



Protected areas as a double edge sword: An analysis of factors driving urbanisation in their surroundings

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ABSTRACT

Protected areas (PAs) are the most effective tools to protect biodiversity and ecosystem services. They have proven to be effective in stopping extensive land use conversion in well-conserved terrestrial ecosystems. However, land cover changes around PAs threaten biodiversity and ecosystem services within their limits and reduce ecological connectivity. In this study, we analysed the urban sprawls on the boundaries of 159 PAs (national, regional, and natural parks) in Spain, using 2.5 and 5 km non-protected buffer zones from 1990 to 2018. We clustered PAs based on biophysical and socio-economic characteristics and modelled urban sprawl in different buffers and periods. Hierarchical clustering revealed three groups of PAs: (a) proximate urban parks, (b) mountainous parks, and (c) parks in the Madrid autonomous region. We found that urbanisation in the surroundings of PAs in Spain has nearly doubled since 1990. General linear models explained a significant proportion of the urbanisation trends observed, with the number of municipalities in the boundary of the PA, the distance to a main road, and the distance to a big city acting as the most important drivers of urban sprawl. Our results also show that some PAs exert significant effects on urbanisation trends in their surroundings through the park-view effect. Finally, we highlight three coexisting phenomena that might explain the observed urban sprawl processes: (a) PAs attracting urbanisation in their surroundings due to the park-view effect, (b) PAs as a deterrent for urban sprawl within their limits, and (c) PAs occupying residual areas among previously urbanised lands.

1. Introduction

Protected areas (PAs) are a necessary spatial planning tool to protect biodiversity and prevent land use/land cover changes within their boundaries (Gaveau et al., 2009; Gray et al., 2016; Palomo et al., 2014). However, many PAs have failed to resist human pressure, particularly the non-forested ones (Geldmann et al., 2019), becoming isolated by land use changes (specifically intensive agriculture and urbanisation) in their surroundings, as reported by different studies in the tropics (DeFries et al., 2005; Foley et al., 2005; Laurance et al., 2012), New Zealand (Ewers and Rodrigues, 2008) and Spain (Rodríguez-Rodríguez and Martínez-Vega, 2017). The effect of these changes in the efficiency of PAs has also been addressed from different perspectives, such as

species declines within PAs boundaries (Butsic et al., 2012; Rayner et al., 2014; Rada et al., 2019) or landscape ecological connectivity, pointing to the need to be more ambitious with the management of non-protected land.

A better understanding of urban sprawl in the boundaries of PAs is a prime element in the context of climate change, which may cause several species migrations (Hannah, 2008; Mingarro and Lobo, 2021). Permeability between PAs and their boundaries is mainly related to different degrees of human activity across regions, such as distance to roads and the presence of roads, human density, farming, and urbanisation (Hofmann et al., 2021). Among land-uses, urban areas represented only 2% of the global surface in 2001 (Lambin et al., 2001) and 3% in 2014 (Liu et al., 2014). Nevertheless, urbanisation affects land

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change by transforming urban–rural linkages (Lambin et al., 2001), increasing pressure on PAs boundaries and amplifying associated land uses, such as recreation and urban green spaces (van Vliet et al., 2017). Moreover, contemporary urbanisation is fundamentally characterised by many interconnected dimensions at global, regional, and local scales (Seto et al., 2010). Consequently, some studies have addressed the phenomena of urban sprawl in PAs boundaries, highlighting that it jeopardises the conservation value of PAs (Radeloff et al., 2010; Gimmi et al., 2011). For example, urbanisation in the surroundings of PAs increases the number of non-native species inside (Gavier-Pizarro et al., 2010). Furthermore, Seto et al. (2010) call for research on certain urbanisation challenges, demonstrating our limited understanding of the dynamic interactions in urban areas and which forms of urban growth have less environmental impact.

Several factors that generate PA isolation have been widely studied in the scientific literature. For instance, Cook et al. (2019) showed that the perimeter-to-area ratio of PAs appears to have increased significantly over time, suggesting higher exposure to edge effects. Moreover, they also observed a significant increase in the proportion of PAs boundaries that adjoin incompatible land uses, which was also reported by Primack (2006). Population density has also been identified as one of the main changes in PA boundaries (Wittemyer et al., 2008), suggesting that PAs attract rather than repel human settlements. Nevertheless, Joppa et al. (2009) pointed out that even if PAs may experience unusual population pressures near their edges, there is no evidence of a general pattern of disproportionate population growth near PAs. In this sense, population growth near the borders of PAs results from an expansion of nearby human populations, which may spread the activities that alter land cover toward the PAs over time (Seiferling et al., 2012). These contrasting views demand further analysis at fine scales on the evolution across time of pressure to PAs from their surroundings (Ament and Cumming, 2016).

PAs in the Mediterranean region provide an adequate context for

understanding the processes of urbanisation and isolation due to the long-term co-evolution between nature and society (Antrop, 2004) and the alteration of ecosystems and urbanisation processes that impact ecosystem services (Martín-López et al., 2011; García-Nieto et al., 2018). Spain has one of the most extensive and varied PAs networks in Europe (15 national parks, 152 natural/regional parks, and 27.4% of the Spanish territory is under Natura 2000 protection) and is a widely acknowledged rapid urban sprawl hotspot (Santos-Martín et al., 2019). In this study, we analyse the processes of urban sprawl in 159 PAs and two surrounding buffers (2.5 km and 5 km) in Spain from 1990 to 2018 and explore the factors that influence these processes (Fig. 1). PAs were first clustered based on geographical and socioeconomic variables, and then general linear models were used to predict urbanisation trends in the surroundings of PAs. Finally, we discuss three different urbanisation processes that occur around PAs in Spain, which can provide insights to other PAs globally: (1) the park-view effect, which attracts urbanisation to the periphery of certain PAs, exhibiting a significant positive effect of park proximity on residential development (Brambilla and Ronchi, 2016); (2) the declaration of PAs as a deterrent of urban sprawl, which mainly occurs around big cities, where PAs serve to stop urbanisation in high conservation-value areas; and (3) the creation of PAs in residual non-urbanised land, resulting in highly populated areas in their immediate boundaries.

2. Methods

The three categories of PAs with the highest level of protection under Spanish legislation were considered in this study: national, regional, and natural parks, all of which are type II and V in the IUCN categories (Castro et al., 1999). These three categories comprise 159 PAs in Spain, covering 8% of Spain's inlands. Island and marine PAs were excluded from the analysis due to intrinsic differences, as they are mostly affected by overexploitation of fishing resources, whereas inland PAs are affected

