



# Diagnosis of the ecological condition of the drove road network in the Autonomous Community of Madrid (central Spain)

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## Abstract

**Context** Drove roads are landscape corridors traditionally used for livestock movement in many regions of the world, including Spain, where they cover about 0.8% of the land. They have ecological importance due to their role in connectivity, seed dispersal, soil preservation, habitat and biodiversity conservation, and the provision of ecosystem services. Drove roads are experiencing deterioration due to the abandonment of extensive grazing and transhumance.

**Objectives** We aim to characterize the conservation status and main predictors of deterioration of the drove roads in the Community of Madrid, a region in Spain with a high presence of these corridors.

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**Methods** We considered all the network of the region, with the main analyses based on a sample of 160 segments of 200 m-long, which were evaluated using GIS and fieldwork.

**Results** Nearly one third of the network surface is occupied by crops, communication infrastructure, and urban or industrial surfaces. Natural habitats make up 60% of the network and are affected by soil degradation and grazing abandonment. Landscape matrix was the main predictor of drove road status, with urban and cropland matrices leading to a reduction in spatial integrity and availability for natural habitats. Grazing was most preserved in grassland matrices. Eco-district, drove road width, and distance to city center also had influence on conservation status.

**Conclusions** Despite their concerning state, the network is restorable in many areas of the region. Restoration should focus on intensified and simplified landscapes, where the network plays a more decisive role, and should consider the reintroduction of livestock.

**Keywords** Ecological corridors · Transhumance · Extensive grazing · Conservation status · Ecological restoration

## Introduction

Drove roads, also known as drovers' roads (Ruiz and Ruiz 1986), stock driveways (Starrs 2018), livestock routes (Acín-Carrera et al. 2013) or transhumance

routes (Mastronardi et al. 2021) are the corridors traditionally used for mobile pastoralist livestock in many regions of the world (Ruiz and Ruiz 1986; Manzano and Casas 2010). In some countries of the Mediterranean basin, these corridors can be permanent and occupy considerable areas. In the case of Spain, the network is granted legal protection since 1995 (Drove Roads Act), a large part of it is well mapped, and it extends over 125,000 km, occupying 421,000 ha, approximately 0.8% of the national surface (Mangas Navas 1992, 2004). Drove roads can have considerable widths, up to 75 m in Spanish *cañadas* (Merino García and Alier Gándaras 2004) or 111 m in Italian *tratturi* (Mastronardi et al. 2021), and follow their own rationale in relation to geomorphology and human habitats, making them important features in the landscape (Gómez Sal and Lorente 2004).

The presence of drove roads has relevant ecological implications (Bunce et al. 2004). At broad scales, and as long as transhumant use is maintained, drove roads allow seed dispersal over very long distances (up to 400 km, Manzano and Malo 2006), and can act as stepping stones for bird communities (Malo and Mata 2021), contributing through these and other mechanisms to increase connectivity between remote areas. At local and landscape scales, drove roads preserve soils (Acín-Carrera et al. 2013), and act as reservoirs of habitats and biodiversity, which has been shown for plants (Azcárate et al. 2012), ants (Hevia et al. 2013; Azcárate et al. 2013) and wild bees (Hevia et al. 2016). Changes in community composition driven by the presence of drove roads also imply relevant functional effects. For example, the greater availability of pollinators is probably the cause of the lower inbreeding observed in certain plant populations when growing inside drove roads (García-Fernández et al. 2019). The higher availability of wild bees also improves the pollination service in surrounding crops (Hevia et al. 2016). Other regulating, provisioning, and cultural services are also provided by well-preserved drove roads (Gómez Sal and Lorente 2004; Oteros-Rozas et al. 2012a, 2013; López-Santiago et al. 2014). In short, drove roads have a wide number of economic, natural, cultural, and recreational values, and their conservation and management should take care of this multifunctionality (Merino García and Alier Gándaras 2004, Gómez Sal and García 2007, Alenza García 2022), avoiding

simplistic views focused on one or very few of these dimensions.

Reduction or abandonment of traditional farming is a widespread phenomenon in many regions of Europe (Lasanta et al. 2017) and other developed countries (Queiroz et al. 2014; Li and Li 2017), including Mediterranean grasslands (Peco et al. 2006). Both the disappearance of extensive farms and their replacement by highly intensified production models are resulting, in many cases, to marked loss of biodiversity and ecosystem services (Stoate et al. 2001; Bugalho et al. 2011; Plieninger et al. 2015). Further, the farming industry leads grazing systems to intensification in the more productive areas and abandonment in marginal zones (Peco et al. 2006), with large negative effects on biodiversity (Uchida and Ushimaru 2014; Hilpold et al. 2018). In this context, the decline of extensive transhumant livestock farming (Gómez Sal and Lorente 2004; Oteros-Rozas et al. 2012b; Liechti and Biber 2016) is causing the ecological deterioration of seasonal grazing areas (Carmona et al. 2013) and of the drove roads themselves (Hevia et al. 2013). However, few attempts (but see Mastronardi et al. 2021) have been made to evaluate the magnitude and characteristics of the changes experienced by drove roads, despite their importance in the landscape.

Changes in the use and ecological status of the drove roads can be expected to be dependent on the general factors driving land use changes. These factors include the demographic and socioeconomic trends of the region, productivity and climate conditions, topography, field size, the distance to population centers, and the existence and type of protected areas, among others (Maiorano et al. 2007; Prishchepov et al. 2013; Kerckhof et al. 2016; Levers et al. 2018; Xu et al. 2019). In addition, the specific characteristics of drove roads can determine other patterns and trajectories of change. For example, the linear geometry of these corridors may imply a higher incidence of specific impacts, such as the occupation by transport or driving infrastructure (for example, paved roads).

Spain is an ideal study case to analyze the changes undergone by the drove roads, given the importance of the network (Ruiz and Ruiz 1986; Mangas Navas 1992; Manzano and Casas 2010) and the existing ease of monitoring the drove roads given their legal entity, which allows most of them to be adequately

mapped. The situation, however, is very uneven among regions. The Community of Madrid stands out in this regard, with a particularly dense and extensive network (4168 km and 13,093 hectares), occupying up to 1.63% of the regional territory, the highest value for the Spanish autonomous communities as a whole (Merino García and Alier Gándaras 2004). This region is located in the center of the Iberian Peninsula, which makes it an area of passage for several large drove roads that connect the pastures of the south with the mountains of the north, while the existence of a mountain range of importance (*Sierra de Guadarrama*) has favored the existence of transhumant movements on a smaller scale. To this past closely linked to transhumance, is added the peculiarity of the city of Madrid and its large metropolitan area, with its transforming power over the whole territory (Hewitt and Escobar 2011; Arnaiz-Schmitz et al. 2018).

