



A pressure indicator for the impact of Iberian wild goat on moss and soils in a Mediterranean climate

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Abstract

In the Sierra de Guadarrama National Park (central Spain), the population of Iberian wild goat, also known as Spanish ibex (*Capra pyrenaica*) has grown strongly since its reintroduction three decades ago. The plant community is now under heavy browsing pressure due to this high population. A study of the presence of moss on rocks was used herein as the basis for the design of an indicator, named impact on mosses (*im*), to describe the environmental pressure exerted by the Iberian wild goat in terms of moss removal. Granite and gneiss zones at medium altitudes with continental Mediterranean climate are the most suitable areas for successful application of the indicator. The hypotheses to test are: (1) the indicator will discriminate between areas with different wild goat pressure levels, (2) wild goat pressure will explain a high proportion of moss loss variance, and (3) the *im* indicator will be useful to establish a mathematical model between wild goat pressure and moss loss. The proposed indicator was analyzed using both statistical and data science techniques. The results support the mentioned hypotheses. Specifically, statistically significant differences were found regarding the impact on mosses between areas with different levels of Iberian wild goat pressure. Thus, a high proportion of the variance was associated with wild goat pressure (80% for high-pressure areas, 56% for low-pressure areas). A modified parabolic function was fit to express the relationship between Iberian wild goat pressure and impact on mosses. In conclusion, the *im* indicator was shown to be a useful tool to assess pressure due to Iberian wild goat. Therefore, *im* can help assess and manage Iberian wild goat populations and determine their sustainable levels.

Keywords Spanish ibex · Moss cover · Soil degradation · Indicator analysis · Data science · Step quadratic function model

Introduction

For more than 30 years, the Iberian wild goat has been part of the Sierra de Guadarrama landscape. In 1990, 67 individuals of the subspecies *Capra pyrenaica victoriae* (Refoyo et al. 2015) were reintroduced and from the outset showed

healthy population growth, reaching 5403 animals in 2021. The current population represents a density of over 52 ind km⁻² (Refoyo et al. 2019), excessively high to be ecologically sustainable (Perea et al. 2015). For comparison, other wild populations of similar ungulates in Europe show densities of between 0.2 and 16 ind km⁻² (Fandos et al. 2010; Armstrong and Seddon 2008).

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The Iberian wild goat has been recorded as feeding on over 230 different plant species, including woody species, herbaceous plants, lichens, and mosses (Martínez 1992). The constant pressure exerted on the environment since their reintroduction has produced significant damage on woody plants (Perea et al. 2015), mosses, and soils. This results in an unbalanced and unsustainable relation (García-Rodríguez 2018). The impact of wild herbivores on woody plant species is relatively well studied and known (Stillman et al. 1997; Hui 2006; Rooney 2009; Perea et al. 2014). However, its effect on bryophytes growing in Mediterranean habitats on granites and gneisses remains largely unknown. The impact of wild ungulates on moss cover was found to be nonsignificant in environments with greater water availability and plant cover (Marozas et al. 2009). The present study focuses on an area with low water availability to check for a possible negative relationship between the abundance of Iberian wild goat and moss cover on rocks. Mosses may become an important food item when no alternative resources are available (Concostrina-Zubiri et al. 2014, 2017). In addition, as wild goats have excellent rock-climbing skills, their impact on moss cover may also be related to trampling and rock erosion.

The Spanish National Parks Act 30/2014 establishes the need to create a “Monitoring and Evaluation Plan of the National Parks Network.” It also requires environmental indicators to be defined, enabling monitoring of changes in different biological, geological, and ecological parameters within these protected areas (PNSG 2020). A well-designed indicator explains processes through the synthesis of information from various sources and additionally provides support for better management decisions concerning these protected areas by public authorities. However, for such an indicator to be useful, it must exhibit certain characteristics (Dale and Beyeler 2001): it must be easy to measure, predictive, and sensitive to different stress levels, enabling improvement outcomes through management measures. It must also be integrative, covering key gradients in ecological systems such as vegetation and soil types, or geomorphological environments. However, since we cannot monitor all the components of an ecological system, we must identify a small number of indicators that characterize the most relevant parts of the system (Gaillard et al. 2008).

One important change in ecosystems produced by ungulates is soil and rock erosion (Concostrina-Zubiri et al. 2014, 2017). Elimination of vegetative cover because of browsing or trampling exposes soils and rocks to erosional forces, thereby creating unstable surfaces (Pegau 1970). Specifically, elimination of mosses implies the loss of the primary edaphic sustenance, which is required for more evolved soils. Furthermore, the disappearance of moss from rocky outcrops reduces their surface roughness, facilitating particle movement. Without mosses, water moving faster over

rock surface increases hillside erosion around the outcrops. This favors unearthing of rock blocks and erosion of unconsolidated material. This process is more frequent in areas of steep slopes or in alpine environments where soil erosion can advance drastically (Evans, 1996). Earlier studies (García-Rodríguez 2015; García-Rodríguez et al. 2017) showed a good correlation between rock moss loss and soil erosion in surrounding areas. Therefore, in this study, we aimed to validate the indicator *im* (impact on mosses) to understand how Iberian wild goat population pressure affects rock mosses. That could help to monitor the magnitude of erosive processes throughout the national park.

The definition of the *im* indicator relies on the relationship between ungulate population pressure and moss loss in dry areas. Hypotheses will be linked to the *im* indicator features and its usefulness. We hypothesize that our *im* indicator will be able to:

- (a) Distinguish between areas with different Iberian wild goat grazing pressure. An indicator unable to distinguish between areas with different grazing pressures would be useless.
- (b) Accurately assess different impact degrees (high proportion of variance) between areas with different degrees of browsing pressure. An indicator that can accurately assess different areas will facilitate comparison among areas.
- (c) Establish functional relationships of (which explain and predict) Iberian wild goat pressure effects. An indicator expressed as a function indicates the different strength of relationships at different variable levels, leading to accurate predictions.

Materials and methods

Study area

The Sierra de Guadarrama National Park (SGNP) is located in the Spanish Central Range that was formed during the Variscan Orogeny (Peinado et al. 1981). Intrusions of plutonic bodies in diverse phases occurred at the end of this period (Pérez-Soba and Villaseca 2010). After a long period of erosion, the Variscan Orogeny followed, defining different erosion surface levels (Pedraza 1978). Later, the Alpine Orogeny elevated the current Spanish Central Range, reactivating the Variscan fractures and creating a relief with horst and graben morphology.