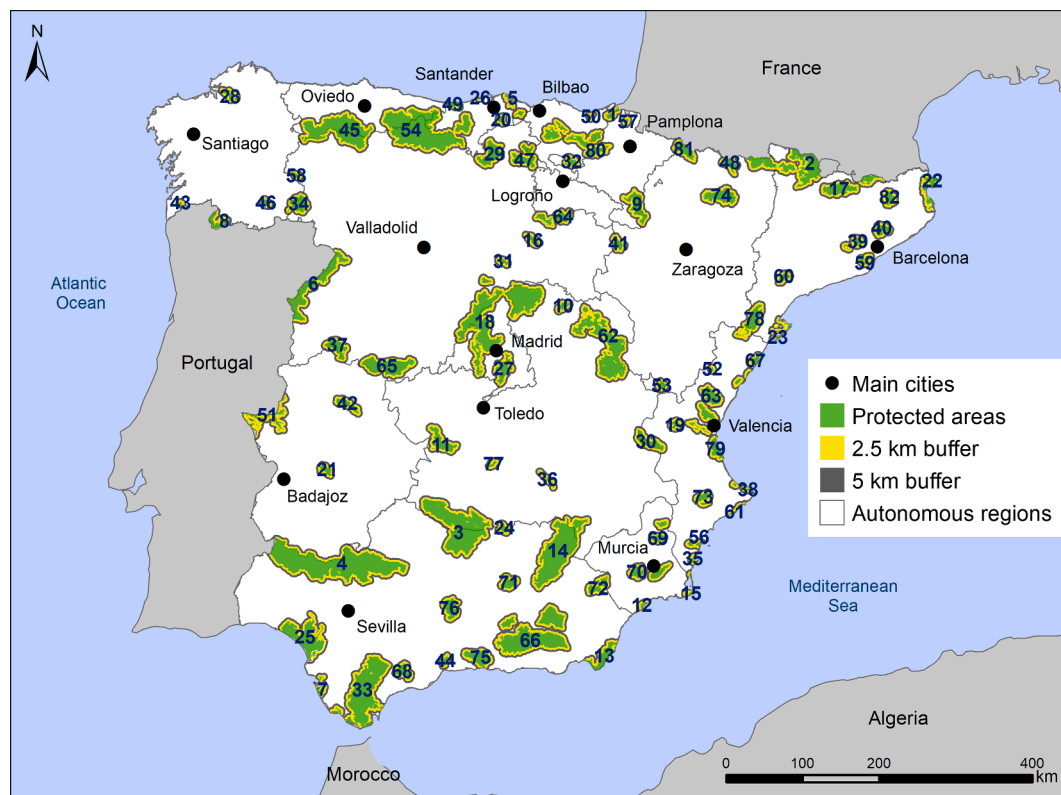


Fig. 1. Protected areas in peninsular Spain and their buffers. The core of protected areas is shown in green and the buffers in yellow (2.5 km buffer) and grey (5 km buffer). Numbers are the codes to identify the protected areas in the S1 Appendix.

by land use changes. We also excluded Natura 2000 sites that do not overlap with national protection categories.

We dissolved the PAs that overlapped or shared boundaries with another to avoid the potential effect of multiple PAs in the surroundings of the core PA (Fig. 2A and B). Next, we created a multiring buffer of 2.5 and 5 km from the PAs boundaries, which reduced the total number of PAs-conglomerates from 159 to 82 (Fig. 2B and C). This reduction of PAs-conglomerates is a consequence of PAs in Spain often being separated by less than 10 km, so that buffers from different PAs merge. The list of PAs agglomerations with their names, types, years, and numeric codes is provided in the S1 Appendix.

We used data from Corine Land Cover (CLC) 1990, 2000, 2006, 2012 and 2018 (Fig. 2D) for land use/land cover (CLC1990, CLC2000, CLC2006, CLC2012, and CLC2018). We then selected codes from 111 to 142, corresponding to artificial surfaces (as labelled in Corine Land Cover database), and started a process of correcting errors. As reported by Martínez-Fernández et al. (2019), CLC has considerably varied the methodology after 2006, and therefore, corrections should be done for the data before the development of temporal analysis. To solve this problem, we first evaluated the non-corrected CLC by intersecting each year with the PAs buffers and detected non-logic area values in 54 out of 246 buffers (each PA contains the park, 2.5 km and 5 km buffer). These non-logic values consisted of changes between periods higher in the year before than in the next period; therefore, we assumed that a decrease in artificial surfaces was not possible. To solve this problem, we revised 162 high-resolution satellite imagery from 2006, 2012 and 2018 (CNIG, PNOA, 2018) and verified that artificial surfaces did not decrease between years (see S2 Appendix for more details). To correct each year with the year before, we dissolved years in pairs as follows: 1990 dis 2000 = 2000'; 2000' dis 2006 = 2006'; 2006' dis 2012 = 2012' and 2012' dis 2018 = 2018'. Once all the layers were corrected, we intersected all years with the layer of PAs and buffers and calculated the total

area for each period (Fig. 2E).

After the treatment of the CLC, we calculated the average value of the following variables in the 82 PAs-conglomerates:

- (1) Altitude: Elevation is a powerful explanatory variable in PAs analysis and it is negatively correlated with some impacts such as alien species richness (Pauchard and Alaback, 2004), type of vegetation/cover (Rodríguez et al., 2013) or lower deforestation and agricultural yields (Brun et al., 2015). Elevation values were obtained from the DEM at a 5 m resolution (CNIG, 2018).
- (2) Slope: This variable has been used in other studies, such as Joppa and Pfaff (2009), to detect biases in PAs locations, and it is also a determinant in the location of some land uses such as agriculture or urbanisation. We obtained the slope in percentage throughout the *slope* tool from ArcGIS and the DEM.
- (3) Distance to a city: We estimated the distance from the PAs boundaries to the boundary of the closest city with more than 50,000 inhabitants following Rodríguez-Rodríguez et al. (2019). Other studies have considered this variable in the effect of land use changes in PAs, such as McDonald et al. (2009). We used the *near* tool from ArcGIS to estimate this variable.
- (4) Distance to a main road: Similarly, distance to a main road has been demonstrated to affect land use changes in the boundaries of PAs (Curran et al., 2004) and is a determinant variable in the isolation of PAs (Newmark, 2008). We calculated the distance from the boundary of the PA to the main road (BCN200-CNIG, 2018) using the *near* tool from ArcGIS.
- (5) Main road density: This variable was obtained by dividing the total length of the roads inside the PA (in kilometres) by the total surface area of the PA. This variable has been used in other studies to analyse the impact of species conservation and biodiversity (Bennett, 2017) and is also related to urbanisation