This study aims to characterize the current status of the drove roads of the Community of Madrid (Spain), including an evaluation of their ecological condition from a multifunctionality point of view. For this, we use a set of criteria, whose state is analyzed as a function of several social-ecological factors. The results of the study are used to make a general diagnosis of the network, as well as for the proposal of several context-dependent ecological restoration strategies. Drawing upon the framework proposed by

Hockings et al. (2006), this study represents the first step of a project cycle (context analysis, with value analysis and threat analysis), and will serve as the basis for a detailed planning of restoration actions that will be part of the operational phase (Battisti 2018).

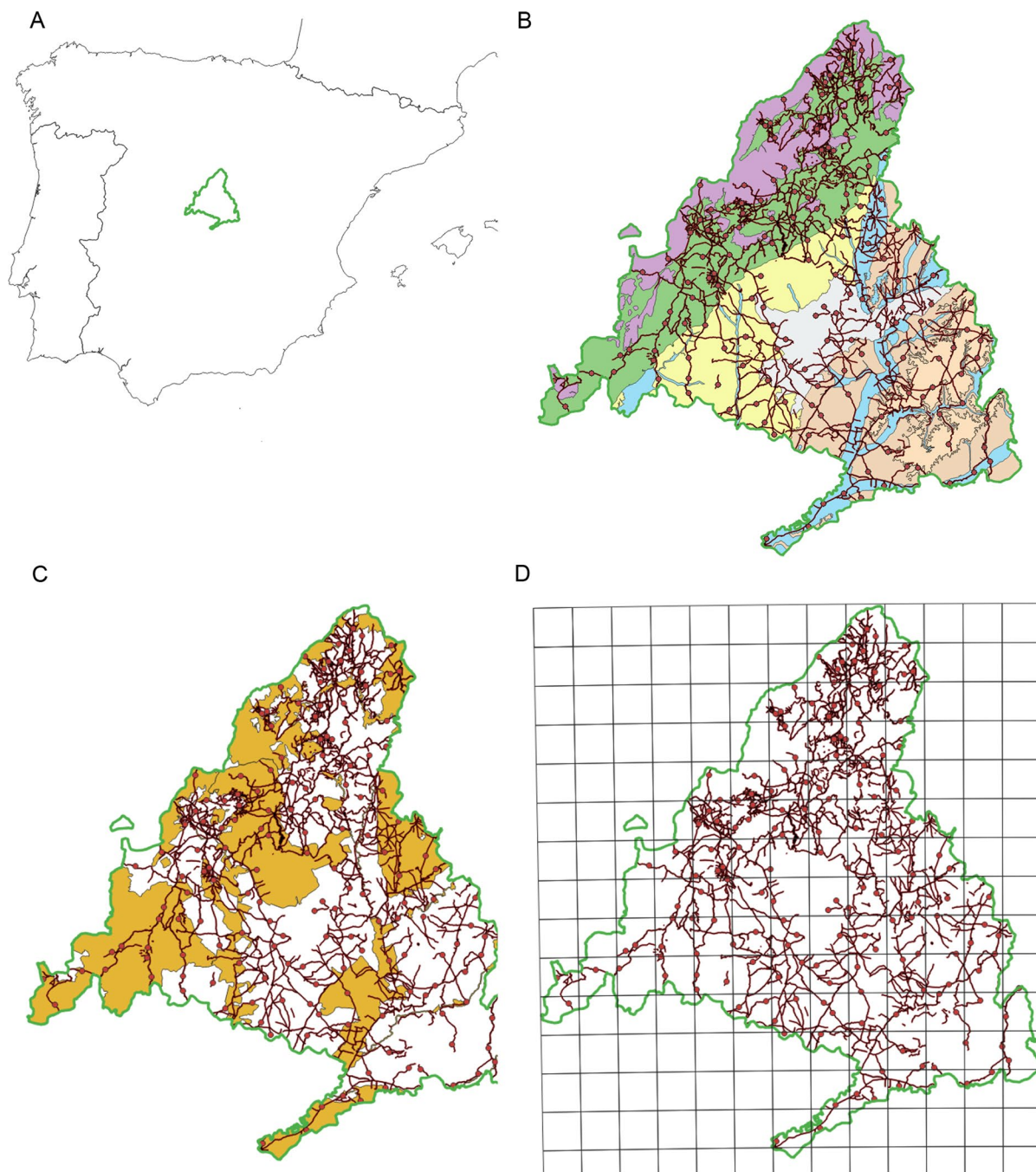
## Methods

### Study area

The Community of Madrid (Fig. 1A) has a relatively small size (8021 km<sup>2</sup>), but comprises a remarkable ecological variability, with a large elevation gradient (445 m a.s.l.– 2430 m a.s.l.) and a diverse lithology. The region is strongly influenced by the presence of the capital city of Spain and its metropolitan area, which are home to most (approximately 5 million) of the region's total population (approximately 6.8 million). While most of the population is engaged in the tertiary sector, a large part of the regional territory is used for moderate agricultural and livestock activities (Kuemmerle et al. 2016). For this study, and in order to summarize this complex socio-ecological reality, we have distinguished seven eco-districts, represented on the map shown in Fig. 1B and described in Table 1. A considerable part of the region (3198 km<sup>2</sup>, 39.9% of the total area) is included in the Natura 2000 network (Fig. 1C).

**Table 1** Diagnostic characteristics of the seven eco-districts in the Community of Madrid that have been defined for this research

Eco-district	Definition
Slopes and summits	Peaks and main alignments of the Central System, with generally pronounced reliefs, mostly on pre-Ordovician igneous and metamorphic rocks. The area is mainly occupied by conifer and broadleaf forests, scrubland, and mountain grassland. Without relevant villages or human settlements
Pediment	Piedmonts and inland valleys of the Central System, with relatively gentle reliefs, mostly on pre-Ordovician igneous and metamorphic rocks. Predominantly livestock raising area, with oak and ash <i>dehesas</i> (a sort of wood-pasture), grasslands, forest in areas with more slope, and some residual crops in some inland valleys. Small to medium-sized villages
Arkosic countryside	Rolling hills and gently sloping plains on Miocene arkosic sediments. Rainfed crops and, in areas with some slope, acidophilic grassland and scrubland and <i>dehesas</i> . Medium-sized villages
Clayey countryside	Rolling hills and gently sloping plains on Tertiary clayey sediments. Rainfed crops and alkaline or gypsophilic scrubland in areas with more slope. Medium-sized villages.
Limestone plateau	Plateau located on Miocene lacustrine limestones. Rainfed crops and medium-sized villages
Alluvial plains	River plains, on Quaternary materials, traditionally used for irrigated crops, although they now have a partially urbanized and industrialized landscape. Towns and cities of moderate size in some cases
Metropolitan area	Area occupied by the city of Madrid and the surrounding suburbs and bedroom cities, with hardly any natural or semi-natural spaces. Although it occupies materials equivalent to those of alluvial plains and arkosic and clayey fields, the predominance of urban and industrial surface is its main characteristic



