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Mapping Balkan chamois habitat use and assessing human disturbance and renewable energy impacts on Mount Oiti, Greece

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Abstract

The Balkan chamois (*Rupicapra rupicapra balcanica*) is a protected ungulate with poor conservation status in Greece. We conducted seasonal surveys (2023) to collect 652 species' occurrences on Mt. Oiti (study area: 156 km^2). The seasonal ranges and the respective core areas (Kernel Density Estimates) showed limited size variation and a great spatial overlap, indicating limited seasonal movements. The suitable habitat (suitability values ≥ 0.6) as defined by Species Distribution Models (SDMs) covered 12.2 km^2, with 28% extending beyond the Natura 2000 network of protected areas. The chamois inhabited forests throughout the year, besides grasslands in the summer and autumn. The three variables contributing most to the SDMs were related to human disturbance. The species strongly avoided areas near livestock pens, roads, and hunting grounds. Three wind power stations are planned; if constructed, the species will lose 17% of its suitable habitat and could reduce its range. The impact of nine proposed small hydroelectric stations remains uncertain. These findings emphasize the need to avoid infrastructure and road construction in suitable chamois habitats, expand protected areas and wildlife refuges, and manage livestock activities, supporting the implementation of the national action plan for the species.

Keywords *Rupicapra*, Distribution range, Forest, Habitat selection, Habitat suitability, Hunting, Livestock, Wind power stations

1 Introduction

Human disturbance profoundly impacts wildlife through multiple mechanisms, including habitat loss and alteration due to infrastructure development, pollution, and climate change. It also directly reduces population densities through hunting and harvesting, creates anthropogenic landscapes of fear, and reshapes biological communities by introducing predators or pathogens [1]. Ungulate species have developed several human-avoidance strategies, including increased nocturnal activity [2, 3], reduced movement range [4], and modifications in resource use patterns [1, 5, 6]. Furthermore,

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human-driven global warming is expected to shrink the range of mountain ungulates by pushing them to higher elevations or into forests to escape rising temperatures [7, 8].

Gaining a deeper understanding of the ecological requirements of the species vis-à-vis the human-induced pressures is essential for mitigating threats, and habitat suitability models serve as a key tool in this effort. These models analyze the relationship between species occurrences and environmental and human disturbance variables, concluding with mapping the suitable habitat for the species and pinpointing the key factors shaping it [9]. Such predictions provide valuable insights for conservation management and planning. For example, they can guide decision-makers to designate protected areas, predict range shifts due to climate change, and accomplish restoration projects [10–13].

One species of conservation concern that has been nationally prioritized to benefit from such conservation actions is the Balkan chamois (*Rupicapra rupicapra balcanica*). Its global population is less than 10,000 individuals across nine countries, with 1330–1765 individuals in Greece across 30 populations, showing an increasing national population trend [14]. It is protected under European legislation (listed in Annexes II and IV of the Habitats Directive 92/43/EEC), but its conservation status in Greece is poor and classified as Inadequate-Bad (U2) [15], despite its hunting prohibition for over fifty years. For this reason, a national action plan for population recovery has been compiled and approved for implementation [16]. According to the action plan, approximately 7,409 km2 of Greece (5.6% of the national territory) qualifies as a potential habitat for chamois. Still, chamois currently occupy only about one-quarter of this area (1.5% of Greece), and the quality of these habitats has not yet been evaluated. Synergistic pressures from chamois poaching, new road construction and hunting of other species predominate, while additional pressures include competition with livestock in mountainous pastures, tourism, mining, genetic isolation, and climate change [16].