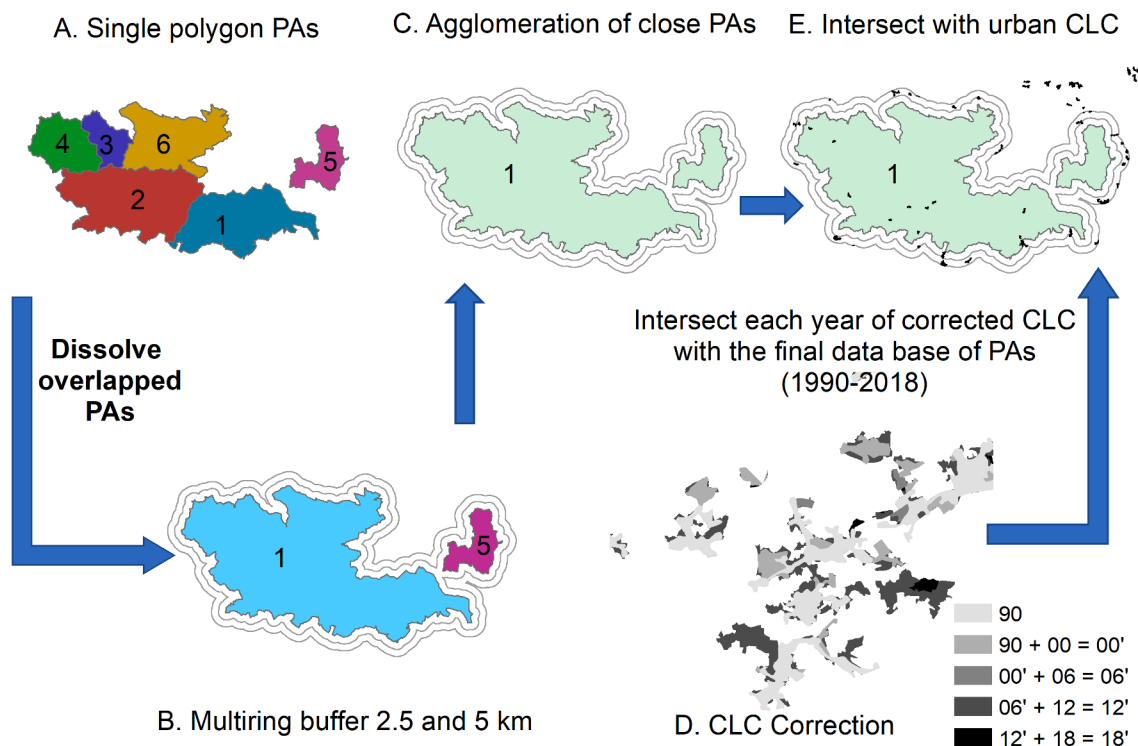


Fig. 2. Methodological steps followed in the research. PAs = protected areas; CLC = corine land cover. Step A shows a single PA that shares a boundary and one PA (5) separated from the core PAs. Step B shows how PAs that share boundaries were dissolved to define a single boundary, then buffers of 2.5 and 5 km were created. Step C shows how those PAs that share buffers (1 and 5 in step B) finally become a single PA agglomeration for the analysis. Step D shows the method followed for the correction of CLC database for the years 1990, 2000, 2006, 2012 and 2018. Step E shows the intersection of CLC with PAs and their buffers (urbanised land in black colour).

processes. We obtained the roads from BCN200-CNIG (2018) and calculated the area of PAs in ArcGIS.

- (6) Number of municipalities in the boundaries of PAs: We selected this variable because municipalities are the administrative units in which land use decisions are taken in Spain (González-García et al., 2020) and other countries (Hersperger et al., 2018), which may affect the PAs borders. We obtained the municipality layer from the CNIG (2018). We then created a buffer of 100 m from the PAs border and intersected it with municipalities to get the number of municipalities in each PAs agglomeration border.
- (7) Urban ratio between 2.5 and 5 km buffers: We subtract the total surface of urban land in the 2.5 km buffer by the total surface in the 5 km buffer to create a variable representing the proportion of urban land close to PAs borders. This variable can be positive if the urban land in the 2.5 km ring is larger than 5 km or negative if the urban land in the 5 km ring is larger than 2.5 km.

Other variables, such as population or PA perimeter, were also calculated but were excluded from the analyses because they were highly correlated with some of the variables mentioned above. Finally, we standardised the above variables (1–7) and used them to perform a hierarchical cluster analysis of PAs for each period (five clusters) based on the Euclidean distance and Ward's agglomerative method. We selected three groups based on the validation process that we performed, consisting of hazardously taking half the PAs of each group and remaking the cluster analysis. In the validation process, we obtained the same groups and concluded that the selection was correct. Then, General Linear Models (GLMs) were used after checking normality (log-transformed) to examine how variables 1 to 7 (independent variables) predicted the increase in urbanisation between 1990 and 2018 (dependent variable) for each buffer and PAs group.

3. Results

3.1. Hierarchical cluster analysis of protected areas

The percentage of occupied urban land in PAs increased from 0.16% in 1990 to 0.3% in 2018 (67 km² and 123 km², respectively). Similarly, the occupied urban land in the buffers of PAs in Spain has nearly doubled from 644 km² to 1,082 km² between 1990 and 2018 (from 2.1% to 3.9% in 2.5 km buffer and from 1.9% to 3.6% in 5 km buffer), following a linear pattern ($R^2 = 0.98$). Three groups were obtained in the hierarchical cluster analysis for all the periods: (1) proximate urban parks (PUP, $n = 43$), (2) mountainous parks (MP, $n = 39$) and (3), Madrid autonomous region parks (MARP; $n = 1$); (Figs. 3 and 4). All years presented the same clusters without permeability from one group to another. The main characteristics of each axis of the factorial analysis and the dendrogram can be found in the S3 Appendix. Factor 1 (31.8% of variance) is defined by altitude, slope, and distance to city, while factor 2 (22.3% of variance) is defined by the number of municipalities and the urban ratio between the 2.5 km and 5 km buffers. The same PAs appear in the five different hierarchical clusters that we developed for each year (1990–2000–2006–2012–2018), highlighting that the patterns observed in 1990 did not change throughout the study period.

PUP are close to main roads (0.2 km of distance on average), have 0.066 km of road per km², and are very close to main cities (5.7 km on average). They are also characterised by low altitudes (341 m a.s.l. on average) and moderate slopes (10.4% on average). The average number of municipalities in the PUP surroundings is 10. This group presented more hectares urbanised in the 2.5 km buffer than in the 5 km buffer in all periods (Fig. 4B), exhibiting positive values for the urban ratio in all years (Table 1). In general terms, PUP present a proportion of urbanisation in their surroundings between 4% and 6% of the total area in each buffer, which is 4 to 6 times larger than in MP.

MP exhibit an average distance to roads more than ten times higher than peri-urban parks (2.7 km on average) and considerably fewer km of