Most materials present in the SGNP are granites and gneisses, which define various geomorphological environments (Pedraza et al. 2014). The landscape mainly includes elements comprising large exposed rock outcrops and mixed areas of large rock blocks standing in sandy substrates

(Centeno 1989; García-Rodríguez 2015). It also includes other areas of loose materials deriving from alterations of the geological substrate. The SGNP shows a strong altitudinal gradient, with height ranging from around 900 m to slightly above 2400 m at the top of Peñalara Peak (Fig. 1).

The climate in the area is of continental Mediterranean type, with cold winters and hot dry summers. The climatic conditions vary markedly with altitude, with three zones showing different characteristics (Comunidad de Madrid 2010). The lowest zone lies between 900 and 1400 m, with 750 mm annual average rainfall, annual average temperature of 10 °C, and maximum and minimum of 28 °C in summer and −6 °C in winter, respectively. Between 1400 m and 2000 m, the annual average rainfall is around 950 mm, with annual average temperature of 8 °C and average maximum and minimum temperature of 25 °C in summer and −8 °C in winter, respectively. Precipitation regularly falls as snow between December and April. In the highest mountain zone, above 2000 m, the annual rainfall is highly variable, ranging from 1200 to over 1500 mm while the average annual temperature fluctuates from 6 to 7 °C, with a summer maximum of 22 °C and winter minimum of −12 °C. In this zone, precipitation usually falls as snow between November and May.

The vegetation in the SGNP comprises a wide variety of species showing an extraordinary degree of adaptation to the difficult rocky environment with poorly developed

soils. This includes pastures and shrubs in the highest areas, and forests on the slopes and in the valleys below 1800 m (Morales 2003).

At least 323 moss species have been catalogued in the Sierra de Guadarrama (Blanco Castro and Acón Remacha 1984; Vicente and Ron 1989; Luna and Estébanez 2008), accounting for 12.6% of all the plant species in the Community of Madrid (Morales 2003). Some examples of common species in the Sierra de Guadarrama include (Lara et al. 2005): *Andreaea rupestris*, *Brachythecium populeum*, *Bryum gemmiparum*, *Fissidens pusillus*, *Funaria convexa*, *Amblyodon dealbatus*, and *Encalypta streptocarpa*.

The variety and richness of plant species in the Sierra de Guadarrama have provided a huge food source that has enabled the proliferation of the Iberian wild goat (*Capra pyrenaica* Schinz, 1838) in the absence of natural predators for more than two decades (Fig. 2).

Impact of Iberian wild goat on mosses (*im* indicator)

The proposed indicator assesses the disappearance of rock moss cover due to Iberian wild goat grazing and/or trampling. Rocks cleared of moss due to Iberian wild goat presence exhibit pale areas indicating the exact distribution and surface area of the patches previously covered by mosses (Fig. 3). Lichen typically surrounds moss

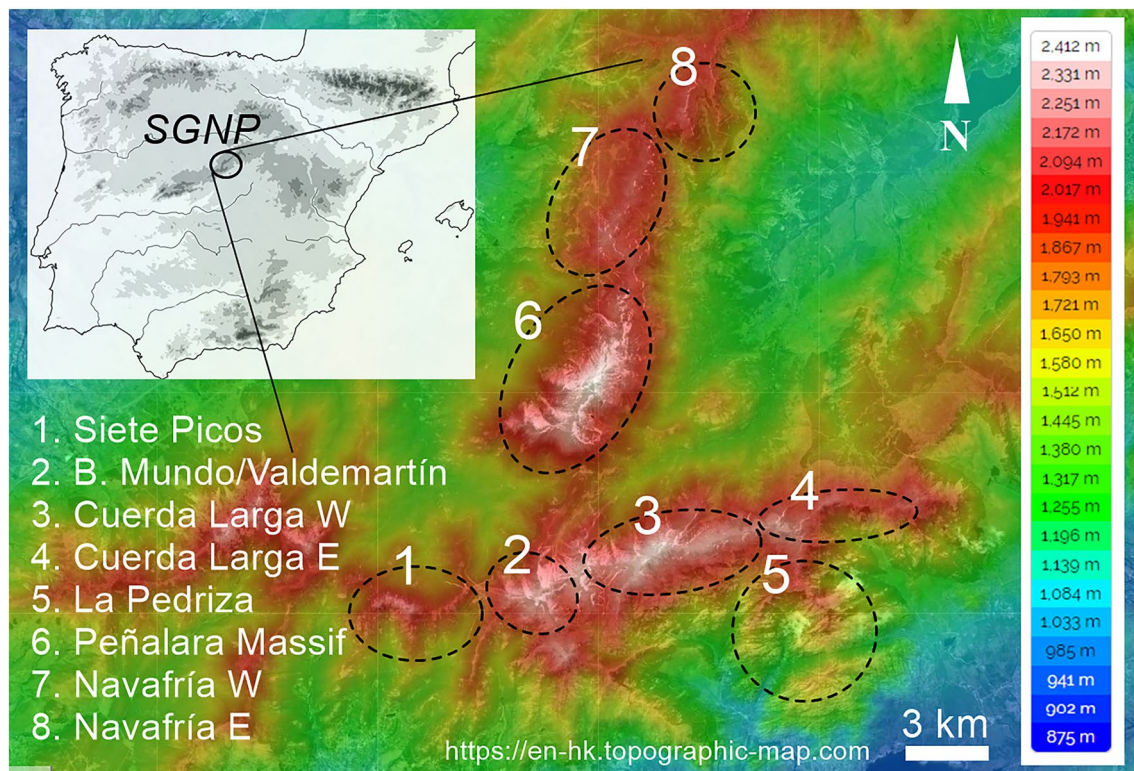


Fig. 1 Sierra de Guadarrama National Park locations, study areas, and altitudes

Fig. 2 **a** Iberian wild goat grazing on mosses in an area where no other food resources remain (photo: Haday López Portillo). **b** Iberian wild goat group browsing on tender buds from a holm oak (*Quercus ilex*) growing in a rock crack (photo: Juan Luis Salcedo)