The current study focuses on the Balkan chamois population on Mt. Oiti, a renowned mountain for its flora diversity and endemism [17], hosting a rich fauna [18] and being protected as a National Park since 1966. The mountain is located near Mt. Giona, both occupying the southern part of the Balkan chamois distribution range. A particular "Mediterranean" seasonal distribution pattern has been reported for Giona, with the population aggregating around the highest available summits during summer, to overcome the aridity stress imposed by the warm summer period [19]. We explored whether this pattern would also apply to the population of Mt. Oiti, as it is characterized by similar climate conditions of hot and arid summers and mild winters, but on the other hand, it has more extended forests and permanent water availability. The population on Mt. Oiti could follow either the "Mediterranean" pattern (stress period in summer), observed in arid mountains (Mt. Giona and Mt. Olympus) [19, 20], either the typical "Continental" pattern (stress period in winter) observed in cooler and more humid mountains (Mt. Tymfi) [21], or not to undergo any seasonal stress. We also asked if the population shows forest-dwelling behaviour or follows the typical chamois seasonal rotational movement pattern [22]. This pattern is reported for other populations in Greece: animals inhabit lower forested habitats mainly in wintertime, gradually ascend to open mountainous grasslands above the tree line in summer, and remain there in autumn during the rutting season [19–21]. We aimed to assess the species' suitable habitat on Mt. Oiti, identify key shaping factors, and pinpoint which anthropogenic pressures outlined in the action plan are present in the area. Furthermore, we discuss the likely impact of planned new

renewable energy infrastructures [23] and their potential impact on chamois habitats. There is growing evidence of the cumulative negative impacts of renewable energy infrastructures on wildlife and natural ecosystems, including direct species mortality, habitat loss, degradation and fragmentation, deforestation, erosion, noise and light pollution, disruption of hydrological cycles, and carbon stock loss [24–26]. However, the impact of such renewable energy projects on chamois populations has not been studied, and our understanding of the impacts on terrestrial mammals in general remains limited [27]. As the wind energy sector develops fast in Greece, with the country being among the top most attractive renewable markets globally [28], our study serves as a typical paradigm of conflicting biodiversity vs renewable energy policies that require sustainable spatial planning solutions [29]. We set four objectives for the case study of the Balkan chamois population on Mt. Oiti. We aimed to: (a) explore the annual and seasonal ranges, including core areas frequently used by the population (b) pinpoint the key factors shaping suitable habitat and deliver a habitat suitability map, (c) explore the habitat preferences of the species, and (d) assess the impact of planned renewable energy infrastructure on chamois habitat. We finally discuss our findings from a conservation perspective, in the frame of the national action plan suggested actions [16].

2 Methods

2.1 Study area

The study area is located on Mt. Oiti in southern Greece (38°49′43″N 22°17′19″E). It covers 156 km^2, aligning with the species range on Mt. Oiti according to the IUCN red list of threatened species [14] (Fig. 1). It is a mountainous area with a mean altitude of 1361 m, extending from 92 to 2152 m (Pyrgos peak) with 81% of its extent being above 1000 m. The geological bedrock consists mainly of limestone (60%) and flysch