**Fig. 1** A Position of the community of Madrid within Spain. B Distribution of the drove road network and the 160 sampling segments in relation to the seven eco-districts: Purple: *Slopes and summits*; Green: *Pediment*; Yellow: *Arkosic countryside*; Brown: *Clayey countryside*; Pale brown: *Limestone plateau*; Blue: *Alluvial plains*; Grey: *Metropolitan area*. C Distribution

of the drove road network and the 160 sampling segments in relation to the Natura 2000 network (coloured). D Distribution of the drove road network and the 160 sampling segments in relation to the grid of 10 km x 10 km cell size used to ensure adequate geographical representation. In B, C and D the drove road network has been thickened to facilitate its visibility

According to official information (<https://www.comunidad.madrid/servicios/medio-rural/red-vias-pecuarias-comunidad-madrid>), the Community of Madrid has 4104 km of drove roads (hereafter, DRs), covering an area of > 13,000 ha (Fig. 1). The regional network includes four main DRs or ‘*cañadas reales*’ (*Leonesa Oriental*, *Segoviana*, *Galiana* and *Soriana Oriental*), which cross the region from southwest to northeast (with an official width of 75 m); and a large number of *cordeles*, *veredas* and *coladas* (lower order DRs of narrower width), as well as resting places, watering areas and other public spaces for livestock management. In addition to the national law, the Community of Madrid has specific legislation that protects the DR network (Act 8/1998).

### Sampling design and data collection

To assess the territorial reach of the DR network in the Community of Madrid, a descriptive study was conducted using QGIS 3.20 (QGIS Development Team 2021), consisting of measuring the length and surface area occupied by DRs in each of the seven eco-districts defined in this work. The extent to which the surface area of Madrid could be affected by the proximity of a DR was also analyzed. To do this, a sample of 10,000 points was randomly distributed throughout the region, and the distance to the nearest DR was measured. The obtained variable was represented by a probability density function, and the maximum distance at which 50% and 75% of the accumulated observations were found was estimated. These same values were estimated for the eco-districts.

This study was carried out on a sample of 160 segments of 200 m-long DRs with variable widths (6–116 m, depending of the type of DR). The sample was distributed using a grid of 10 km × 10 km cell size (Fig. 1D) to ensure adequate geographical representation and avoid bias, and it was ensured that at least 1 and a maximum of 4 segments occurred in all the squares, except those incomplete or where there was no network. Beyond this restriction, the 160 segments were randomly distributed along the length (not the surface) of the network, taking the shapefile layer of DRs (available at <https://idem.madrid.org/>). The segments and their environment contexts were characterized through a combination of photo-interpretation (Fig. 2),

geographic analysis using QGIS 3.20 (QGIS Development Team 2021), and field work. This characterization was carried out through two approaches, based on the analysis (1) of the land cover and (2) of the ecological condition of the segment.

### Analysis of land cover inside the drove roads

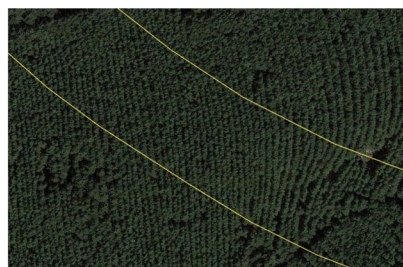
This approach was carried out to have an estimate of the distribution, use and current occupation of the surface area of the DRs in Madrid, both for the region as a whole and for each of the eco-districts. In most cases, the DR contains a dirt road or path, necessary for the movement of livestock farmers’ vehicles (but compatible with other recreational uses), while the rest of the DR should be covered by pastures and other types of natural or semi-natural vegetation. However, many DRs are often totally or partially occupied by other uses, which correspond to some of the main threats to biodiversity proposed in Salafsky et al. (2008), such as buildings (threat 1: Residential and commercial development); crops and private farms (2. Agriculture and aquaculture); paved roads (4. Transportation and service corridors), etc. In addition, due to the proliferation of motorized traffic and inadequate recreational uses (threat 6: Human intrusions and disturbance), many DRs show a high degree of degradation, which is evidenced by the appearance of large areas lacking vegetation and signs of soil compaction and erosion.

Thus, for each segment (using QGIS), we measured the area occupied by (1) pasture or other natural habitats, (2) the DR’s own path and (3) other uses, corresponding to usurpations or occupations unrelated to communal livestock. These categories were subdivided into subcategories at two more hierarchical levels, according to the scheme shown in the Table 2. The average surface areas occupied by each category and subcategory in the DRs of each eco-district were estimated from the cover values measured for each segment. This estimate was made by weighting each segment by its surface area. This estimate was also made for all the DRs in the Community of Madrid, weighting the averages obtained for each eco-district by the surface area of DRs that each eco-district contributes to the network as a whole.

**Fig. 2** Different states of spatial occupation and conservation in 10 segments of drove roads located in different ecoregions of the Community of Madrid



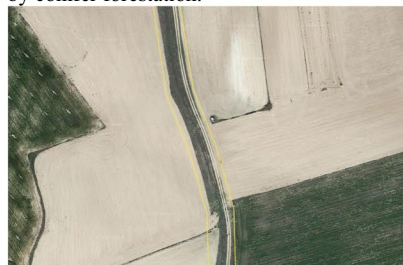
**A** *Cañada* in the limestone plateau occupied by croplands except for the dirt road.



**B** *Cañada* in the slopes & summits occupied by conifer forestation.



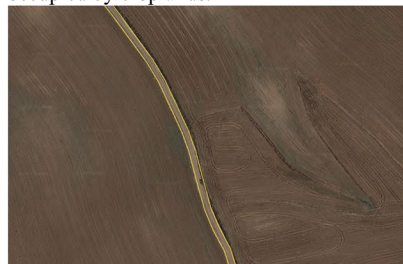
**C** *Cordel* in the pediment, partially occupied by a road.



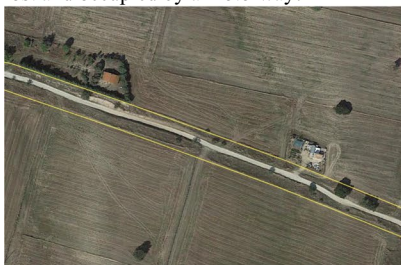
**D** *Vereda* in the alluvial plains, partially occupied by croplands.