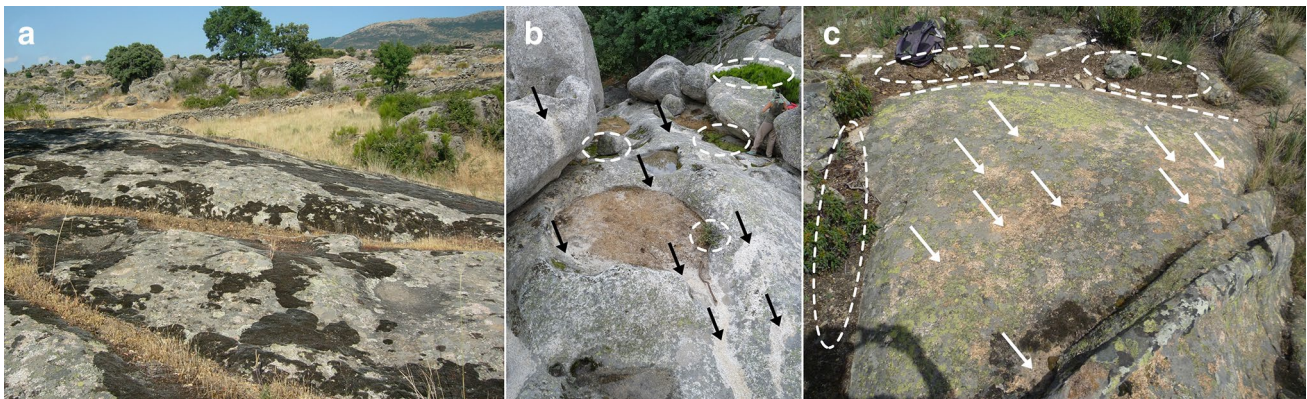
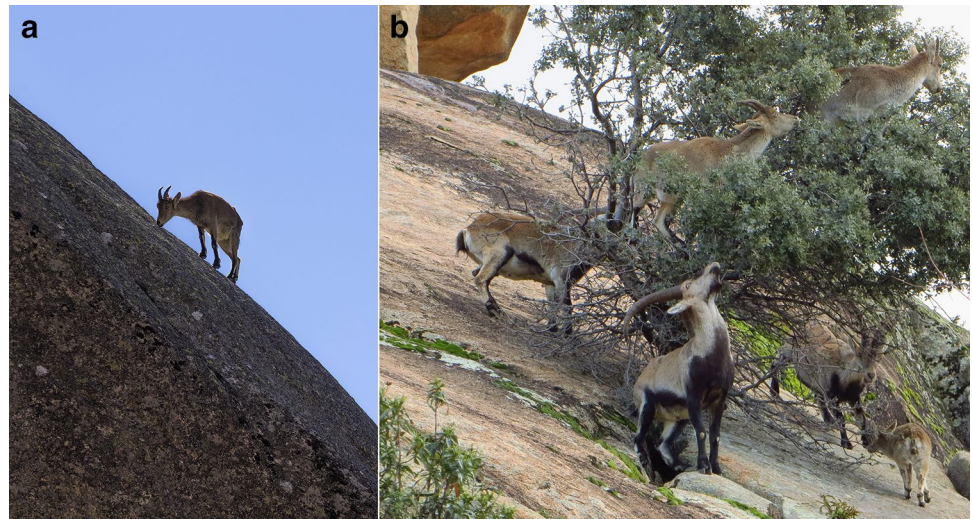


Fig. 3 **a** Granitoid domic surface outcrop with intact moss cover. This is a zone, near the SGNP border, located at an altitude of 900 m, with no presence of Iberian wild goat. The *im* value at this area equals 0, reflecting an absence of Iberian wild goat pressure. Around this rock outcrop, there are no signs of soil erosion or vegetation browsing. **b**, **c** Granitoid outcrops at La Pedriza, where 90% of moss has disappeared

due to Iberian wild goat browsing (*im* around 0.9). Arrows indicate clear areas from where moss was eliminated. Ovals indicate woody plant browsing, soil elimination, and plenty of Iberian wild goat pellets. Dotted lines (photo **c**) signal limit perimeter banding of rock exposition due to regolith erosion

areas. This facilitates the localization of disappeared moss patches areas, because their perimeter is clearly defined by a change in color and texture (García-Rodríguez 2015).

The value of the *im* indicator ranges from 0 to 1. A value of 0 indicates no moss loss, linked to no pressure exerted by Iberian wild goat. A value of 1 indicates complete moss loss, because of grazing and/or trampling. Up to values of 0.2, moss loss can be due to other natural causes. This threshold is derived from a group of areas with *im* values from 0 to 0.2 where there is no Iberian wild goat presence (Table 1).

Concerning the application of the *im* indicator, three geomorphological scenarios (Pedraza et al. 2014) were described: (a) rock outcrops, (b) screens, and (c) mixed terrain with both loose materials and rocks. Additionally,

wide sandy areas of loose materials occur in the Sierra de Guadarrama, where the indicator cannot be applied.

Rock outcrop (R)

These are represented exclusively by granites and gneisses, covered by lichens and mosses (Fig. 4a). These rocks may form fractured and stepped walls, smooth rounded surfaces, or large rock blocks of tens of meters in size. Rock outcrops showing open fractures tend to be filled with muddy or sandy materials, leading to soil formation. This soil supports a wide range of plant species, including trees (Izquierdo 2007; Centeno and García-Rodríguez 2008).

Table 1 Wild goat impact on mosses and number of pellet groups at each sampled site

