserva hídrica natural los Gigantes Reserva hídrica natural la Quebrada Corredor biogeográfico Chaco Árido
Municipal PAs	Área protegidas AP1 Villa Carlos Paz Reserva urbana San Martín Reserva natural Quisquisacate Reserva forestal natural Sierra de Cuniputo Reserva hídrica natural Salsipuedes Reserva de uso múltiple Villa General Belgrano Reserva hídrica natural Villa Cerro Azul Reserva natural de uso múltiple de la Rancherita Reserva natural municipal el Portecelo Reserva ecológica recreativa Cuesta Blanca Reserva natural cultural recreativa municipal Tanti Reserva parque recreativo natural Río Yuspe Reserva natural comunal Camin Cosquín Reserva hídrica recreativa natural Saldán Inchin Reserva hídrica recreativa natural Bamba Área natural protegidas Villa Cielo Reserva los Manantiales Reserva hídrica recreativa Villa Allende Reserva hídrica recreativa los Quebrachitos Reserva Tiu Mayu Reserva hídrica recreativa natural Mendiolaza Área de protección Alta Gracia

Appendix C

Table A3. Area (ha) of different land-cover types in the Sierras Chicas of Córdoba for the year 2019 and for the 2050 scenarios: BAU, SUST, and INT.

	2019	2050		
		BAU	SUST	INT
Urban	50 822.72	109 688.39	73 307.73	111 754.18
Productive	215 900.50	206 441.30	205 228.32	216 827.65
Grassland	114 156.38	75 161.11	81 138.69	74 826.44
Shrubland	323 393.63	350 368.13	351 369.91	362 057.75
Native forest	108 200.53	70 764.31	101 543.96	45 774.14
Glossy privet forest	4 147.11	4 981.21	4 916.26	6 318.85
Pine forest	2 393.91	3 124.80	2 980.50	2 997.23

Appendix D. dECA and dA Values

Table A4. dECA values for 1989–2019 and for 2019–2050.

	1989–2019	2019–2050		
		BAU	SUST	INT
<i>Chlorostilbon lucidus</i>	−15.19	−0.43	−5.85	−2.71
<i>Dryocopus schulzii</i>	−33.83	−3.71	−27.97	−27.18
<i>Milvago chimango</i>	−26.93	−2.36	−22.97	2.58
<i>Saltator aurantiirostris</i>	−14.54	0.31	−7.92	−4.87
<i>Poliophtila dumicola</i>	−7.36	4.00	−11.01	2.25

Table A5. dA values for 1989–2019 and for 2019–2050.

	1989–2019	2019–2050		
		BAU	SUST	INT
Grassland	−35.82	−34.16	−28.92	−34.45
Shrubland	51.15	8.34	8.65	11.96
Native forest	−31.93	−34.60	−6.15	−57.70

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