**E** *Cordel* in the metropolitan area, entirely lost and occupied by a motorway.



**F** *Colada* in the clayey countryside, consisting only of the path.



**G** *Vereda* in the arkosic countryside, in a good conservation status.



**H** *Cordel* in the pediment, in a good conservation status.



**I** *Vereda* in the arkosic countryside, with signs of soil compaction and erosion.



**J** *Vereda* in the arkosic countryside, transformed into a garden area.

**Table 2** Categories and subcategories established for the measurement of land covers within the surface of drove roads. Some of these subcategories were further divided into more detailed ones, as shown in the supplementary material (Table S.1)

Category	Subcategory	Explanation
Occupied	Crops	Invasion, from the margins, by neighboring crops, which have replaced the pasture and habitats characteristic of the DR
	Transport infrastructure	The DR has been completely or partially used to build roads, railways, and other transportation infrastructure incompatible with livestock movement within it
	Urban and industrial	The DR has been completely or partially absorbed by urban or industrial spaces, including parks and gardens
	Other	Space occupied by forest reforestation, livestock farms, residential or recreational properties, military land, etc
Path or dirt road		Space used for the path or dirt road necessary for the movement of livestock, compatible with public use
Available for natural habitats	Soil strongly degraded	Soil heavily compacted, eroded, or covered in debris and waste, and cannot be recovered without active intervention
	Soil moderately degraded	Soil with signs of erosion and compaction, recoverable with passive measures
	Ungrazed	No physical degradation issues, but vegetation is overgrown as a result of prolonged neglect of grazing
	Grazed	No physical degradation issues, properly grazed, and therefore in good condition

### Analysis of the ecological condition of the drove roads

The quality of a DR must be evaluated from a multifunctional approach (Merino García and Alier Gándaras 2004). This means using several criteria to assess not only the ability of the DRs to allow livestock to pass safely and to have access to food, but also to maintain territorial connectivity and to support natural areas in good conservation status, ideally with pastures that have adequate levels of herbivory. Following this approach, the evaluation of the ecological condition of the DRs was carried out using five

descriptors, which were evaluated (in the field, visiting all segments) as binary (0/1) variables (Table 3): (1) *integrity* (DR conserving original dimensions), (2) *livestock walkability* (passage of livestock is possible), (3) space enough for *natural habitats* within the DR, (4) occurrence of *grazing* within the DR, and (5) conservation of *soils* within the DR (no signals of soil erosion or compaction). We then analyzed the dependence of these descriptors on a set of variables related to the landscape configuration and land use in the DR environment (Table 4): (a) *eco-district*, (b) *landscape matrix*, (c) occurrence of a *Natura 2000 site* (indicative of the effect of land protection on the

**Table 3** Binary (1/0) descriptors used for the ecological diagnosis of the 160 drove road segments. The explanation indicates the conditions that the segment must meet to be rated with the value '1'

Descriptor	Explanation
Integrity	The drove road is well delimited and maintains its entire legal width intact, without any type of occupation
Livestock walkability	Although it may be partially occupied, the drove road allows for the safe movement of livestock, as there are no roads or infrastructure that pose a risk to the herders and animals
Space for natural habitats	The drove road has a width available for natural habitats (excluding the road and any possible occupations) of more than 10 m, independently of its conservation status
Grazing	The available surface for natural habitats is well grazed.
Conservation of soils	The available surface for natural habitats has good soil condition, without any spills or signs of erosion or compaction

**Table 4** Variables related to the landscape configuration and land use used as predictors of the conservation status in the 160 drove road segments evaluated

Variable	Type	Explanation
Eco-district	Categorical	The seven eco-districts explained in Table 1
Landscape matrix	Categorical	Dominant land use in a buffer of 500 m around the segment. Four categories: (1) <i>Grasslands</i> , (2) <i>Croplands</i> , (3) <i>Forests and shrublands</i> , (4) <i>Urban and industrial</i>
Natura 2000	Categorical	Occurrence of a Natura 2000 site. Two categories: (1) <i>Inside</i> , (2) <i>Outside</i> .
Distance to Madrid city center	Continuous	Distance of the segment to Madrid city center (“Puerta del Sol”). The variable was measured in meters, and then standardized prior to the analysis
Drove road width	Continuous	Average width (three measurements) of the drove road segment, visualized in the official layer available in <a href="https://idem.madrid.org/">https://idem.madrid.org/</a> . The variable was measured in meters, and then standardized prior to the analysis

conservation of the DR), (d) *distance to Madrid city center* (indicative of the pressure by visitors and recreational use), and (e) the original *width* of the DR itself according to Drove Roads Act.

The analyses consisted of estimating logistic regression models for each of the descriptors of the conservation status of the DR in response to the five independent variables. The two quantitative variables (*DR width* and *distance to Madrid city center*) were standardized before the analyses. To improve the robustness of the estimations, we conducted a model averaging procedure to select the set of predictors that best explained each descriptor of ecological condition, using the “MuMIn” R package (Barton 2009). We retained as best-fitting models all models with an AIC difference ( $\Delta AIC$ ) < 2, and averaged predictor estimates selected across them, using the conditional averaging approach of the function ‘model.avg’. The possibility of collinearity among the independent

variables was ruled out through the calculation of the generalized variance inflation factor (GVIF, Fox and Monette 1992) for all the estimated models (supplementary material, Table S.2).

## Results

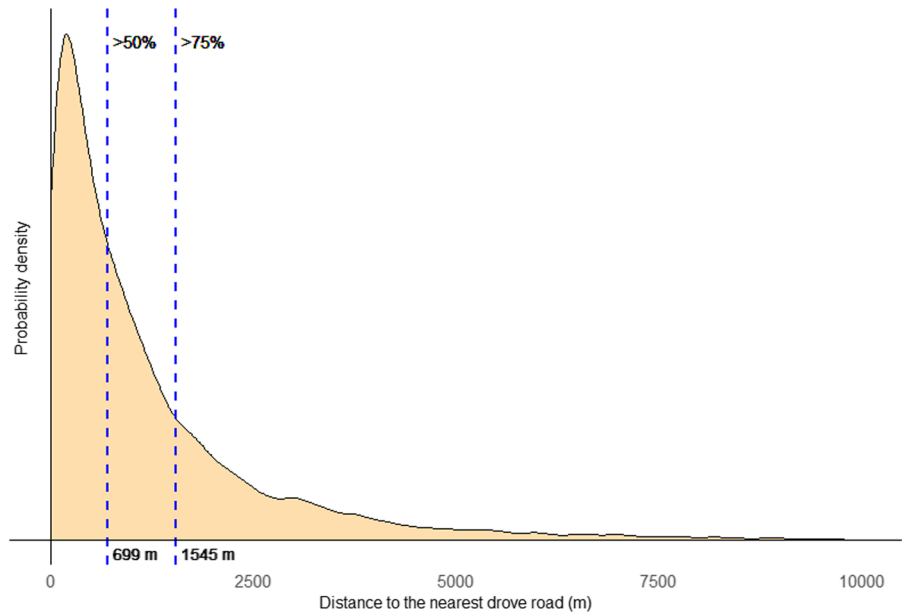
The surface area of the Community of Madrid’s DRs is distributed heterogeneously among the seven eco-districts (Table 5). Nearly half of this surface area (45.08%) belongs to the *pediment*, despite this eco-district only covering a quarter of the regional territory. This overrepresentation is evident in that more than 3% of the *pediment* is within a DR. In contrast, the agricultural districts and the *metropolitan area* have relatively low coverage of DRs, with the lowest values in the *clayey countryside* (0.89% of the surface area). Despite this, most of the territory in the