Location	LG	Id	<i>im</i>	<i>pg</i>	Location	LG	Id	<i>im</i>	<i>pg</i>
La Pedriza	1	1	0.00	1	Bola Mundo/Valdemartín	2	49	NA	17
La Pedriza	1	2	0.50	0	Bola Mundo/Valdemartín	2	50	NA	12
La Pedriza	1	3	0.70	2	Bola Mundo/Valdemartín	2	51	NA	6
La Pedriza	1	4	0.60	5	Bola Mundo/Valdemartín	2	52	NA	17
La Pedriza	1	5	0.85	21	Bola Mundo/Valdemartín	2	53	0.20	7
La Pedriza	1	6	0.70	12	Bola Mundo/Valdemartín	2	54	0.60	15
La Pedriza	1	7	0.80	8	Siete Picos	0	55	0.00	0
La Pedriza	1	8	0.70	14	Siete Picos	0	56	0.10	0
La Pedriza	1	9	0.60	6	Siete Picos	0	57	0.20	0
La Pedriza	1	10	0.70	6	Siete Picos	0	58	0.10	0
Cuerda Larga West	1	11	0.80	16	Siete Picos	0	59	0.00	0
Cuerda Larga West	1	12	0.40	8	Siete Picos	0	60	0.10	0
Cuerda Larga West	1	13	0.90	16	Siete Picos	0	61	0.00	0
Cuerda Larga West	1	14	0.80	7	Siete Picos	0	62	0.10	0
Cuerda Larga West	1	15	0.70	9	Siete Picos	0	63	0.05	0
Cuerda Larga West	1	16	0.50	3	Siete Picos	0	64	0.05	0
Cuerda Larga West	1	17	0.70	5	Siete Picos	0	65	0.05	0
Cuerda Larga West	2	18	NA	4	Siete Picos	0	66	0.05	0
Cuerda Larga West	2	19	NA	3	Peñalara Massif	3	67	0.10	3
Cuerda Larga West	2	20	NA	21	Peñalara Massif	3	68	NA	2
Cuerda Larga West	2	21	NA	3	Peñalara Massif	3	69	NA	3
Cuerda Larga West	2	22	NA	35	Peñalara Massif	3	70	NA	10
Cuerda Larga West	2	23	NA	5	Peñalara Massif	3	71	NA	32
Cuerda Larga West	2	24	NA	11	Peñalara Massif	3	72	NA	10
Cuerda Larga West	2	25	NA	33	Peñalara Massif	3	73	NA	11
Cuerda Larga West	2	26	NA	5	Peñalara Massif	3	74	NA	2
Cuerda Larga West	2	27	NA	10	Peñalara Massif	3	75	NA	7
Cuerda Larga West	2	28	NA	15	Peñalara Massif	3	76	NA	0
Cuerda Larga West	2	29	0.50	6	Peñalara Massif	3	77	0.00	0
Cuerda Larga West	2	30	0.10	11	Navafría West	3	78	NA	1
Cuerda Larga West	2	31	NA	6	Navafría West	3	79	NA	8
Cuerda Larga East	2	32	0.20	8	Navafría West	3	80	NA	44
Cuerda Larga East	2	33	NA	32	Navafría West	3	81	NA	26
Cuerda Larga East	2	34	NA	8	Navafría West	3	82	NA	2
Cuerda Larga East	2	35	NA	15	Navafría West	3	83	NA	20
Cuerda Larga East	2	36	NA	17	Navafría West	3	84	NA	14
Cuerda Larga East	2	37	0.20	0	Navafría West	3	85	NA	7
Cuerda Larga East	2	38	0.40	2	Navafría East	0	86	0.00	0
Cuerda Larga East	2	39	0.50	3	Navafría East	0	87	0.05	0
Cuerda Larga East	2	40	0.70	20	Navafría East	0	88	0.00	0
Cuerda Larga East	1	41	0.80	12	Navafría East	0	89	0.05	0
Cuerda Larga East	1	42	0.80	4	Navafría East	0	90	0.10	0
Cuerda Larga East	1	43	NA	4	Navafría East	0	91	0.20	0
Bola Mundo/Valdemartín	2	44	NA	3	Navafría East	0	92	0.20	0
Bola Mundo/Valdemartín	2	45	NA	18	Navafría East	0	93	0.05	0
Bola Mundo/Valdemartín	2	46	NA	34	Navafría East	0	94	0.20	0
Bola Mundo/Valdemartín	2	47	NA	13	Navafría East	0	95	0.05	0
Bola Mundo/Valdemartín	2	48	NA	26					

LG, location group, Id, identifier; *im*, impact on mosses; *pg*, pellet groups; NA, not available

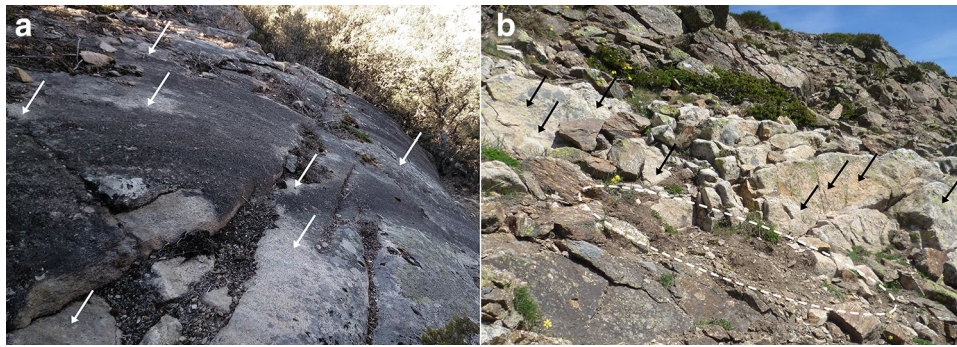


Fig. 4 **a** Granitoid domical surface at steep slope area. Moss disappearance reduces rock rugosity, facilitating diverse size particle movement. Overgrazing contributes to soil and vegetation loss, observable at rock cracks. Runoff at rainy periods accelerates hillside erosion around the outcrop. **b** Gneiss rocky ground at high mountain areas

(2000 m). Moss elimination from rock and soil favors rock block unearthing and unconsolidated material erosion. Arrows indicate moss elimination in overgrazing areas in both pictures (**a** and **b**). Dotted oval (photo **b**) indicates an area of strong erosion, wild goat browsing, and abundance of pellets

Screes (S)

This term refers to the accumulation of rocks on mountain slopes (Fig. 4b). These screes form due to the breakup of rocks forming the mountain peaks, which fall and move down the slopes. These are frequent in the high mountain zone of the Sierra de Guadarrama (Palacios et al. 2003; Carrasco et al. 2016). The rock fragment sizes in screes vary from a few centimeters to more than 1 m long.

Mixed terrain of loose materials and rocks (M)

Rock outcrops and loose materials are combined (Scarciglia et al. 2007; Lucía et al. 2011). This is the commonest scenario at Sierra de Guadarrama. This scenario clearly shows the relationship between rock moss loss and erosion processes surrounding outcrops with runnels, gullies, or mass material movements.

Altitude must be considered while assessing *im*. Above 2100 m, moss presence is naturally less frequent than lower down, making this indicator more difficult to apply. Above 2000 m, accumulated winter snow persists for several months, frequently making it hard for mosses to develop (Palacios and García 1997).

Another factor to consider is rock type. In the ridge area of the SGNP, granites and gneisses alternate. Gneisses have a more irregular surface texture where the moss cover is also more irregular than on granitic surfaces. That is why granitic outcrops are recommended for data collection and indicator analysis.