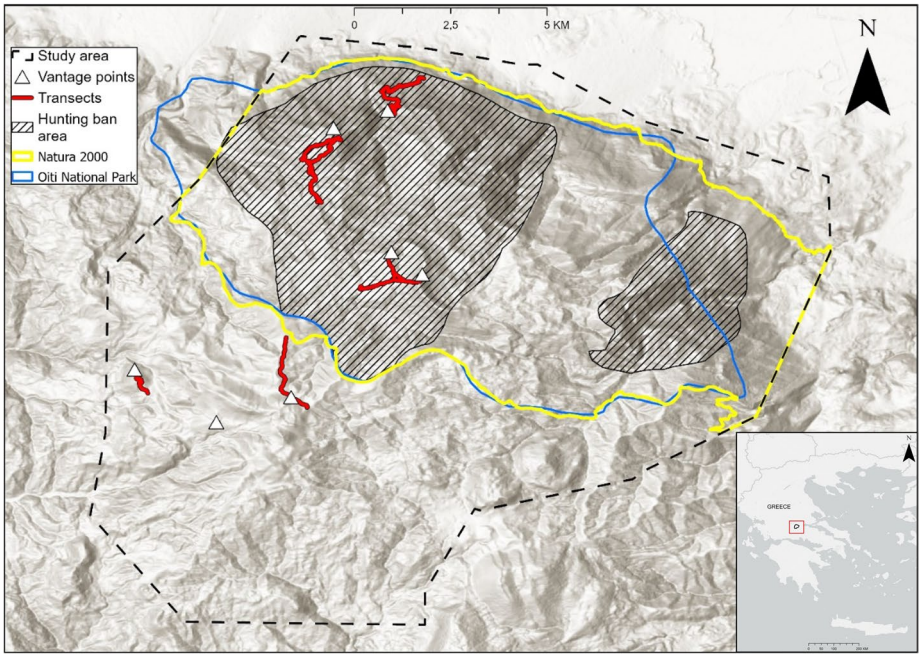


Fig. 1 Study area on Mt. Oiti and chamois survey transects and vantage points conducted in 2023. The map shows the borders of Oiti National Park (founded in 1966) and the merged borders of the three Natura 2000 sites within the study area (GR2440003, GR2440004, GR2440007) along with the hunting ban areas (the larger polygon is the core area of Oiti National Park and the smaller the wildlife refuge). Further details in Fig. S3

(32%), and the mountain is characterized by perennial streams and water bodies (Fig. S1). The annual precipitation was 854 mm, and the temperature ranged from – 16.4 °C (average of minimum values) to 33.7 °C (average of maximum values) (Data from Vrizes Meteorological Station, 1250 m: 2020–2022). It is a forested area (76% forest cover), dominated by coniferous forest, mainly of Greek fir forests (*Abies cephalonica*), with a small northeastern area featuring black pine (*Pinus nigra*), according to EUNIS typology [30]. Broadleaved forests comprise mainly deciduous oak forests (*Quercus* spp.). Mixed forests consist mostly of mixed oak and fir stands in the southern and western parts. Mountainous grasslands dominate at higher altitudes (16% cover) combined with rock and scree patches. Scrubs (5% cover) consist of thermophilous evergreen broadleaved species (*Quercus ilex*, *Pistacia lentiscus*, *Arbutus* spp., *Quercus coccifera*).

The Balkan chamois population increased from an estimated 10–30 individuals in the 1980s [31] to 65–80 individuals in 2016 and shows an increasing trend [16]. Other wild ungulate species in the area are the roe deer (*Capreolus capreolus*) and the wild boar (*Sus scrofa*). Chamois predators include the grey wolf (*Canis lupus*) and the golden eagle (*Aquila chrysaetos*). Brown bears (*Ursus arctos*) have also been reported in the area occasionally. Human activities in the study area include mountainous tourism, forestry, and free-ranging cattle and sheep/goat farming that usually takes place from late June to September (9,438 animals accounting for 0.09 Livestock Units per hectare in 2015) [32] (Table S1). Livestock grazing is considered mild in terms of stocking rates, as compared with the national average [33].

Over half of the study area (52%) falls within the borders of the Natura 2000 network of protected areas, encompassing three overlapping sites totalling 80.5 km^2 out of the 156 km^2 of the study area (Fig. S2) [34]. One of these sites (GR2440004) is Oiti National Park, including a strictly protected core area (34.7 km^2) that corresponds to the category II of IUCN (National Park) [35], where road construction and other developments, hunting, and logging are not allowed. Furthermore, one wildlife refuge (8.5 km^2) overlaps with the three Natura 2000 sites [34], where hunting is prohibited (category IV of IUCN: Habitat/species management area) [35] The Management Unit of Parnassos and Oiti National Parks and Protected Areas of Eastern Central Greece of the Natural Environment and Climate Change Agency (NECCA) manages the area. Forest management is undertaken by the Forest Service.

2.2 Chamois surveys

We surveyed five transects totaling 24 km in length in conjunction with seven vantage points across all four seasons in 2023, covering all major chamois habitats from 470 m to 2,120 m altitude (Fig. 1). Each seasonal survey was conducted during seven successive field days (spring: 27/4-3/5; summer: 27/6-3/7; autumn: 22/9-28/9; winter: 7/12-13/12). The four seasons reflected the key phases of the chamois' annual cycle [36]: spring (including parturition period, 10/03–09/06), summer (warm period, 10/06–09/09), autumn (10/09–09/12, including the rutting period that starts in November [22]), and winter (cold period, 10/12–09/03). Considering the visibility along the transects' line of sight, we effectively surveyed 17% of the study area (26.6 km^2) (Fig. S3). With the help of binoculars and a telescope, we collected chamois direct observations (animals) as well as indirect observations (pellets and tracks), and we georeferenced all observations (GPS device). In the case of a group, we recorded each individual separately. Pellets that were

not fresh, determined by their color and texture, were attributed to the previous season, and very old pellets were not recorded. Non-filtered occurrence datasets can lead to both geographic and environmental bias, resulting in the over-representation of environmental conditions associated with more heavily sampled areas [37]. To address this issue, we applied spatial thinning by overlaying a 25 × 25 m grid and retaining only one observation per grid cell, using the "spThin" package in R [38]. Spatial thinning reduces overfitting and improves model performance by minimizing spatial autocorrelation and sampling bias [39].