**Table 5** Surface of the seven eco-districts, and descriptors of the presence of the drove road network in each of them

Eco-district	Eco-district area (km <sup>2</sup> ) (% of the Community of Madrid)	Drove road area (Km <sup>2</sup> ) (% of the eco-district area) / (% of the network)	Drove road length (Km) (% of the network)	N° segments (% of the sample)
Slopes and summits	1118.0 (13.92)	20.0 (1.78) / (14.58%)	446.8 (10.45)	19 (11.9)
Pediment	2014.8 (25.09)	61.6 (3.06) / (45.08%)	1639.9 (38.36)	54 (33.7)
Arkosic countryside	1283.0 (15.98)	13.3 (1.04) / (9.71%)	473.0 (11.06)	22 (13.7)
Clayey countryside	1294.4 (17.36)	12.4 (0.89) / (9.05)	510.3 (11.94)	19 (11.9)
Limestone plateau	606.6 (7.55)	5.8 (0.95) / (4.24)	232.3 (5.43)	14 (8.7)
Alluvial plains	933.4 (11.62)	15.0 (1.61) / (10.97)	599.4 (14.02)	16 (10.0)
Metropolitan area	680.3 (8.47)	8.7 (1.28) / (6.36)	373.4 (8.74)	16 (10.0)
Community of Madrid	8030.5 (100)	136.7 (1.70) / (100)	4275.0 (100)	160 (100)



**Fig. 3** Probability density function of the variable “Distance to the nearest drove road,” measured in a sample of 10,000 points randomly distributed throughout the territory of the Community of Madrid. The vertical lines indicate the values that accumulate 50% (median) and 75% of the observations



**Table 6** Maximum distance (m) to a drove road of the 50% and 75% of the territory of each of the seven eco-districts, obtained from a probability density function estimated from 10,000 random points distributed throughout the Community of Madrid

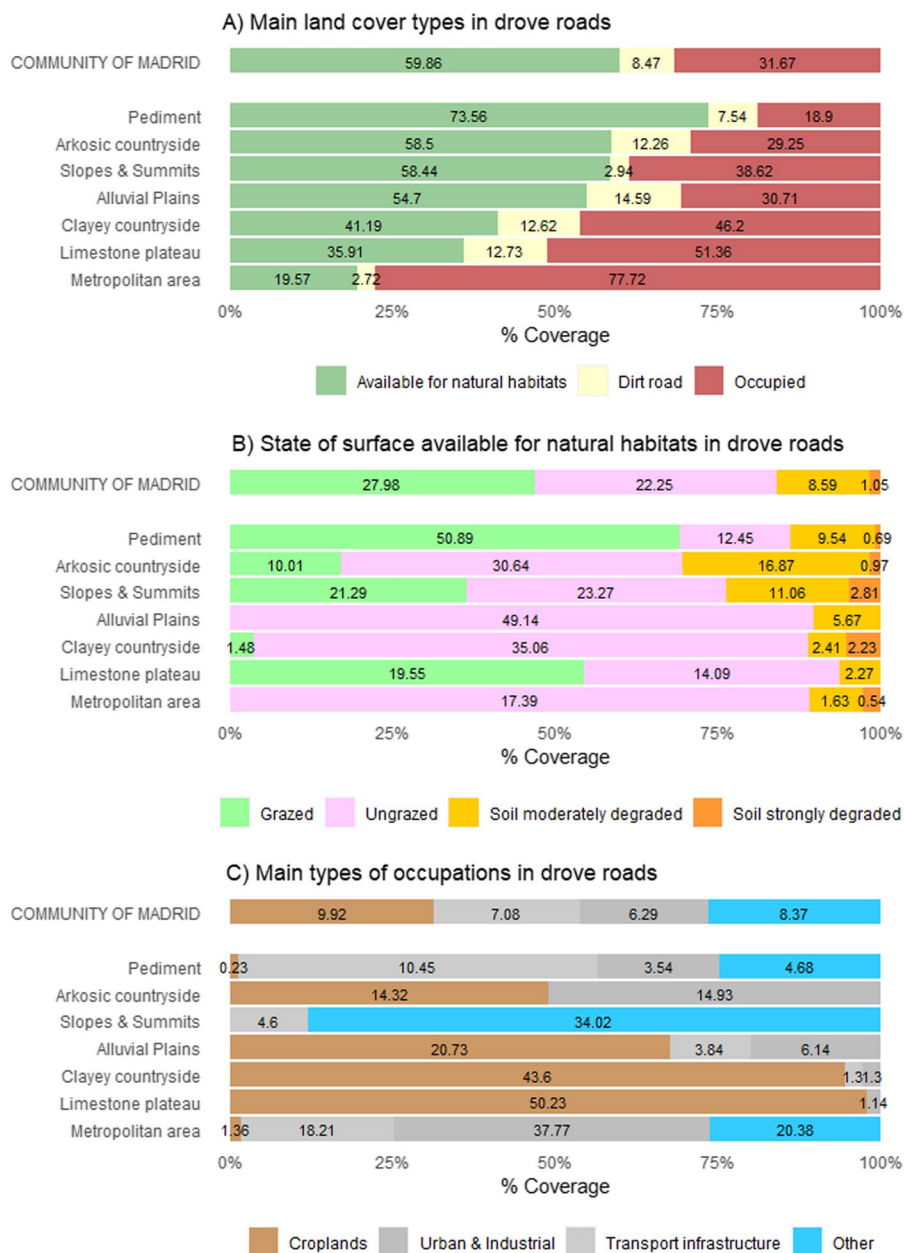
Eco-district	50% territory	75% territory
Slopes and summits	890.5	2068.4
Pediment	438.5	1102.3
Arkoscic countryside	861.2	1762.2
Clayey countryside	879.5	1730.7
Limestone plateau	977.7	1656.9
Alluvial plains	587.3	1317.7
Metropolitan area	569.0	1175.1
Community of Madrid	699.0	1545.0

Community of Madrid is characterized by the presence of some DR in the vicinity. The distribution of distances to the network obtained from a random sample of 10,000 points is a curve with a marked positive skewness, with a very high concentration of points at low values (Fig. 3). Taken as a whole, 50% of the territory is below 699 m distance from the network, and 75% within 1545 m. In relation to the eco-districts, the *pediment* is again the one with the most widespread distribution of DRs (50% within 438 m distance), and the *limestone plateau* the one with the least (50% within 978 m distance) (Table 6).