In this sense, Pedriza de Manzanares is the area where this indicator is most easily and suitably applied in the SGNP because of the high frequency of granites and rock outcrops, as both rock faces and isolated blocks.

Regarding the Iberian wild goat factor, several considerations must be noted. In those areas of the Sierra de

Guadarrama without Iberian wild goats, rock moss cover is virtually complete (Lara et al. 2005; García-Rodríguez 2019). Moss loss may be caused by long dry periods. Nevertheless, it was shown that moss cover does not show significant losses in areas without Iberian wild goat, even when south facing, at altitudes under 900 m, and subject to high temperature and low rainfall. This provides a baseline before the impact of the reintroduction of the Iberian wild goat.

To link moss loss with Iberian wild goat pressure, a series of requirements are needed: (a) identify similar rocks areas that are accessible and inaccessible of Iberian wild goat, which effectively justify moss presence, (b) presence of browsing evidence on woody and herbaceous plant species, and (c) presence of Iberian wild goat excrement in the area.

This indicator can be applied to any rock accessible to Iberian wild goat and with moss cover. This includes the three geomorphological scenarios described above.

Data collection

A total of 95 different points were selected for this study (Table 1), distributed in areas of the SGNP with different abundance of Iberian wild goat (Refoyo et al. 2019).

At each selected point, 300 m² of rock surface was surveyed. When rock outcrops were smaller, a series of dispersed outcrops were surveyed until this total surface area was reached. The presence of Iberian wild goat at each of these 95 survey points was determined following Perea et al. (2015), where wild goat droppings, pellet groups (*pg*), were counted at each point corresponding to a sampling area of 314 m² (10-m-radius circle). The dropping counting surveys took place at the same location and during the same dates as the surveying for moss cover and rock erosion. The estimate of the habitat use, via counting of the groups of Iberian wild goat excrement (*pg*), followed the procedures of Pfeifer et al. (1996) and Smart et al. (2004). Rock outcrop

im measurements were done at the same surface where pellet groups were assessed. Quantification of the indicator was based on studying rock surface moss loss percentage. This moss-free surface was identified visually and quantified with the help of photographs. The *im* value for each selected point was averaged from the individual *im* values for that spot.

Based on the Iberian wild goat pressure, rock-type geomorphological scenarios, and altitude, eight types of zone were predefined to enable comparisons and validate the proposed indicator. These areas were, from low to high altitude: La Pedriza, Siete Picos, Navafría (East and West), Cuerda Larga (East and West), Bola del Mundo and Valdemartín, and Peñalara Massif (Table 2).

Statistics and data analysis

The following tools were employed for data analysis: Python, version 3.7.3.; Anaconda client, version 1.7.2.; Conda, version 4.7.5.; Jupyter, version 1.0.0.; Jupyter client, version 5.2.4.; IPython, version 7.4.0.; Numpy, version 1.18.2.; Scipy, version 1.2.1.; Pandas, version 0.24.2.; Matplotlib, version 3.1.1.

The approach encompassed both data analysis and statistical analysis. Classical statistics and newer data science techniques were used for either data exploration or hypothesis testing. This focus is supported by both a proposal of systemization (Karpatne et al. 2017), and its application in several scientific fields such as geology (García-Rodríguez et al. 2015), psychology (Manzanero et al. 2019), and education (Aroztegui Vélez, et al. 2020). The specific techniques used were: (a) exploratory data analysis, (b) scatter plots, (c) box plots, (d) class I analysis of variance (ANOVA), (e) null hypothesis significance test (*p*-value) of ANOVA results, (f) coefficient of determination, used as an effect size measurement, (g) null hypothesis significance test (*p*-value) linked to coefficient of determination results, (h) least-squares function fit. The *curve_fit* function from the *scipy.optimize* library was used for function adjustments. The *curve_fit*

function uses the squared minima procedure as detailed by Branch et al. (1999), (i) the goodness of fit function for the data through the coefficient of determination, and (j) graphical representation of functions.

Scatter plots show the values and distribution of the raw data collected. Some key data distribution patterns are only accessible through these types of analyses, as has been known for a long time (Anscombe 1973). Awareness of their relevance has continued to grow over time (Matejka and Fitzmaurice 2017).

Class I analysis of variance was used to test hypotheses concerning statistically significant differences between groups being compared. Analysis of variance is a relatively robust technique even in the face of noncompliance of its assumptions, including both a normal distribution (Blanca et al. 2017) and homoscedasticity (Kohr and Games 2014). It is selected, given its clarity, even in cases where all these assumptions are not met.

Results and discussion

The results are presented below after the hypotheses to be tested on the statistical behavior of the *im* indicator.

The box plot in Fig. 5 shows descriptive statistics of data groupings. Median values of *im* for the Cuerda Larga West and La Pedriza areas are notably higher than those for Siete Picos or Peñalara Massif. The variation is also shown by the graphical representation of interquartile range and extremes (Fig. 5). In this sense, the variability is greater at Cuerda Larga East and lesser at Peñalara Massif or Siete Picos. Intermediate values were found at the Bola del Mundo and La Pedriza areas. However, the interquartile variability may be an inadequate representation of average variability. Data variability at Siete Picos or Peñalara Massif, with low *im* values, overlaps little with those of high *im* values. These results make sense if the particularities of each area are taken into account. Iberian

Table 2 Description of study areas according to Iberian wild goat presence and pressure, rock type, geomorphological scenario, and altitude

Zone	Iberian wild goat presence/pressure	Rock type	Geomorphological scenarios	Altitude (m.a.s.l.)
La Pedriza	Yes/High	Granites	R	1400 (900–1700)
Siete Picos	No/–	Granites and gneisses	M, R	1800
Navafría East	No/–	Granites and gneisses	M, R	1900
Navafría West	Yes/Low	Granites and gneisses	M, S, R	2000
Cuerda Larga East	Yes/High	Granites and gneisses	M, S, R	1900
Cuerda Larga West	Yes/High	Granites and gneisses	M, S, R	2100
Bola del Mundo and Valdemartín	Yes/High	Granites and gneisses	M, S, R	2000
Peñalara Massif	Yes/Low	Gneisses	M, S, R	2200 (peak 2428)