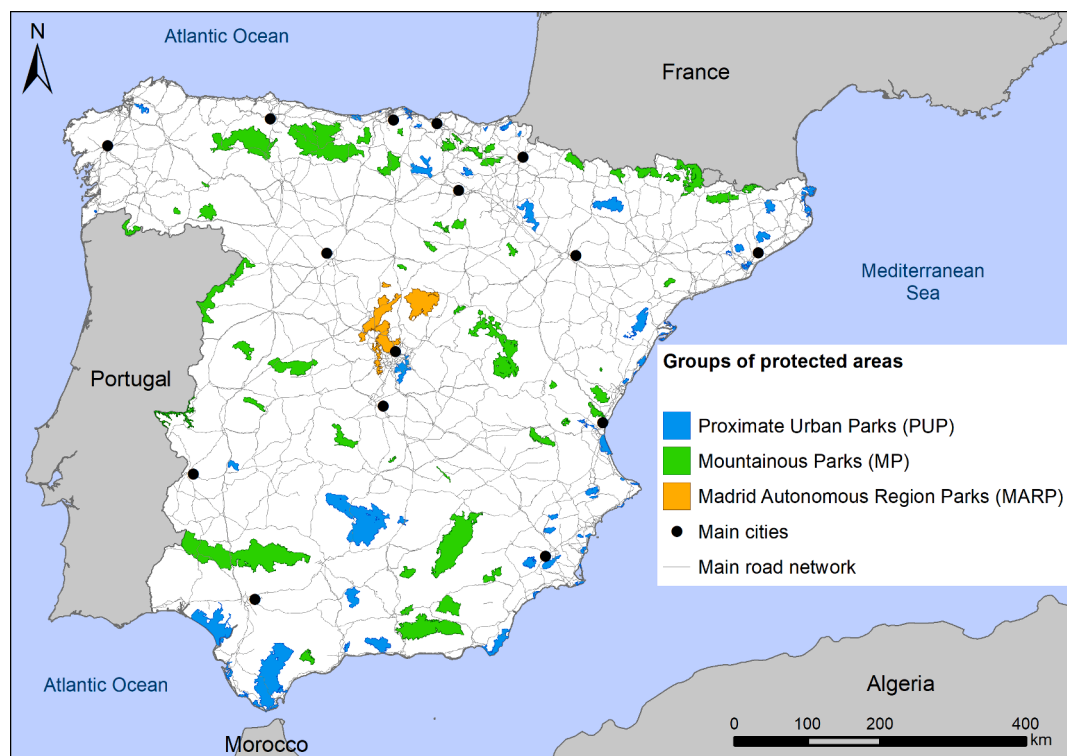


Fig. 3. Urban sprawl trends in the three groups of PAs that emerged from the hierarchical cluster analysis. Blue colour represents proximate urban parks that present, usually, low or medium altitudes and are close to cities and roads. The green colour represents parks usually in high altitudes and far from cities and roads. Orange colour represents the group composed by a single protected areas agglomeration present in Madrid autonomous region.

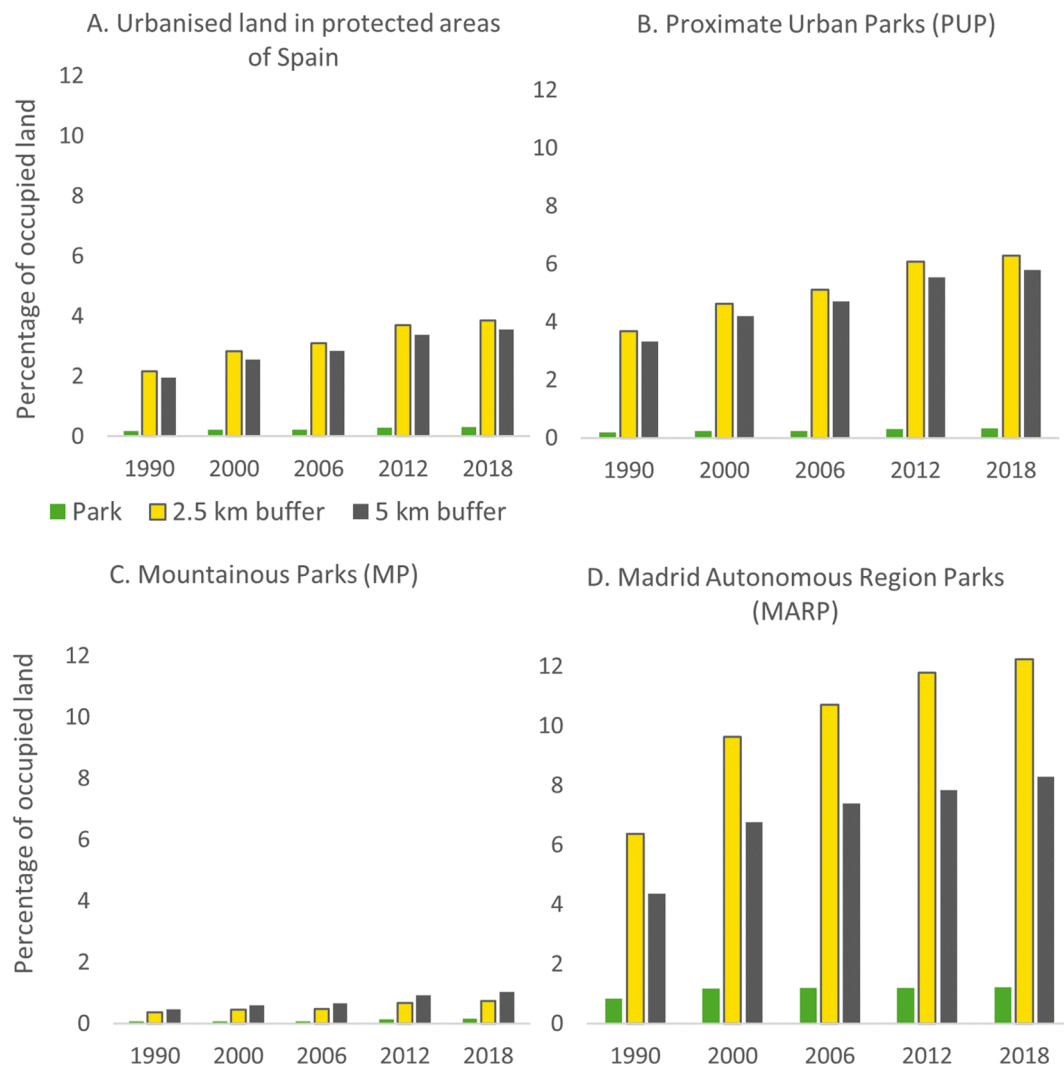


Fig. 4. Percentage of the PA (green), 2.5 km buffer (yellow), or 5 km buffer (grey) that is occupied by urbanization. Graph A shows the general trend of all PAs used in the study. Graph B shows urbanisation in proximate urban parks. Graph C shows urbanisation in mountainous parks. Graph D shows urbanisation in Madrid autonomous region parks.

Table 1

Average values for the variables used in the hierarchical cluster analysis in each of the three protected area groups. MRDs: Main Road Distance (km); MRDn: Main Road Density (km/km²); DC: Distance to City (km); Slp: Slope (%); Alt: Altitude (m a.s.l.); NoM: Number of Municipalities (n); UR 90, 00, 06, 12, 18: Urban ratio between 2.5 km and 5 km buffers (hectares in 2.5 km less hectares in 5 km) in the five-time periods studied.

		MRDs	MRDn	DC	Slp	Alt	NoM	UR90	UR00	UR06	UR12	UR18
Proximate urban parks	N = 43	0.2	0.066	5.7	10.4	341	10	155.3	196.8	193.4	246.3	244.2
Mountainous parks	N = 38	2.7	0.017	29.8	16.4	951	20	-27.6	-46.5	-61	-77.3	-91.5
Madrid autonomous region parks	N = 1	0	0.047	0	8.7	1018	134	5,605	8,184	9,319	10,735	10,898

road per km² (0.017). Additionally, the distance to the main cities is almost six times larger than that of PUP. This group has an average altitude of 951 m a.s.l. and an average slope of 16.4%. Additionally, the number of municipalities in their boundaries is twice that of PUP, mainly because of the large perimeter of these parks. In general terms, this group present higher urbanisation in the 5 km buffer than in the 2.5 km buffer. Moreover, the percentage of urbanised surface in the buffers is less than 2% of urbanisation, exhibiting a significant difference with PUP (Fig. 4C).

The hierarchical cluster analysis revealed a highly differentiated agglomeration of PAs within the most densely populated autonomous region of Spain, Madrid, with 840 inhabitants per km². The high proximity to the city and roads has led to an independent pattern compared

to the ones observed in the other PAs. Thus, the distance to the main roads is zero as many roads reach the limits of the parks. Road length per km² of PA is 0.047 km, and the distance to the city is zero because it reaches the border. Nevertheless, the average altitude of this cluster is 1018 m a.s.l., in contrast with the slope (8.8%), which is associated with an altitudinal gradient from city to mountains. The number of municipalities in the periphery is the highest observed because of the very large perimeter of the cluster of PAs located very close to each other. Finally, the differences between the urbanisation in the buffer of 2.5 km and 5 km are the highest observed, exhibiting a 2% difference in the year 1990 and reaching a 4% difference in 2018 (more than 100 km²). The proportion of area urbanised in the surroundings reached 12% in 2018 (Fig. 4D). This remarkable proportion of urbanised buffer in MARP is

almost three times higher than the total urbanisation in the MP group.