Practically one third of the network (31.67%, Fig. 4; supplementary material, Table S.1) is occupied by uses or surfaces other than communal livestock use. Agriculture is the main land use of occupation (9.92% of the surface area of the DRs under cultivation), followed by communication infrastructures (7.08%; mostly roads) and urban or industrial surfaces (6.29%). Most of the surveyed Sect. (67%) had a path or a dirt road (of the remainder, 57% had a street or a paved road). The width of dirt roads or paths was often excessive (average 4.4 m, 27% > 6 m, several cases up to 10 m). We estimate that 8.47% of the network surface is currently occupied by these dirt roads. Discounting the areas occupied by outside uses and by the dirt road itself, the area available for pasture and other natural habitats would be limited to 59.86% of the network. Almost a fifth of this area, however, would present problems of soil erosion or compaction, so that the estimated area in which the soils are not degraded (soil not occupied by other uses unrelated to livestock, not occupied by the dirt road, and without signs of erosion or compaction) is approximately half of the total area of DRs (50.23%). Of this area, just over half is grazed (27.98% of the total), with the rest showing clear signs of grazing abandonment (22.25% of the total; supplementary material, Table S.1).

The occupation of the surface area of the DRs varied greatly between eco-districts (Fig. 4;

**Fig. 4** Estimation of land cover inside the drove roads of the Community of Madrid and for each of the seven eco-districts. Covers for the Community of Madrid are the weighted averages of the eco-districts. The values inside the bars indicate the percentage of surface area over the total. It should be noted that the sum of the values in (B) is equal to the “Available for natural habitats” values in (A), and the sum of the values in (C) is equal to the “Occupied” values in (A)



supplementary material, Table S.1). The one with the largest area lost is the *metropolitan area*, for which we estimate 77.72% of occupation (mostly by urban or industrial land and communication infrastructures), while in the *pediment* occupation drops to 18.90%. The regions most affected by farmers’ intrusions are the *limestone plateau* (50.23%), the *clayey countryside* (43.60%) and the *alluvial plains* (20.73%). The *arkosic countryside* presents very similar estimated losses for urban and industrial areas (14.93%)

and crops (14.32%). Finally, the DRs on the *slopes and summits* also show significant losses, estimated at 38.62% of the surface area, mostly as a result of occupation by rural estates dedicated to a wide variety of uses. Regarding the areas available for natural habitats, the differences are also notable. In the *clayey countryside*, *arkosic countryside*, *alluvial plains* and *metropolitan area*, ungrazed vegetation predominates (between 17.30% in the metropolitan area and 35.06% in the clayey countryside), while grazed pastures are

minimal (1.48% in the *clayey countryside*, 10.01% in the *arkosic countryside*) or even practically nil (*alluvial plains* and *metropolitan area*). In the *limestone plateau*, the grazed area (19.55%) would exceed the ungrazed one (14.09%), although the small area of natural habitats means that both values are very low. The highest values of grazed pastures were found in the region of the *pediment* (50.89% of the total area), decreasing again in the *summits and slopes* (21.29%), where 23.27% of the area would be under scrub. The eroded surface area (moderately +strongly) ranges from 2.17% in the metropolitan area to 17.84% in the *arkosic countryside*, although in the *metropolitan area* this low value is an obvious consequence of the predominance of paved or built-up surfaces.

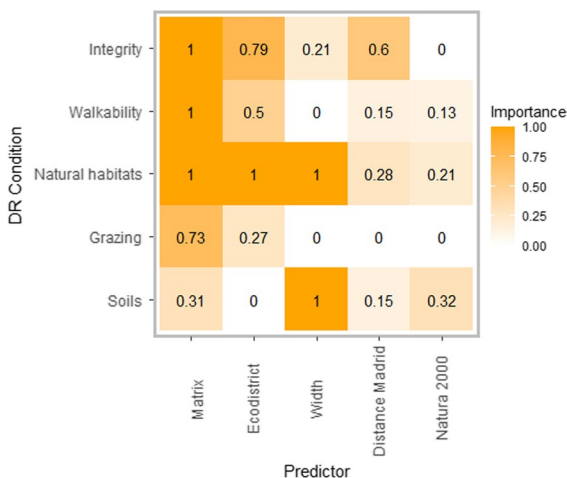
The descriptors of the conservation status of the segments responded at different extents to the *eco-district*, the *landscape matrix*, the *DR width* and the *distance to Madrid city center*, but were not affected by the existence of a protected area belonging to the *Natura 2000 Network* (Figs. 5 and 6; supplementary material, Table S.2). Taking DRs in grassland landscapes of the pediment as reference levels, Fig. 6A shows that the probability of a segment retaining its integrity was lower in *urban* and *cropland* landscape matrices, as well as in the *slopes and summits* eco-district. A shorter *distance from the city* also meant a

greater risk of loss of integrity. Walkability for livestock was lower in *urban matrices* and on *slopes and summits* (Fig. 6B), while the probability of presenting natural habitats was lower in *urban* and *cropland* matrices and on *slopes and summits*, as well as in DRs of lower *width* (Fig. 6C). Considering only the segments with space for natural habitats, grazing was most likely to be preserved in grassland matrices, falling clearly in the other three landscape types (Fig. 6D), while soil degradation was only clearly dependent on the *DR width*, being more likely to find eroded or compacted surfaces in wider ones (Fig. 6E).

## Discussion

Linear corridors are considered effective tools for conserving biodiversity and ecosystem functions and services (Damschen et al. 2006, Cannas et al. 2018, Travers et al. 2021), although there have also been warnings about some conceptual weaknesses in their definition and practical application (Battisti 2011; Gippoliti and Battisti 2017; see also Foltête 2019), as well as the risks they pose for the spread of exotic species (Bennett 1999). Positive effects of corridors are particularly relevant in areas of intensive land use (Pryke and Samways 2012; Dainese et al. 2017), and DRs are a good example of this (Gómez Sal and Lorente 2004; Oteros-Rozas et al. 2012b; Hevia et al. 2016). Our study reveals that the Community of Madrid is ideally positioned to use its network of DRs as a network of linear corridors, which could greatly benefit the conservation of biodiversity and ecosystem services and functions on a regional scale. The region possesses one of the most extensive networks in Spain, and also all of its eco-districts surpass the Spanish national average in terms of the proportion of surface area occupied by DRs (0.8%, Mangas Navas 2004). One clear indication of the ubiquity of the network is that 50% of the territory is located within 700 m of a DR, with no eco-district where this distance reaches even one kilometer.