2.3 Data analysis

2.3.1 Environmental variables

We set up an environmental database of ten variables at a 25 × 25 m scale related to topography, main vegetation types, and human disturbance. We computed three topographic variables (elevation, slope, and terrain roughness) using a Digital Elevation Model (DEM) of 25 m resolution (Copernicus Land Monitoring Service, Version 3, 2021). For slope and roughness calculations, we used the "terrain" function of the package "terra" [40] in R. We considered three major vegetation types: forests (G1-G5), grasslands (E1, E2, E4, F2), and scrubs (F5) according to EUNIS typology [30] (Table S2). We calculated four parameters related to human disturbance. We used the road network (263 km) [41] to generate a GIS layer showing the distance to the nearest road (paved and unpaved) (Fig. S3). We also used the available database of livestock pens (50 pens) [32] (Fig. S3) provided by the local Management Unit of NECCA and the polygons of the hunting ban areas (data from geodata.gov.gr) (Fig. 1) to generate two GIS layers of distances to these two features. Furthermore, we mapped the escape terrain as steep ($>45^0$) and extended ($\geq 2{,}500\ m^2$) slopes [20] and we calculated the distance of the observations from it. We performed the distance calculations in ArcGIS Pro (version 3.1.0) using the "Distance accumulation" tool.

2.3.2 Annual and seasonal ranges

To determine the seasonal and annual ranges of the Balkan chamois on Mt. Oiti, we used the whole dataset of direct and indirect observations for the part of the study area surveyed, and employed Kernel Density Estimates (KDE) and the "adehabitatHR" package [42] in R, with the 95% fixed kernel estimation [43]. Additionally, we delineated the seasonal and annual core areas, defined as the zones with the highest spatial use intensity (i.e., areas where chamois are likely to spend the most time) [44]. We calculated the annual range and core area by merging the four seasonal ranges and core areas, respectively. Calculations of data treatment and analysis were performed using ArcGIS Pro (version 3.1.0) and R program (version 4.3.0) [45].

2.3.3 Habitat suitability model

We used the "sdm" package in R [46] to model the species' suitable habitat and deliver the respective habitat suitability map. Initially, we assessed multicollinearity among the variables using the Variance Inflation Factor (VIF) with the "vifstep" function (< 3) [47, 48]. The VIF is based on the square of the multiple correlation coefficient (R^2) resulting from regressing the predictor variable against all other predictor variables and is a more precise method than Pearson correlation [46]. Forests, slope, and distance to escape

terrain were found to exhibit collinearity with grasslands, roughness, and distance to hunting ban areas, respectively, and were excluded from the analysis.

Since we lacked true absence data, we adapted our presence-only database for use in a presence-pseudoabsence modeling framework by generating pseudoabsence points. To do so, we used the Random Forest (RF) modeling technique and a 1:1 ratio of presence to pseudoabsence points, as recommended for RF models in ecological applications [49] and allocated 30% of the data as test data for model validation. We used two evaluation metrics to assess model performance: Area Under the Curve (AUC) and True Skill Statistic (TSS). AUC evaluates the ability of the model to distinguish between presence and absence points, with values ranging from 0.5 (random prediction) to 1 (perfect prediction), and is a widely used metric for model evaluation in ecological studies [50]. TSS accounts for both sensitivity (true positive rate) and specificity (true negative rate), with values ranging from − 1 to 1, with 1 indicating perfect agreement and values ≤ 0 suggesting performance no better than random [51]. We then combined the outputs of all RF models to create an ensemble prediction ("ensemble" function) that integrates multiple models, thereby capturing a broader range of projections and generating more reliable habitat suitability forecasts [52]. We evaluated the relative importance of the variables included in the model using the Pearson correlation and AUC metrics. Person correlation highlights the direct linear contribution of each variable to the model [53], and the AUC captures the overall contribution of variables to the model [54], including nonlinear effects and interactions. We adopted this dual approach to ensure a more comprehensive evaluation of predictor importance by integrating complementary aspects of variable effects. Furthermore, we defined suitable areas as those with predicted suitability values greater than the mean suitability across training data [55].