M, mixed terrain with loose materials and rocks; S, screens; R, rock outcrops

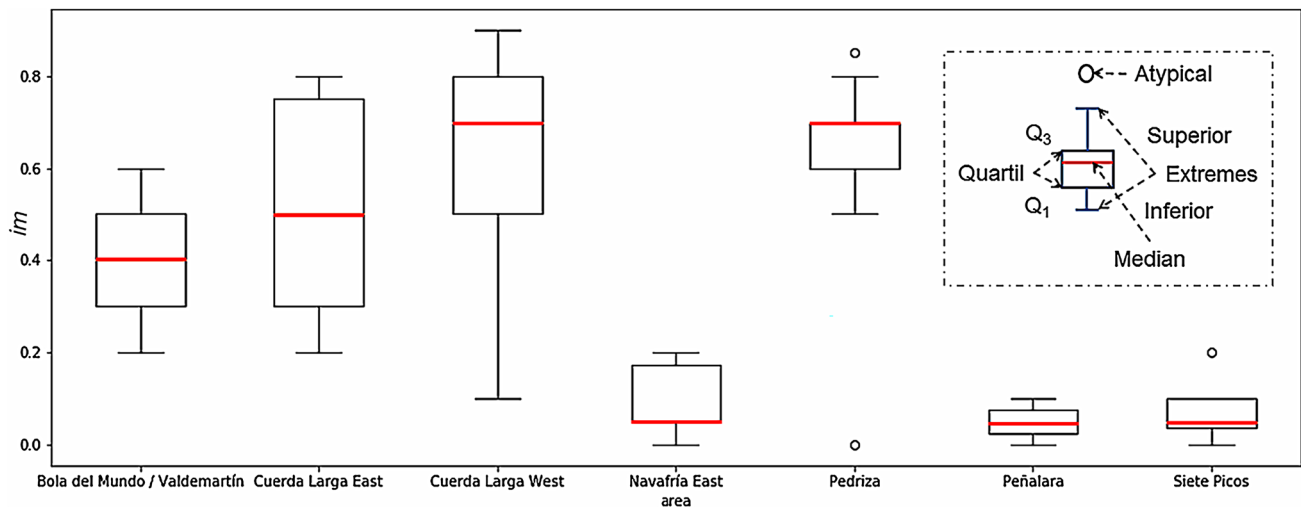


Fig. 5 Data value distribution by location group. Box plot of *im* by SGNP area

wild goat presence has not been recorded at Navafría East and Siete Picos, in line with Refoyo et al. (2019), and the Peñalara peak is situated at an altitude of 2428 m, with wild goat presence but snow cover for 7–8 months a year.

The descriptive data in Table 3 include the number of measurements (n) in each area. The average *im* measurements at Cuerda Larga West and La Pedriza are clearly higher than at Siete Picos. Again, the variability shown through nominal values (such as in Fig. 5) appears different from the variability coming from all the data, as for the standard deviation. In the latter case, the variability at both Cuerda Larga West and La Pedriza is greater and more similar to each other than appeared to be the case indicated by the interquartile range. The standard deviation is notably less at Siete Picos and Peñalara. The obtained data are consistent with previous studies on the presence of the Iberian wild goat (Refoyo et al. 2015), which previously identified Cuerda Larga West and La Pedriza as locations with the greatest historical presence of the species (PNSG 2020).

The *im* indicator will distinguish between areas with different Iberian wild goat grazing pressure

The proposed indicator would not be useful if it failed to identify differences between areas where they exist. Consequently, this test is interesting as it indicates whether *im* will be useful in studies and monitoring projects for discriminating areas with different levels of Iberian wild goat browsing pressure. Similarly, it should not show statistically significant differences between similar areas.

The location groups (LG) 0 and LG 3 (see the groupings in the header of Table 4) show low *im* levels, while LG 1 and LG 2 show high *im* levels. Comparisons of LG 0 compared with LG 1 and LG 2 (first and second rows in Table 4) show statistically significant differences. When comparing LG 0 and LG 3, no statistically significant differences were found. Consequently, the *im* indicator shows the desired characteristics. Therefore, its statistical behavior is useful to indicate areas with different environmental pressure due to Iberian wild goat presence. It should be remembered that

Table 3 Descriptive statistics of *im* values in SGNP areas

Indicator	Bola del Mundo and Valdemartín	Cuerda Larga East	Cuerda Larga West	Navafría East	La Pedriza	Peñalara and Navafría West	Siete Picos
n	2	7	9	10	10	2	12
Average	0.40	0.51	0.60	0.09	0.61	0.05	0.07
Standard deviation	0.28	0.26	0.25	0.08	0.24	0.07	0.06
Minimum	0.20	0.20	0.10	0.00	0.00	0.00	0.00
Q_1 (25%)	0.30	0.30	0.50	0.05	0.60	0.02	0.04
Q_2 (50%)	0.40	0.50	0.70	0.05	0.70	0.05	0.05
Q_3 (75%)	0.50	0.75	0.80	0.17	0.70	0.07	0.10
Maximum	0.60	0.80	0.90	0.20	0.85	0.10	0.20

Table 4 Statistically significant differences (ANOVA) of *im* comparing different location groups in the SGNP

Indicator	LG (0)	LG (1,2,3)	<i>F</i>	<i>p</i> ANOVA	Statistically significant differences?	Average reference site	Average other site
<i>im</i>	0	1	$F(1,39)=157.000$	0.000	Yes	0.077	0.661
<i>im</i>	0	2	$F(1,29)=36.827$	0.000	Yes	0.077	0.378
<i>im</i>	0	3	$F(1,22)=0.289$	0.596	No	0.077	0.050

Location group 0: Siete Picos + Navafría East. Location group 1: Pedriza + part of Cuerda Larga East + part of Cuerda Larga West. Location group 2: part of Cuerda Larga East + part of Cuerda Larga West + Bola del Mundo/Valdemartín. Location group 3: Peñalara + Navafría West

LG 0 includes all SGNP areas where Iberian wild goat has not been recorded. On the other hand, the sites within LG 3 are located between 2000 and 2400 m in altitude. As mentioned above, LG 3 has snow cover for most of the year and represents a limitation of the model as mosses at such elevation are rare. Additionally, the historical presence of the Iberian wild goat in LG 3 is seasonal (in summer) and only over the last 10 years (Refoyo et al. 2019). At LG 2, an area with similar altitudes (Cuerda Larga West and East), permanent Iberian wild goat presence has been described for at least the past 12 years (Refoyo et al. 2019). In spite of the high altitude, it was possible to measure the *im* indicator in LG 2 at some points. The results support the hypothesis. The *im* indicator is able to distinguish between areas with different environmental pressure.