However, our data also shows that there are serious conservation issues with the network. Approximately one third of the surface area is used for other purposes, many of which are difficult to reverse, such as transport infrastructure (7.08%) and urban-industrial uses (6.29%), which in many cases occupied the DR space before the 1995 Act. Crops that invade the DRs

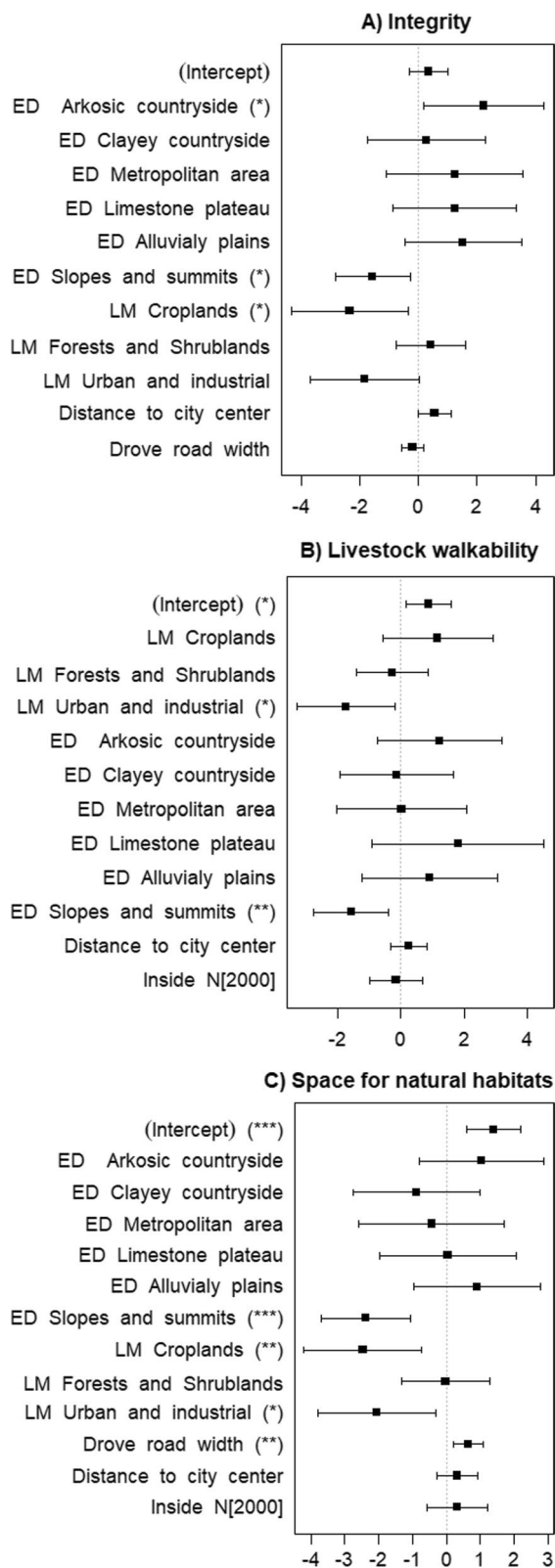


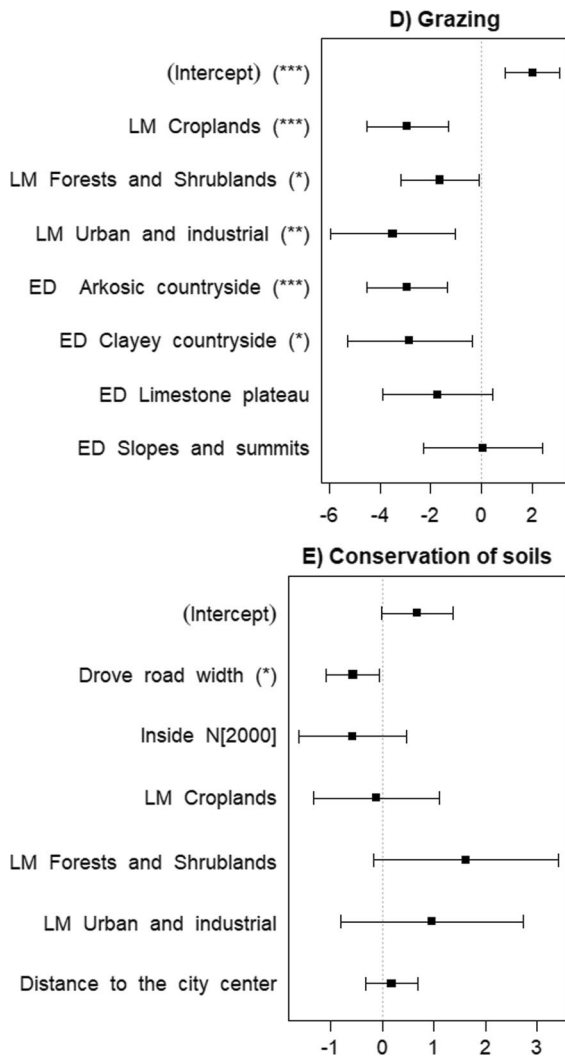
**Fig. 5** Relative importance of the predictors of the drove road (DR) conservation status selected in the best-fitting models. Importance is obtained as the sum of the Akaike weights of all models that included the predictor, considering the number of models in which each predictor appears (function ‘sw’ of the MuMIn R package, Barton 2009)

**Fig. 6** Model-averaged conditional coefficients  $\pm$  CI 95% for **A** integrity of the drove road segment, **B** livestock walkability, **C** availability of space for natural habitats, **D** occurrence of grazing, and **E** conservation of soils within the drove road segment. Reference levels included in the intercept are Eco-district: *Pediment*, Landscape matrix: *Grasslands* and Natura 2000: *Outside*. Continuous variables (*DR width* and *distance to city center*) are standardized. Models **(A)**, **(B)** and **(C)** were estimated with the full dataset ( $N=160$ ), and models **(D)** and **(E)** only with observations in which *space for natural habitats* = 1 ( $N=79$ ). In model **(D)** the levels *Metropolitan area* and *Alluvial plains* of the factor Eco-district were eliminated due to lack of variability in their values ( $N=68$ ). ED: Eco-district; LM: Landscape Matrix; (\*)  $p < 0.05$ ; (\*\*)  $p < 0.01$ ; (\*\*\*)  $p < 0.001$

(9.9% of the surface area) also cause the loss of their value as biodiversity reservoirs (Hevia et al. 2013), although in this case reversibility is more feasible. Another concerning aspect is the proliferation of dirt roads of excessive width, which results in further loss of semi-natural space in already narrow corridors. While dirt roads are necessary for the movement of farmers and livestock and other complementary uses, their size should not compromise the conservation of natural habitats in DRs. Of the space available for natural habitats (59.9% of the network), slightly less than half is grazed, which is driving a clear decline in the presence in DRs of species-rich annual grasslands, highly dependent on grazing (Perevolotsky and Seligman 1998; Peco et al. 2006). Finally, near 10% of the available habitat area has erosion problems, often due to misuse for recreational activities (cycling, motor-cycling) and the circulation of vehicles off the main dirt road.

The models estimated for the conservation descriptors identified the landscape matrix type as the most influential factor, which further demonstrates the importance of landscape-scale management for an ecologically functional and ecosystem service-producing landscape (Cong et al. 2014). The eco-district also had some importance for most of the descriptors, confirming the importance of the socio-ecological context on changes in land use and landscape configuration (Lambin and Meyfroidt 2010; Martín-López et al. 2017; Santos-Martín et al. 2019). In contrast, the width of the DR and the distance to the city were important only in some cases, and being in a Natura 2000 area was barely relevant. This last finding is somewhat surprising and suggests the need for further research on the reasons for the inefficiency of the





**Fig. 6** (continued)

Natura 2000 network in protecting DRs, which contrasts with its positive impact on biodiversity conservation, including species not listed in the annexes of the Nature Directives (Trochet and Schmeller 2013; Lisón et al. 2015).