3.2. Factors driving the urbanization in surroundings of protected areas

A general linear trend was observed in the increase of urbanisation in the 2.5 and 5 km buffers ($R^2 = 0.98$). It was not possible to develop models for MARP because a single PAs agglomeration formed this group. However, two GLMs were obtained for the other two clusters of PAs (Table 2), PUP 2.5 and 5 km buffer, and MP 2.5 and 5 km buffer. All GLMs ranged between 43% and 51% of the deviance explained (d^2). The most explanatory variables were related to the number of municipalities and the distance to cities. The best predictive capacity of the models was obtained in the 5 km buffer for PUP and MP. For PUP 2.5 km, the most explanatory variables were slope and distance to cities ($d^2 = 46\%$). For PUP 5 km, the most explanatory variables were distance to the city and main road density ($d^2 = 51\%$). Similarly, for MP 2.5 km, distance to the city and main road distance were the most explanatory variables ($d^2 = 43\%$). For MP 5 km, the altitude and number of municipalities were the most explanatory variables ($d^2 = 45\%$). Nevertheless, depending on the type of parks and buffers, altitude and slope played a major role in explaining variability. Remarkably, the number of municipalities had different effects depending on the group. For instance, urban land increase between 1990 and 2018 was higher in the MP when the number of municipalities was higher. In contrast, in PUPs, fewer municipalities led to an increase in urbanisation. Finally, the effect of distance to the city and main road density on urban land increase between 1990 and 2018 is higher in PUP than in MP.

3.3. Types of urbanization processes in surroundings of protected areas

For an in-depth understanding of urbanisation processes in the surroundings of PAs, we provide one example per obtained group in the hierarchical analysis. The case of MARP is an iconic one that highlights the complexity of PAs in the surroundings of a megacity (Fig. 5). This agglomeration of PAs is composed of six different PAs with different protection categories, such as national parks, natural parks, and regional parks (see S1 Appendix). The high proximity of these areas generates a big difference in urban sprawl regarding PAs limits because these PAs are scattered throughout an altitudinal gradient from 2400 to 400 m a.s.l. (see Fig. 5A compared with Fig. 5B). About the results obtained in the other groups, the PAs agglomeration located in the Madrid autonomous region presents characteristics of MP as well as PUP.

In Figs. 5 and 6, we present three examples of urbanization around PAs of Madrid in two different zones, the centre of the city and the periphery. Urbanization, in general, increased from the city centre to the periphery in 1990 (Fig. 5; Fig. 6A), but after the declaration of almost all PAs (after 1990), the buffer of 2.5 km shows increased urbanisation compared to that of the 5 km buffer. That suggests a park-view effect, attracting urbanization to PAs surroundings. Nevertheless, the original goal of the declaration of the park was usually to stop urbanization within the boundary. Fig. 5C demonstrates how PA are adapted to the existing reality, defining the shape of the borders to keep most of the

urban land outside PAs limits. Thus, PAs have been located within non-urbanised residual space of high ecological value but ended by acting as an attractor of urbanization in their boundaries. In the example of the periphery (Fig. 5B; Fig. 6B), we found that the difference between the 2.5 km and 5 km buffer is much higher than in the centre, suggesting a clearer park-view effect than in the city centre.

Figs. 7 and 8 show an example of a coastal PUP (A) and an MP (B). Fig. 7A and 8A show an example of a natural park declared in 1989, which combines the urbanisation process of using the residual space and the park-view effect. First, the current shape of the PA has been adapted to existing urban development in the year of the declaration. Second, the park generated a park-view effect after its declaration, as shown by the higher percentage of urbanisation in the 2.5 km buffer. Fig. 7B and 8B show an example of an MP in the north of Spain that presents a better conserved 2.5 km buffer. Additionally, the type of urbanisation tends to be more scattered and less intensive, occupying the 5 km buffer more than the 2.5 km.

4. Discussion

4.1. Processes of urban sprawl around protected areas

Our results show intense urbanisation processes around PAs in Spain, which has nearly doubled since 1990. Moreover, we also observed an increase in urbanisation within PA limits, mostly related to natural and regional parks rather than national parks. These findings are in line with previous studies on urbanisation around PAs in the United States (Radeloff et al., 2010), but the problem is particularly worrying in Spain because of continued urbanisation, which follows a linear trend in both 2.5 and 5 km buffers. A novelty of our study is the disaggregated approach to different PAs typologies and the characterisation of various urbanisation processes, which have been claimed in other studies due to the differences between PAs (Ament and Cumming, 2016). Previous studies have reported occupation of urbanisation in PAs boundaries of 2.7% (de la Fuente et al., 2020) while we obtained different values between mountainous areas (1%), proximate urban areas (6%), and an example of a megacity (12%). This highlights the importance of not aggregating all PAs to understand the different processes occurring within their boundaries.

Further, the isolation by an increase in urbanisation, especially related to the middle-high class population, which generates a more scattered urban sprawl, may produce different effects than intensive agriculture or grazing (Curran et al., 2004). Urbanisation around PAs will be particularly problematic in the future since urban settlements will be harder to modify or restore than agriculture or grazing land, which can be transformed into sustainable ecological corridors if needed under increased climate change effects.

In this study, we addressed three different processes that influence urbanisation around PAs. The park-view effect (first process) has been previously noticed in Brambilla and Ronchi (2016) in the context of Italian PAs, which is consistent with our results for MARP and PUP. However, assuming that all PAs exert an attraction effect for urbanisation would be misleading because many PAs surrounded by urban areas were designated when the urbanisation process has already occurred. Our results suggest that several PAs that were created to stop land-use changes (second process) also generate an effect in the urban planning tools of municipalities, resulting in more urban sprawl close to the boundary of PAs than in the rest of the available land. Finally, regarding the third process described on this research, many PAs could exhibit limits that do not match with biophysical features, since the initial demarcation of their boundaries was adjusted to the remaining high ecological value land. This may explain the unusual shapes exhibited by many PUP PAs in which the designation took place too late or responded to a degradation process that had already happened. Overall, it is important to highlight that we were not able to identify a single process occurring on its own, being more plausible that the three processes occur

Table 2

Results of the GLMs for factors driving urbanization in the buffers of protected areas (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). PUP: Proximate Urban Parks, MP: Mountainous Parks, d^2 : explained deviance.