2.3.4 Seasonal habitat preferences

We calculated the average value of environmental variables in chamois occurrence points for each season and annually (habitat used). We then produced 652 random points (1:1 ratio of presences vs background points) in ArcGIS Pro and estimated their average values in the study area (available habitat). Using the non-parametric Kruskal- Wallis H-test, we investigated whether environmental variables varied significantly throughout the four seasons. We compared the annual environmental variables between the observed and random datasets (used *vs* available habitat) in terms of the Mann–Whitney U test ($p < 0.05$).

2.3.5 Renewable energy plans

We considered the database of the National Regulatory Authority for Energy (RAE) for all renewable energy infrastructure in the study area [23]. We then considered the total area of the three wind power station polygons planned in the study area and calculated their per cent overlap with the annual range found, with the species' suitable habitat (suitability values greater than the mean suitability across training data), as well as with protected areas cover.

3 Results

The dataset included 652 observations of the Balkan chamois on Mt. Oiti, comprising 63 direct observations of animals (9.7%), 541 observations of pellets (83%), and 48 tracks (7.3%) (Table S3). After observation thinning 121 chamois occurrences remained and were used for the analysis.

3.1 Annual and seasonal ranges

The minimum estimated annual range of the Balkan chamois on Mt. Oiti encompassed an area of 50 km^2 and the annual core area accounted for one-third of it (34.8%). The seasonal ranges and their respective core areas for the part of the mountain surveyed exhibited limited size variation and a great spatial overlap (74–90% and 65–87%, respectively) (Table 1, Fig. S4).

3.2 Habitat suitability model

The analysis encompassed seven variables. RF models demonstrated high performance, with an AUC value of 0.96 and a TSS value of 0.85. The top three variables contributing most to the model were associated with human disturbance: distance to livestock pens, hunting ban areas, and roads, followed by elevation. The remaining variables, namely terrain roughness, scrubland, and grassland cover, had lower contributions to the predictive habitat suitability model (Table 2). According to the habitat suitability map (Fig. 2), suitable habitat areas (values above 0.6 or 60%) covered 12.2 km^2, accounting for 7.8% of the study area (Fig. 3). A considerable part of the species suitable habitat (27.9%, 3.4 km^2) fell outside the Natura 2000 network.

3.3 Seasonal habitat preferences

We found no statistically significant seasonal differences for any environmental variables analyzed (Kruskal–Wallis test, $p > 0.05$). All variables except for three (slope, roughness, and forest cover) significantly differed between observation points and the 1,000 random points in the study area (U tests, $p < 0.05$).

The species preferred higher elevation areas and grasslands and avoided scrublands (Table 2). All human-disturbance variables were significantly different in the points of chamois occurrence than random points in the study area. The species preferred areas away from livestock pens, roads, and areas closer to hunting ban areas and escape terrain. However, the latter was only 0.45 km^2, accounting for less than 1% of the study area.

3.4 Renewable energy plans

The renewable energy plans in the study area include three wind power stations that are currently under a production licensing stage, with a total capacity of 81.6 MW (16 wind

Table 1 Annual and seasonal ranges and respective core areas of the Balkan chamois on Mt. Oiti (2023) and their overlap (core areas overlap in parentheses) for the part of the mountain surveyed

Season	Range (km^2)	Core area (km^2)	Core area proportion (%)	Overlap (%) of ranges (core areas)			
				Spring	Summer	Autumn	Winter
Spring	32.9	12.2	37	100	74(75)	74(79)	90(69)
Summer	31.5	11.3	35.9	–	100	85(87)	75(65)
Autumn	36.9	13.6	36.9	–	–	100	77(65)
Winter	36.6	10.7	29.2	–	–	–	100
Annual	50	17.4	34.8	–	–	–	–