The *im* indicator will show a high proportion of explained variance between areas with different browsing pressure

This hypothesis was tested through effect size calculations.

In addition to encountering different browsing pressure levels, it is important to evaluate the size of these differences. Given two areas with statistically significant differences, are these differences large or small? Effect size measurements allow one to test this hypothesis. The coefficient of determination, which equals the Pearson correlation squared, is used. Within each area group, the coefficient of determination is interpreted as the variance associated with the independent variable pellet group (*pg*) and the dependent variable (*im*). In other words, it is interpreted as the proportion

of the variation expected in *im*, knowing the variation in *pg*. The results indicate that 80% and 56% of the associated variance was explained when considering areas with high (LG 1 and LG 2) and low (LG 0) browsing pressure (Table 5). Moreover, the probability that the value obtained was by change is sufficiently low ($p < 0.001$). This suggests that, if *pg* causes *im*, the environmental factors that produce variations of *pg* levels will produce considerable variations in the levels of browsing pressure on mosses.

Comparing the two areas with low browsing pressure (LG 0 and LG 3), the variance observed is negligible. This result, combined with the preceding ones, shows that the *im* indicator is useful to obtain these parameters. At the theoretical level, the effect size indicates which variables have greatest effect, being more relevant for moss loss evaluation. For an applied set, this information is useful to help decide which variables act to maximize the desired effect. The geological and population arguments that explain the results are the same as those given for the previous hypothesis. Finally, *im* indicator measurements showed high proportion of variance for areas with different browsing levels. Again, these results support the stated hypothesis.

A functional relationship to explain and predict Iberian wild goat pressure can be established

To test this hypothesis, we fit a function to the cloud of data with two possible functional relationships: linear and parabolic (Fig. 6a).

The diagram shows that the *im* values increase as *pg* values get larger. Different degrees of *im* variability exist at different

Table 5 Effect size of *im* values comparing different location groups in SGNP

Indicator	LG (0)	LG (1,2,3)	r^2	Associated variance	p r^2	Prob. of random associated variance
<i>im</i>	0	1	0.801	high	0.000	NO
<i>im</i>	0	2	0.559	high	0.000	NO
<i>im</i>	0	3	0.013	none	0.596	YES

Location group 0: Siete Picos + Navafría East. Location group 1: Pedriza + part of Cuerda Larga East + part of Cuerda Larga West. Location group 2: part of Cuerda Larga East + part of Cuerda Larga West + Bola del Mundo/Valdemartín. Location group 3: Peñalara + Navafría West

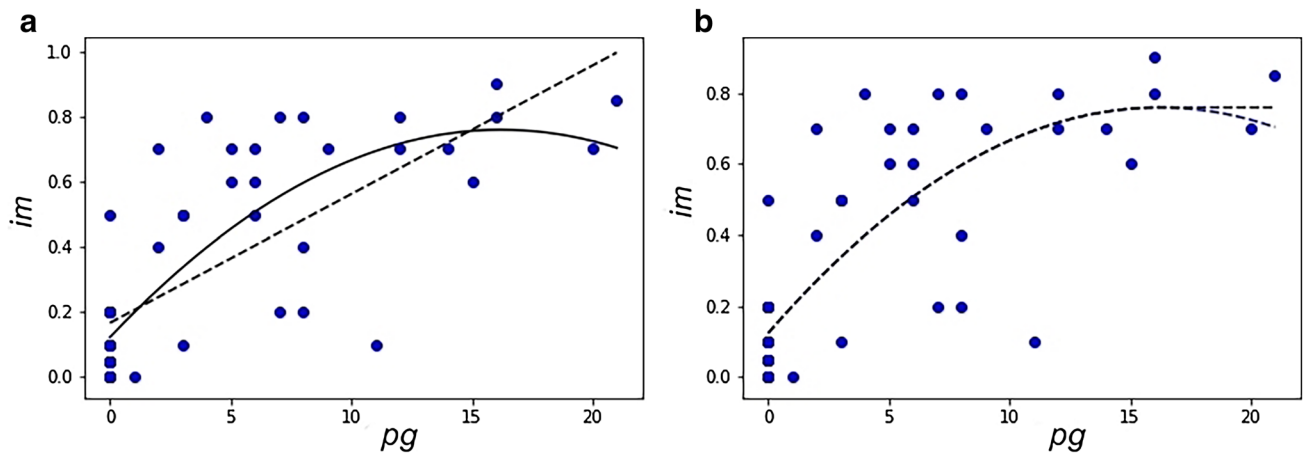


Fig. 6 Fit using several functions of *im* indicator dependent on Iberian wild goat pressure (*pg*). **a** Comparison of degree 1 and 2 polynomial functions. **b** Comparison of degree 2 polynomial function and degree 2 polynomial adjusted function

pg values. The *im* variability is higher at low *pg* values. As *pg* grows, *im* increases. The *im* values grow more at low *pg* levels, making *im* stabilize for greater *pg* values, approaching an asymptote. This may be explained by the lower availability of the food resource (moss) at high *pg* values.

The parabolic function ($r^2=0.630$) achieves a closer fit to data than the linear one ($r^2=0.558$). This adjustment represents a 7.75% improvement, indicating a preferable model. According to this model, an increase in Iberian wild goat presence will lead to an increase in browsing pressure on the mosses. The increase in impact gradually reduces as Iberian wild goat pressure increases, until it reaches a maximum impact level (Fig. 6b) beyond which it does not increase further. However, the parabolic curve suggests a reduction in browsing pressure after reaching this maximum level, which appears to be incorrect. In a proper model, once achieved, the maximum level is maintained. This function, a parabolic curve with a horizontal straight line to the right (Fig. 6b), provides a slightly improved fit to data ($r^2=0.632$). It is also a theoretical model that is more coherent with the process of browsing pressure itself.

The parabolic function obtained was as follows:

$$im(pg) = 0.123 + 0.078 pg - 0.002 pg^2 \tag{1}$$

The value of the *im*(*pg*) function at its maximum is

$$im(16.211) = 0.759 \tag{2}$$

Subsequently, the parabolic curve with a straight horizontal line to the right, which we define as *adjusted im*, *im_{ad}*(*pg*), is represented as follows:

$$im_{ad}(pg) = \begin{cases} im(pg) & \text{if } pg < 16.211 \\ 0.759 & \text{otherwise} \end{cases} \tag{3}$$

This allows one to understand the precise nature of the relationship between Iberian wild goat presence and the pressure exerted on the mosses. This relationship is a direct but nonlinear proportional relationship between *im* and *pg*. It has a greater increase at low values and a smaller increase at higher ones, revealing great sensitivity of mosses to small changes in wild goat pressure at lower pressure values.