Grassland landscapes with extensive livestock use tend to have the best conserved DRs, particularly with regards to their spatial integrity, and the possibility of harboring natural and grazed habitats. Interestingly, landscapes with a higher degree of naturalness such as forests and shrublands tend to have DRs with slightly worse conservation status. This finding supports that the maintenance of livestock use is crucial for the conservation of DRs (Ruiz and Ruiz 1986; Bunce

et al. 2004, 2006). Similarly, the pediment eco-district, where extensive grazing is the main traditional land use (Ruiz and González-Bernáldez 1983; Peco et al. 2006), is also the eco-district with the best conservation status for its DRs. Our data also suggest that the primary use of DRs by shepherds is not for herd movement, but for communal grazing areas. This is supported by the poor conservation status of the DRs in mountain slopes and summits, especially in terms of walkability and integrity conservation. These DRs were important in the past for local transhumant movements, a sort of local-scale transhumance that connected the summer pastures of the summits with the winter pastures of the valley bottoms (Gómez Sal and Lorente 2004). These movements have largely been replaced by a semi-extensive livestock model, which combines pasture use with feed supplements in less productive seasons (Gómez Sal 2001). As a consequence, DRs that used to connect nearby lowlands and highlands are, at present, particularly affected by scrub encroaching, if not completely blurred or occupied by forestations (Fig. 2B).

DRs crossing agricultural landscapes tend to show degraded states for most indicators. These DRs have a higher probability of losing territorial integrity, which in most cases is a result of the invasion of their space by crops. Agricultural landscapes are also associated with a reduction in the use of DRs for livestock grazing or movement. This pattern has been observed in other regions of the Iberian Peninsula and implies the loss of DRs as reservoirs of habitats and biodiversity (Hevia et al. 2013). Land use conflict between farmers and ranchers has a long history in Spain, and was a key factor in the creation of the “Mesta” (a powerful guild of livestock herders) and the delimitation of the main DRs (“Cañadas Reales”) in the 13th century by King Alfonso X (Ruiz and Ruiz 1986). After centuries of effective protection, the conflict has been settled to a large extent in favor of agriculturalists, with the progressive occupation of DRs by farmers (Red Rural Nacional 2013), a phenomenon also observed in Italy (Mastronardi et al. 2021). However, DRs in agricultural landscapes have a better degree of walkability than in other landscapes, which may be due to farmers’ interest in maintaining a minimum active corridor to access their fields. This positive aspect, along with the reversibility of most agricultural occupations, suggests that these stretches are amenable to recovery through ecological restoration plans.

Urban and industrial landscapes often result in significant losses of integrity for DRs. These losses are primarily due to buildings and paved roads, making them almost irreversible. The availability of space for natural habitats and walkability are also greatly reduced in these landscape types. It is worth noting that the occupation of DRs by paved roads is a widespread problem throughout Madrid, not just in the Metropolitan area eco-district (Fig. 4C; supplementary material, Table S.2). In any case, proximity to the Madrid city center is associated with an increased likelihood of loss of integrity, which can be explained by the gradient of environmental degradation associated with the large city in the region. This trend can be explained because the expansion of urban process in the surrounding rural environment of Madrid causes the acceleration of soil degradation (Arnaiz-Schmitz et al. 2018) and an evident decrease in the supply of ecosystem services (González-García et al. 2022).

The width of the DR was associated with the probability of having space for natural habitats, as expected. However, it was also associated with a greater trend to show areas with soil degradation problems. Misuse of DRs by motor vehicles can transform them into networks of bare soil corridors that accelerate soil erosion not only within them, but also at the landscape scale. This problem has not yet received sufficient attention, but given the climate scenario of increasing aridity (IPCC 2022) and erosion risk in the Mediterranean basin (García-Ruiz et al. 2013), it must be considered in the management of DRs.

The present study has allowed for a comprehensive diagnosis and contextual analysis of the entire network of drove roads in the Community of Madrid. The obtained results should be used to advance towards the proposal of operational strategies and actions (Battisti 2018) in order to address, to the extent possible, the main issues of the network. These actions should prioritize efficiency in obtaining environmental benefits through actions that are not necessarily very costly. In this sense, it is important to keep in mind that effects such as connectivity or the habitat and biodiversity reservoir are particularly important in very simplified landscape matrices, where it has been observed that DRs can contribute disproportionately with a high amount of the species pool at the landscape scale

(Azcárate et al. 2012, 2013). It is also in these environments where ecological corridors and green infrastructure generators are most needed (Pryke and Samways 2012; Dainese et al. 2017). In addition, the fact that the area of DRs in agricultural regions is smaller than in others emphasizes the need to conserve them. The DRs located in forest matrices can also have some importance by increasing the diversity of habitats (Azcárate et al. 2013), while those located in livestock matrices would be, in this sense, less critical, in addition to being in a state of lesser deterioration. Finally, DRs located in urban or industrial matrices are less recoverable, and acting on them would require a greater investment.

Although the specific restoration measures to be applied will depend on each case, we propose the reintroduction of livestock management as a central tool. Livestock grazing not only aligns with the traditional use of DRs, but its documented effects on soil condition (Peco et al. 2006), seed dispersal (Manzano and Malo 2006) and other processes essential to maintain grassland quality and biodiversity (Perevolotsky and Seligman 1998; Eskelinen et al. 2022) make it an effective means of restoring DR habitats. Our data, as well as that of other studies, show a connection between livestock presence and the conservation of DRs (Bunce et al. 2006; Ruiz and Ruiz 1986), making grazing a key factor in the socioecological resilience of DRs. However, one potential challenge in reintroducing livestock management is the lack of network connectivity. While our data provide insights into the conservation status of DR space, they do not give us a complete picture of the possibilities of livestock movement in the region. It is therefore necessary to supplement this study with an analysis of connectivity, identifying “black spots” or critical sections that could impede the flow of herds. Intervention in these areas would be an essential step in restoring the livestock movements necessary for herds to access the DRs that are deemed most suitable for restoration and conservation. Furthermore, it is important to consider other challenges associated with the reintroduction of livestock management in the existing network of DRs. The decline in livestock raising practices within the area poses a significant hurdle in finding farmers who are interested and willing to use the DRs. Addressing this issue requires exploring alternative strategies or incentives to attract farmers or stakeholders who can

actively participate in the restoration of DRs. Collaborative efforts with local shepherd associations or government agencies could potentially provide solutions to overcome this obstacle and create a mutually beneficial framework for both the restoration of DRs and the revival of traditional livestock management practices.

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**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

#### Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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