Table 2 Chamois habitat preference: Average values (or frequency percentages) of variables at chamois observation points across seasons and annually compared to 652 random points (R) throughout the study area (Mann–Whitney test, p-values), and variable contribution to the habitat suitability model after Pearson correlation coefficient (P) and Area Under Curve (AUC) criterion

Variable	Seasons				Habitat preference			Contribution to the model	
	Spring	Summer	Autumn	Winter	Annual	R	p	P	AUC
Elevation (m)	1,568 (±376)	1,709 (±446)	1,791 (±315)	1,780 (±236)	1,668 (±365)	1,391 (±487)	*	14.9	12.8
Slope (degrees)	18.2 (±9.7)	14.9 (±6.4)	18.7 (±9)	20.8 (±9.3)	18.4 (±9.3)	17.4 (±8.7)	ns		
Roughness	28.1 (±15.6)	23.2 (±10.9)	28.1 (±14.3)	32.6 (±14.2)	28.5 (±14.8)	26.8 (±15)	ns	2.3	1.7
Forests (%)	92	50	48	83	78	75	ns		
Grasslands (%)	8	50	52	17	22	17	*	1.6	0.8
Scrubs (%)	0	0	0	0	0	4	*	0	0
Distance to roads (m)	548 (±292)	364 (±347)	474 (±422)	618 (±300)	529 (±331)	370 (±330)	*	11.3	7.1
Distance to pens (m)	2,021 (±618)	2,028 (±338)	1,984 (±413)	2,064 (±604)	2,027 (±558)	1,181 (±636)	*	25.4	17.5
Distance to hunting ban areas (m)	353 (±1,031)	71 (±274)	242 (±762)	409 (±1,073)	311 (±942)	1,594 (±1,824)	*	9.8	4.3
Distance to escape terrain (m)	1,973 (±1,948)	1,786 (±1,450)	2,150 (±1,959)	2,568 (±1,898)	2,111 (±1,890)	3,664 (±3,078)	*		

ns: non-significant ($p > 0.05$). *: $p < 0.05$

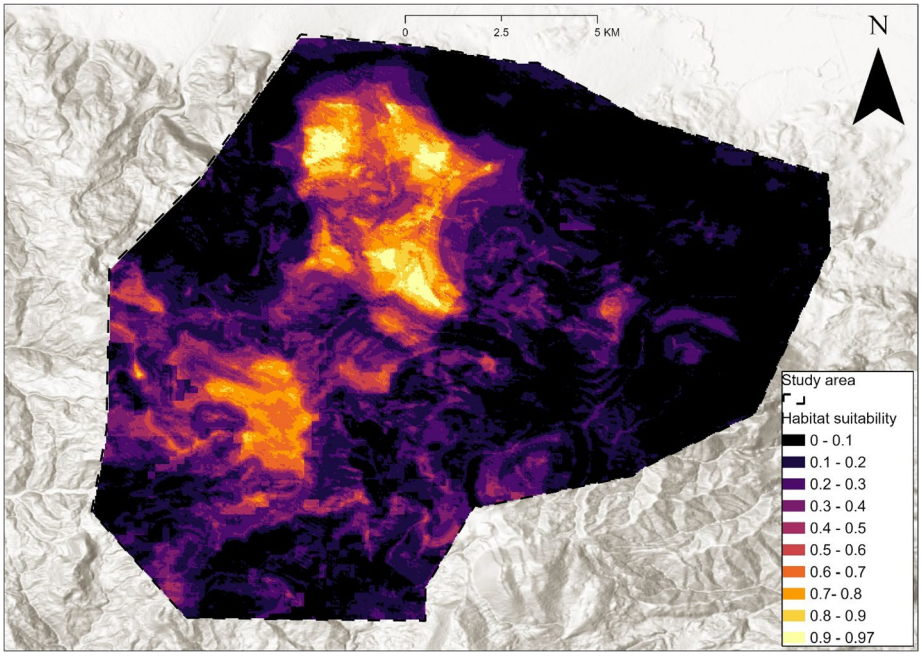


Fig. 2 Habitat suitability map of the Balkan chamois on Mt. Oiti, presented in a ten-scale gradient (10% interval)

turbines of 15.6–34.8 MW each, pylon height of 84–101 m and rotor diameter 131–158 m) and nine small hydroelectric stations (0.48–0.95 MW) totaling 5.6 MW (Table S4). Wind power stations polygons are located outside the borders of Oiti National Park and Natura 2000 network (Fig. 3). The area of the wind power stations' polygons covers