Effectively, the function defined provides knowledge regarding the increase of *im* as a function of the Iberian wild goat population, facilitating comparisons between sites or within sites over different time periods. To illustrate its possible use in research or for monitoring, we take for instance two hypothetical SGNP sites, A and B, yielding Iberian wild goat pressure values of $pg_A=2$ and $pg_B=8$. The *im* values and the percentage increase of *im* in area B compared with A would then be calculated as follows:

In both cases, $pg < 16.211$, so

$$im_{ad}(pg_A) = im_{ad}(2) = 0.123 + 0.078 \cdot 2 - 0.002 \cdot 2^2 = 0.271 \tag{4}$$

$$im_{ad}(pg_B) = im_{ad}(8) = 0.123 + 0.078 \cdot 8 - 0.002 \cdot 8^2 = 0.619 \tag{5}$$

After obtaining the *im_{ad}* values for both areas, the percentage increase in area B compared with area A is calculated as follows:

$$|im_{ad}(pg_A) - im_{ad}(pg_B)| = |0.271 - 0.619| = 0.348 \tag{6}$$

$$\frac{|im_{ad}(pg_A) - im_{ad}(pg_B)|}{im_{ad}(pg_A)} \times 100 = \frac{0.348}{0.271} \times 100 = 128.41\% \tag{7}$$

If the two measurements in the same area refer to different times, with A the first and B the second, the 128.41% result obtained would represent the magnitude of the worsening of the situation between the two measurements.

Returning to environmental considerations, when *im* values are low, moss abundance is high, attracting high number of individuals. As the availability of food resources diminishes, the Iberian wild goat populations move away (Martínez 1992) to other less exploited areas, possibly leaving some moss patches unbrowsed/untrampled, corresponding to the highest *im* values.

Once the highest *im* value is reached (near to 1), the maximum moss impact is linked to the goats moving to a different browsing area. In this sense, the application of the indicator is very relevant to establish a relationship ranging from a null pressure level, without Iberian wild goats, to values close to its maximum (over 0.76). The maximum impact occurs in areas where the overpopulation of Iberian wild goat is five times more than the carrying capacity (Perea et al. 2015). Iberian wild goat population above this size is not reflected by greater *im* values. On the other hand, Iberian wild goat population reduction, either from natural causes or environmental management techniques, does not change *im* until the Iberian wild goat population falls below this maximum impact level. Once that level of population reduction is reached, we would expect moss cover to start recovering, with *im* values decreasing. Further studies should analyze the ability of mosses to recover after significant loss and the time elapsed to fully recover the lost area.

Conclusions

Over the last 25 years, large areas of the Sierra de Guadarrama have suffered from serious erosion problems (García-Rodríguez 2015, 2018). This is caused by natural processes, anthropic activities related to the management of protected areas, mass sporting activities, and overgrazing and/or trampling by the Iberian wild goat and other livestock species (PNSG 2020).

An indicator relating the environmental pressure exerted by Iberian wild goat on moss cover was proposed and named *im*. This indicator allows an estimation of the wild goat pressure in different areas, as well as comparisons between different areas or changes in pressure at the same site over time. This can be useful to characterize and monitor natural areas, through impact maps and environmental management measures. The *im* indicator may thus be used with management measures that aim to control the Iberian wild goat population and its impact. Efficient management would enable the detection of reductions in *im* values, indicating a reduction in environmental pressure, potentially associated with a reduction in browsing and/or trampling. This will favor

vegetation recovery and a reduction in soil erosion (intensity and speed).

The validation process of the *im* indicator confirmed its usefulness to observe the pattern of distribution, progress, nonlinearity, and variability in nonaggregated and descriptively aggregated data. It also enabled the detection of environmental pressure exerted by Iberian wild goat across different areas (ANOVA), to assess the magnitude of Iberian wild goat pressure exerted on mosses (associated variance through coefficient of determination), which was very high in the studied areas. Additionally, the proposed mathematical function allowed the discovery of the relationship between Iberian wild goat pressure and *im* variation dynamics. This function is also found to be highly useful for evaluating spatiotemporal changes in the impact of wild goat on moss cover and, thus, by extension, for monitoring and managing rocky areas dominated by large herbivores.

Moss cover disappearance is a good indicator of environmental pressure, linked to biodiversity loss and eroded areas where the superficial organic layer has been eliminated. Observations in areas with high *im* levels show common processes and effects during the last decade: (a) soil and vegetation elimination in open cracks in large rock outcrops, (b) unearthing and exposure of the rock base where moss has been lost (Centeno and García-Rodríguez 2008; García-Rodríguez 2015), (c) unearthing and exposure of tree roots in the surroundings of rock outcrops with severe damage to or complete elimination of trees and shrubs growing in the rock cracks (García-Rodríguez 2018), (d) browsing and elimination of woody plants, scrubs, and trees (Perea et al. 2015), (e) soil erosion leading to runnels and gullies (Pedraza et al. 2014; García-Rodríguez 2015), (f) mass movement of silts, sands, and even loose rocks at rocky outcrop surfaces (Centeno 1989; Palacios et al. 2003; García-Rodríguez 2019), and (g) general loss of biodiversity dependent on organic soils (Centeno and García-Rodríguez 2008).

These results indicate severe erosion over large areas of the SGNP, with differing final conditions depending on the Iberian wild goat pressure and specific geomorphological features of each site.

The *im* indicator presents high values in areas formed by rocky outcrops and where food sources are scarce or have disappeared.

The negative impacts of overgrazing and trampling typically increase during drought periods as food availability decreases. Iberian wild goat is probably the wild ungulate best adapted to rock outcrops, even in dry areas (Pascual-Rico et al. 2020). Under the current context of climate change, with increasing duration and intensity of drought periods (IPCC 2021), the vulnerability of soils and mosses to wild ungulates is expected to increase. This study suggests that Iberian wild goat overpopulation is probably the main

erosive agent in the SGNP in mid and high mountain areas. Population control of this species is essential to reduce soil and biodiversity loss in this highly valuable national park (PNSG 2020).

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Declarations

Conflicts of interest On behalf of all authors, M.G.R. states that there are no conflicts of interest.

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