	PUP 2.5 km	PUP 5 km	MP 2.5 km	MP 5 km
Intercept	10.661***	9.345***	0.506***	0.76**
Altitude		−0.004		−0.0004
Slope	−0.357**	−0.222*		
Distance to city	−0.0001**	−0.0002**	−7.46E-06**	−7.88E-06*
N municipalities	−0.2**	−0.135*	0.003	0.011*
Main road density	18.548*	11.463*		4.224*
Main road distance			−3.12E-05	
d^2	46%	51%	43%	45%

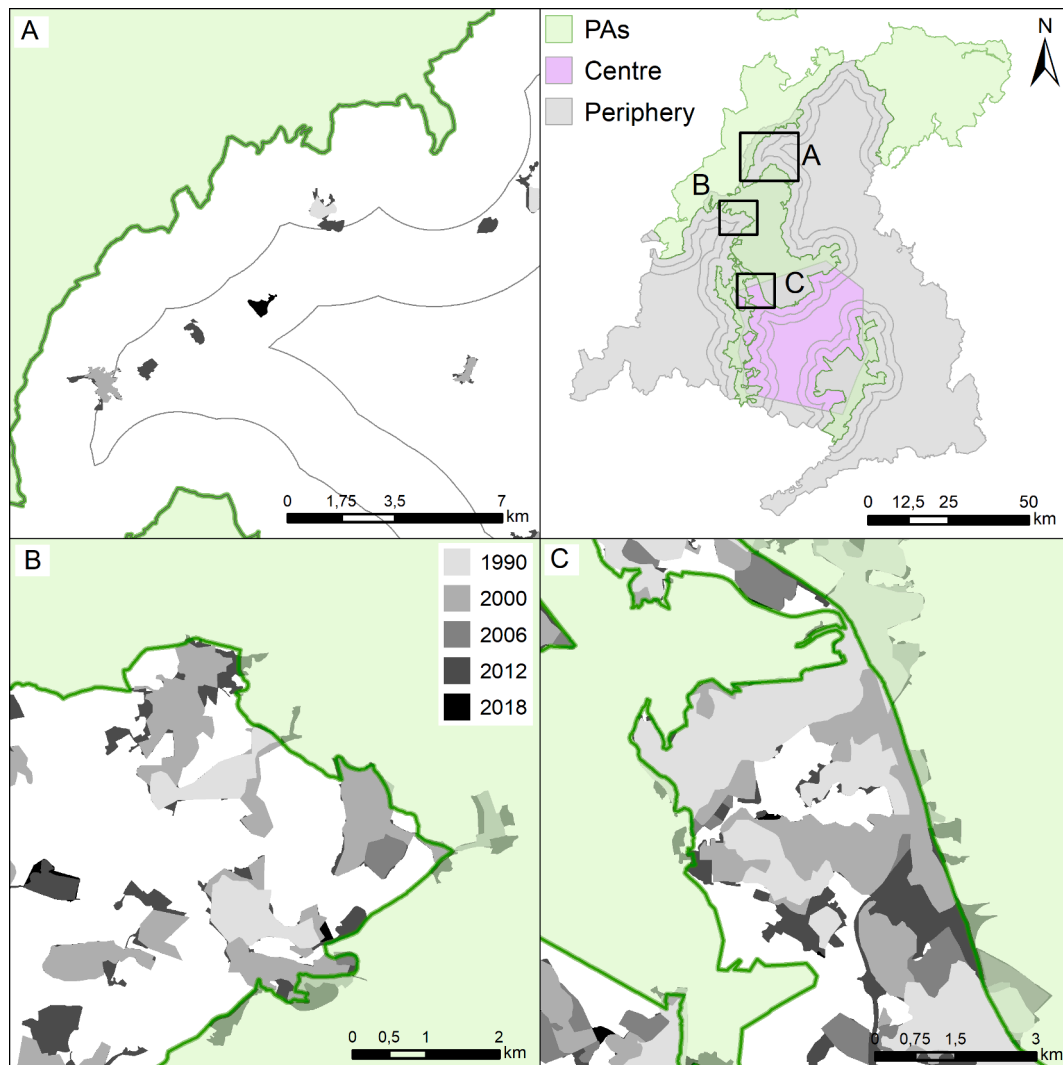


Fig. 5. Examples of urban sprawl in protected areas boundaries of Madrid. The map in the top-right represents two areas: the centre area (purple), where Madrid city is, and the periphery (grey). Dark green represents the boundary of the protected area. Examples A, B and C show the different combinations of urban sprawl processes generated by protected areas: park-view effect in a mountainous area (A), park-view effect/stop urban sprawl (B), and residual space/stop urban sprawl/park-view effect (C). These phenomena do not occur as single phenomena but at the same time. Grey gradients of colours represent increase in urbanisation during the period 1990–2018. Main PAs in the Madrid region were declared between 1985 and 1999. All the protected areas in this agglomeration are listed in S1 Appendix, number 18. (A) corresponds to the “Guadarrama National Park”, B corresponds to the “Cuenca Alta del Manzanares Regional Park” and C to the “Cursos Medio y Bajo del Río Guadarrama Regional Park”.

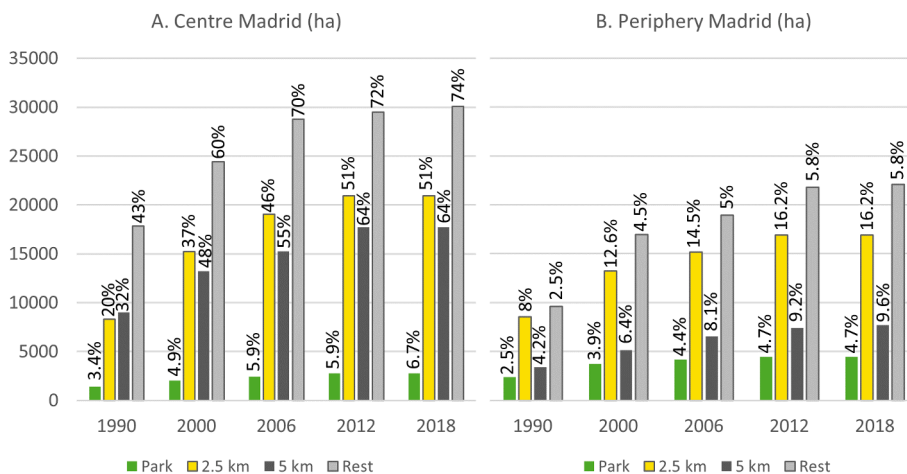


Fig. 6. Percentage of the PA (green), 2.5 km buffer (yellow), 5 km buffer (dark grey) and the rest of the area corresponding with Fig. 5 (light grey) that is occupied by urbanisation. Graphs show the total hectares urbanised in the period 1990–2018, and numbers represent the percentage of the occupied surface in the buffer. These percentages serve as a tool to understand if the process of urban sprawl is due to the occupation of the area (finding new spaces) or related to the attraction of protected areas. Graph A shows the increase in urbanisation in the centre of Madrid (corresponding with purple in Fig. 5). Graph B shows the increase in urbanisation in the periphery of Madrid, corresponding with grey in Fig. 5.