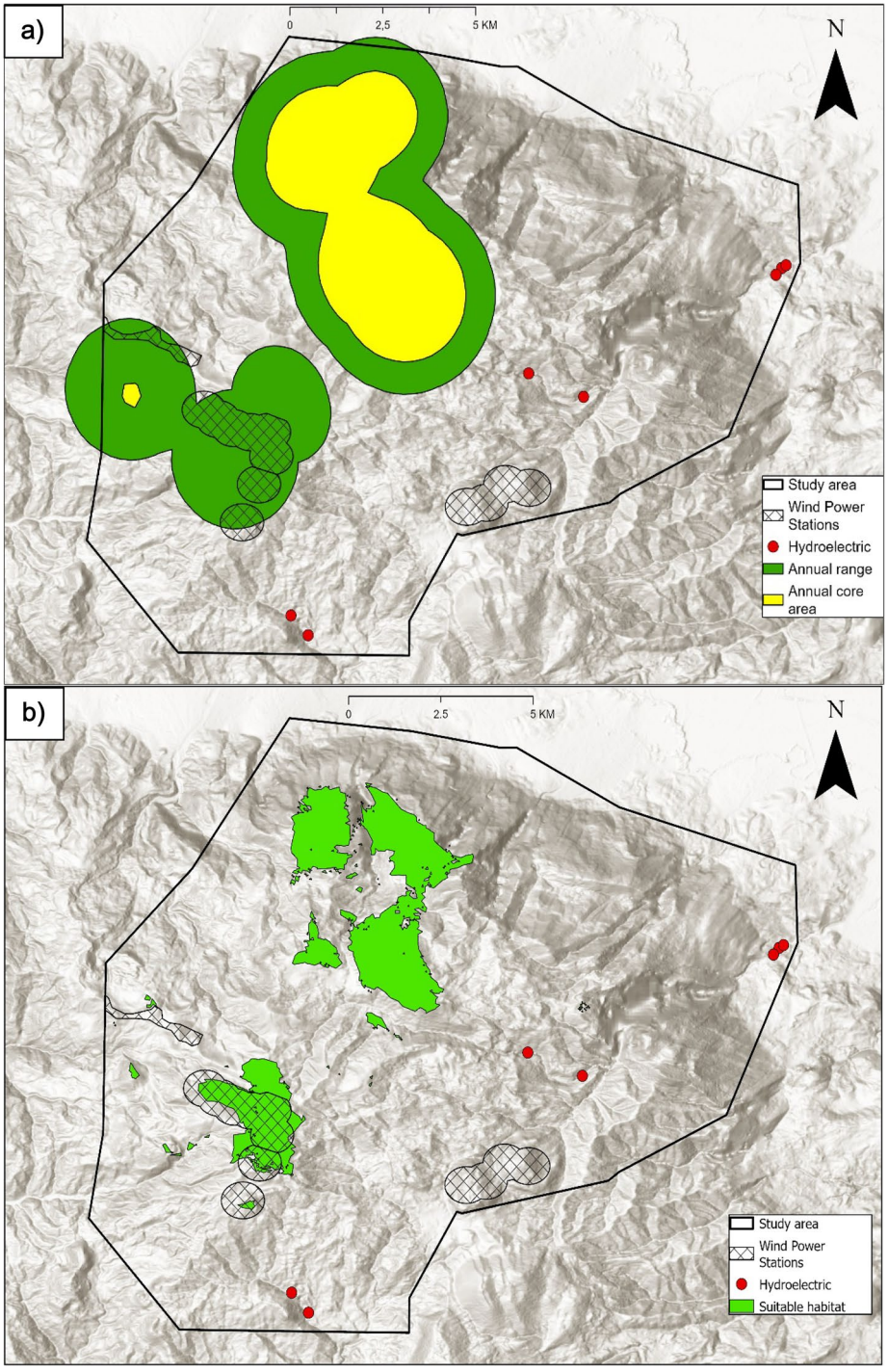


Fig. 3 Planned wind power and small hydroelectric stations on Mt. Oiti across (**a**) the annual range and core area of the species found and (**b**) suitable chamois habitat (values over 0.6)