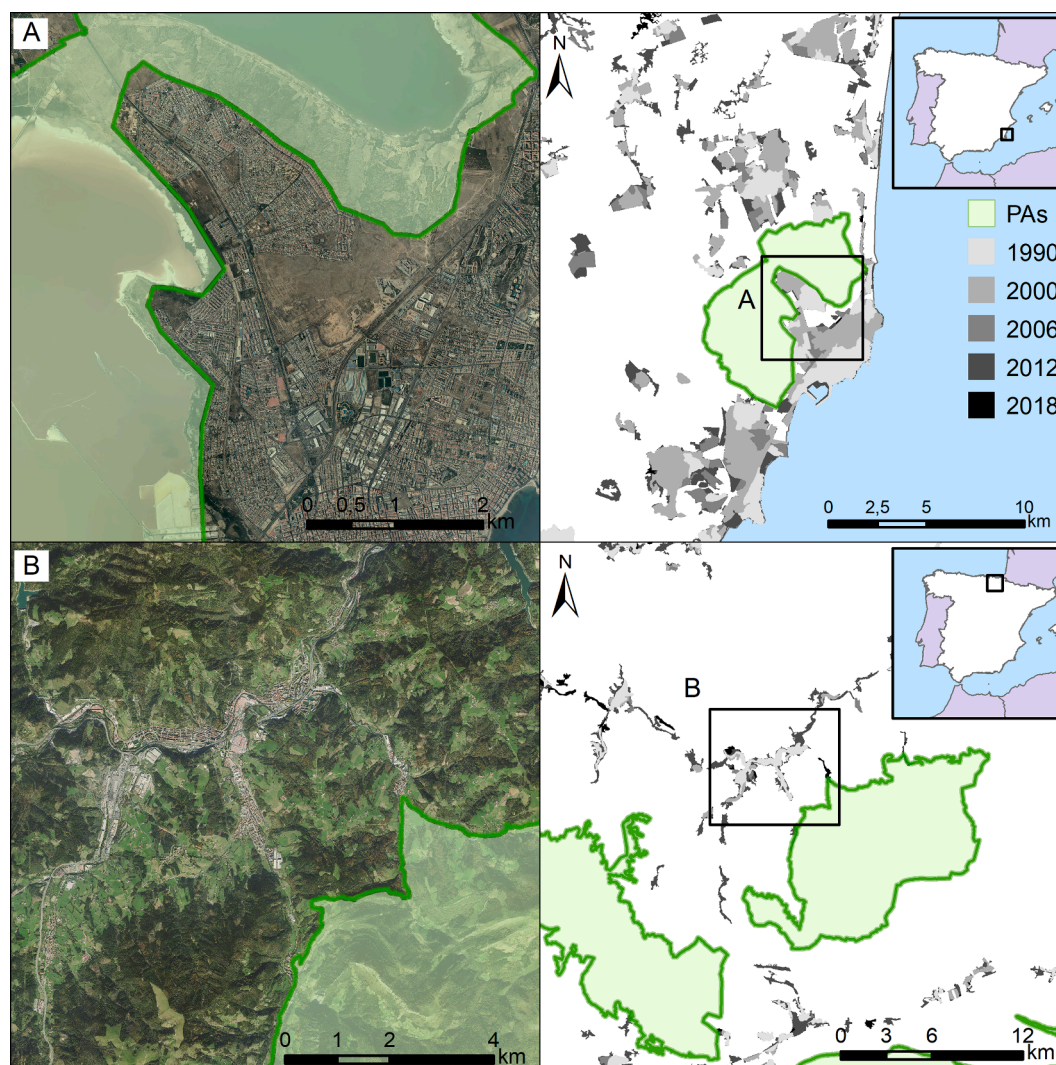


Fig. 7. Examples of urban sprawl in a coastal protected area (top) and a mountainous protected area (bottom). (A) shows an example of the park-view effect combined with adaptation to residual space, and B shows how the process is different in high altitude and high slope areas, where there is more space between protected area boundary and urbanised land.

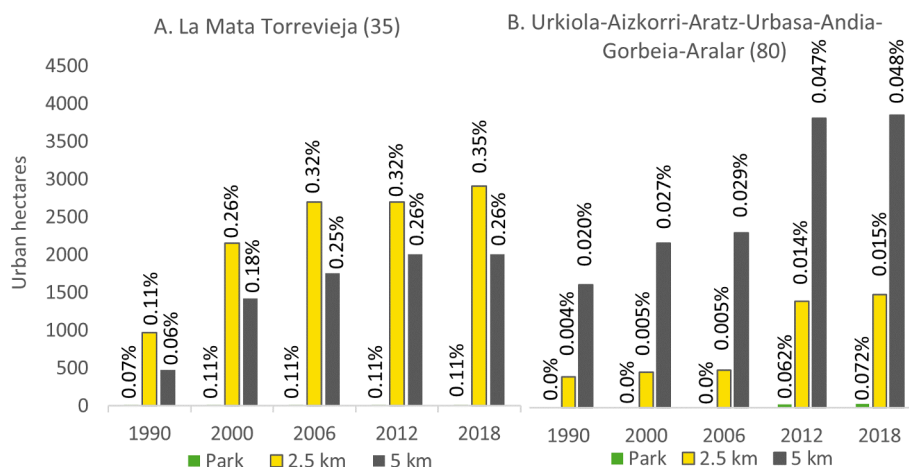


Fig. 8. Percentage of the PA (green), 2.5 km buffer (yellow), or 5 km buffer (grey) that is occupied by urbanisation. Graphs show the total hectares urbanized in the period 1990–2018, and numbers represent the percentage of the occupied surface in the buffer. These percentages serve as a tool to understand if the process of urban sprawl is due to the occupation of the area (finding new spaces) or related to the attraction of protected areas. Graph A shows an example of a PUP park corresponding with Fig. 7A. Graph B shows an example of MP park corresponding with Fig. 7B.

simultaneously with different degrees of relevance.

In the case of megacities, specific models and analyses must be developed to address the isolation of PAs. In our results, PAs around the

megacity of Madrid present a high average altitude (1018 m), suggesting that a megacity can also drive urban sprawl in the surrounding mountains. These results highlight the importance of creating a new

management framework for permeability and ecological connectivity in proximate urban PAs, mountainous PAs, and PAs affected by megacities. In the case of Spain, some studies have reported that land-use changes in the surroundings of PAs are mainly correlated with distance to cities, and they found no relation with the type of protection (i.e., national park, regional park, or Natura 2000; see Rodríguez-Rodríguez and Martínez-Vega, 2019). Additionally, land-use changes were more intense in coastal PAs than in mountainous PAs, which is also highly related to urban sprawl on the Mediterranean coast (Fig. 5A; Rodríguez-Rodríguez et al., 2019).

Our results show that urban sprawl in PUP is more intense in the 2.5 km than in the 5 km buffer, while MP present the opposite pattern. Moreover, the magnitude of urbanisation in each type of PA differs consistently (from 0.7% to 6%). For instance, MP having a higher altitude and slope in the 2.5 km buffer could affect urbanisation in PAs borders in comparison with PUP. This differentiation highlights the effect of cities surrounding PAs, which may exert more pressure in the form of urbanisation than agriculture and other intensive land uses (Seiferling et al., 2012). Our clustering method has helped separate the megacity of Madrid as an example of a highly intense process of urbanisation and isolation (6% vs. 12% urbanised compared with PUP). As a result, if the trend is not reversed, in a few years, PAs in proximate urban areas will be (if they are not already) non-connected islands with the high occupation of their non-protected boundaries by urbanisation and this could be potentially irreversible. This phenomenon can be observed in other areas that present very different characteristics than those in our study area highlighting the effect of the city in the PAs, i.e., impact in Mexico (Caro-Borrero et al., 2021) and the USA (Gimmi et al., 2011).

Further, the attraction of population, urbanisation, and recreation activities by green areas in cities has been widely demonstrated in other studies (Christopoulou et al., 2007; Carrus et al., 2015). PAs close to cities, especially in the context of an increasingly interconnected world, are associated with the idea of high quality of life. That is an observed phenomenon in the case of the Madrid autonomous region, which is a recognised hotspot of urban sprawl in Europe (Kuemmerle et al., 2016), and tends to urbanise first the periphery rather than rehabilitate the city centre or maintain a strict radial urbanisation pattern by searching for places with more natural value and good connection with the city centre (Rubiera et al., 2016; Arnaiz-Schmitz et al., 2018). This phenomenon has also been observed in other parts of the world (Couch et al., 2007; Glaeser and Kohlhase, 2004). In contrast, MP are not experiencing the same process since urban development is focused on the 5 km buffer and may be related to tourism and second residences rather than first residences (Scott, 2006).

4.2. The challenge of analysing spatial planning tools

The fact that PAs are fundamental spatial planning tools for biodiversity conservation collides with the fact that they may act as a double-edged sword, by attracting urbanisation in their boundaries. Our results show the importance of the number of municipalities in predicting urbanisation in PAs boundaries. Even if the number of municipalities were highly correlated with the perimeter of PAs, the perimeter was not a significant variable in any model, highlighting an important issue regarding spatial planning tools that needs to be addressed. In our case study, municipalities have their planning tools called “general urban plans”, making them administrative units in which land-use/land-cover changes occur (González-García et al., 2020). When a PA affects one municipality, the planning tools of the municipality adapt to the restrictions of the PA, but the rest of the territory automatically becomes the “available land for activities.” Hence, PAs as a planning tool will generate an immediate dichotomous response in the context of local planning tools. This study suggests that fewer municipalities in small PAs provoke more urbanisation as a response to the creation of the PA, and this could be related to a lower diversity of institutions and actors

(Lockwood, 2010). Moreover, PUP tend to be small patches close to or surrounded by urban land, in which municipalities could be more interested in urbanising since the natural areas close to the cities are more attractive places (Arnaiz-Schmitz et al., 2018).

Several studies demonstrate the inefficiency of PAs because they are not able to stop land-use changes outside their boundaries (Geldmann et al., 2019). The reality is that PAs are not intended to protect biodiversity far from their boundaries, but instead protect biodiversity and prevent land-use changes within their boundaries (Ewers and Rodrigues, 2008; Gray et al., 2016). Here, we do not question the effectiveness of PAs regarding land use changes, but we emphasise that urbanisation in the surrounding areas will have negative effects for biodiversity and ecosystem services within PAs in the long term, especially in the context of climate change. Moreover, we expect to animate the discussion on what kind of land-based approaches in PAs boundaries will synergise with the objective of PAs, that is, nature-based solutions in the surroundings for transformative change (Palomo et al., 2021), ecological agriculture, bioconstruction, bioeconomy, circular economy, or other complementing urban development, such as conservation developments (Mockrin et al., 2017).

Isolation of PAs due to urbanisation in their surroundings is a political issue since PAs cannot manage what occurs beyond the borders. Thus, the inclusion of a social-ecological planning perspective would be possible if the remaining planning tools act together synchronously (González-García et al., 2022). For instance, a major challenge in other parts of the world is to manage the spatial connections between PAs and their surroundings. Border degradation is not only a result of poor governance, as pointed out in other studies (Cumming, 2016), but the absence of integrated territorial planning. In this sense, focusing on ecosystem services linked to PAs borders and including them in planning tools to improve the social-ecological connectivity of the PAs' surroundings could generate good incentives from PAs (García-Llorente et al., 2018; Hanaček and Rodríguez-Labajos, 2018). Nevertheless, multi-level spatial planning, governance, and management approaches across scales will be unavoidable to improve the connectivity of PAs at the same time in all scales (Heck et al., 2018). For example, if we focus on regulating land use inside PAs, thus protecting high valuable ecosystems, we indirectly promote the displacement of land use to other places in which more intense practices would create more complex environmental problems (Lambin and Meyfroidt, 2011). Hence, urbanisation in the PAs' surroundings must be seriously considered not only in the planning tools of PAs but also in those of administration units that manage the borders of PAs (Martinuzzi et al., 2015), not necessarily avoiding the creation of urban spaces but favouring urbanisation forms that promote and assure ecological and social-ecological connectivity.

4.3. Caveats and future research

Some caveats must be acknowledged regarding the methodology of this study. First, the CLC is known to present some glitches after 2006, several of which were corrected using satellite imagery, but we acknowledge that few errors associated with the base method may have affected the calculations (Martínez-Fernández et al., 2019). Next, the variables that we used for clustering and modelling could vary depending on the territorial context; for example, applying this methodology to islands could give different patterns of urbanisation related to the coastal attraction effect (Rodríguez-Rodríguez et al., 2019). Therefore, future research should study urbanisation processes in islands, coastal areas, and marine/coastal PAs. Additionally, we were unable to address the housing units, as has been done in Radeloff et al. (2010), which would be interesting to predict the type of urbanisation occurring in the boundaries of PAs such as buildings or single houses and first or second residences. Nevertheless, housing number does not consider the amount of land altered for urbanisation; therefore, this methodology complements other studies that have used housing numbers. For instance, the impact of urban land on PAs borders is not

only related to urbanised surfaces but also with associated activities and pressures that arise from urban metabolism. Further research in the context of the type of urbanisation is needed to address the problem of isolation (Seto et al., 2010) because permeability throughout borders could be possible if urbanisation and other land uses are adapted to the intrinsic characteristics of PAs. Thus, it is unclear whether the effect of land sharing and land sparing on the permeability of borders, or the relationship between social-ecological knowledge and traditional activities with permeability, could reduce the isolation effect. In our study, MP were shown to present less isolation and more urbanisation in the 5 km buffer, and this type of isolation may have less impact than other types. Additionally, we did not include Natura 2000 sites or other valuable natural spaces such as biosphere reserves. Hence, future studies should include more precise knowledge on what is happening inside and outside these sites regarding urbanisation (Concepción, 2021). In addition, biosphere reserves could balance some mismatches between the planning tools of municipalities and PAs; thus, future studies should consider this category an opportunity for coordination.

5. Conclusions

This study aligns with others that have pointed to the increasing isolation of PAs. We observed that urbanisation in the surroundings of PAs has nearly doubled since 1990, with differentiated processes for different PA typologies: PUP (6.2% in 2.5 km buffer and 5.7% in 5 km buffer), MP (0.7% and 1%), and MARP (12% and 8.2%). Thus, we recommend including a disaggregated approach based on socio-economic and geographical characteristics when analysing and modelling urban sprawl and other pressures around PAs globally. This study also reveals that distance to cities and roads, road density, and the number of municipalities are the factors that most influence urbanisation processes around PAs. Further, we highlight three different but complementary urban processes that occur in the surroundings of PAs. The three processes occur concurrently, are synergistic, and may exert a response effect that turns some PAs into a double-edged sword. Thus, it is not possible to evaluate the effect of PAs attracting urbanisation throughout a single phenomenon. We conclude that a social-ecological approach in the planning process is necessary to integrate PAs in their surroundings, reduce isolation, and make PAs more effective.

CRedit authorship contribution statement

Alberto González-García: Conceptualization, Methodology, Software, Writing – original draft. **Ignacio Palomo:** Conceptualization, Writing – original draft. **Manuel Arboledas:** Formal analysis. **José A. González:** Writing – original draft, Supervision. **Marta Múgica:** Supervision. **Rafael Mata:** Conceptualization, Supervision. **Carlos Montes:** Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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