6.2 km^2, out of which 61% falls within the annual range of the species found (3.8 km^2) and 33.9% (2.1 km^2) overlaps with chamois suitable (habitat suitability values over 0.6) (Fig. 3). If they get permission to be constructed, 17.2% (2.1 km^2) of the suitable habitat will be lost on Mt. Oiti. None of the nine hydroelectric stations planned coincide with the current annual range or the suitable habitat of the species. Seven are included in the Natura 2000 network (two of them in Oiti National Park) (Table S4).

4 Discussion

4.1 Methodological insights

Spatial ecology studies employing GPS telemetry data provide highly reliable results for habitat modelling and distribution ranges [56]. Without such high-cost equipment, the current research employed field surveys that involved extensive fieldwork. However, two challenges arose: forest cover limited visibility along transects, allowing 17% of the study area to be scanned, and inaccessible terrains due to steep topography, such as areas near the Gorgopotamos Gorge in the eastern part of the mountain, could not be surveyed. Therefore, the annual range is not representative of the whole study area. Our study provided a first insight into seasonal ranges and their core areas of intense use at the population level. Future studies should focus on the movement ecology of chamois at the individual level using GPS-tagged animals to deliver individual home ranges, potentially overcoming the accessibility problem. Such studies could reveal an expanded annual range on Mt. Oiti, as well. The study also delivered a habitat suitability model of adequate performance and allowed us to reliably pinpoint the human factors negatively affecting the chamois habitat use. Other variables, such as solar radiation or exposition were not considered in the modeling process due to scale or data limitation issues, but the latter has been reported not to have a significant effect on habitat use or to be interpreted by other topographic variables, such as the proximity to escape terrain [19, 21]. Further research is recommended to delineate the suitable habitat of the Balkan chamois across the Greek mountains and broader spatial scales and pinpoint the common drivers that shape it.

4.2 Annual and seasonal ranges

Considering as a study area the species range reported in the IUCN red list of threatened species [14], we found that the annual range of the Balkan chamois population on Mt. Oiti covered at least one-third of it (Fig. 2). Chamois may also inhabit other parts of the mountains, given fieldwork limitations and the presence of suitable habitats beyond the annual range (Fig. 3). In any case, the annual range is dynamic and may shift over time due to changing human disturbance regimes and the species growing population at local and national scales, which gradually results in colonization of new suitable habitats [16].

We found minor range size variation across seasons and a high spatial seasonal range overlap (74–90%) (Table 1), implying greater habitat fidelity and limited seasonal movements from lower forested zones in winter to higher altitudes grasslands in summer and autumn (Table 2). Likewise, the species on Mt. Oiti does not seem to follow any of the two seasonal distribution patterns reported in Europe or face significant climatic stress. In cooler climates, chamois usually search for adequate microhabitats providing shelter from extreme weather conditions and offering food resources of higher forage quality, resulting in a restricted winter range, according to the "Continental" pattern [21, 57–59]. In warmer climates, the Balkan chamois seems to retreat to cooler microhabitats that still hold fresh palatable food resources during the arid summer period, justifying the restricted summer range of the "Mediterranean" pattern. This pattern is reported for two populations in Greece, inhabiting the arid mountains of Giona and Olympus [19, 20], but not for the more humid mountain of Timfi in northern Greece, where the species adopts the continental pattern [21]. Although Mt. Oiti is in the southern part of the species distribution, having similar low precipitation rates to the neighboring mountain of

Giona, the population doesn't seem to experience aridity stress. Animals inhabit forested areas throughout the year, benefiting from the extended forests, allowing thermoregulation and providing shelter from extreme temperatures as well as food resources [60], while also benefiting from the mild winter conditions, and the permanent water availability in streams and water bodies year-round.

4.3 Habitat and human disturbance

We found that Mt. Oiti holds extended suitable habitats for the Balkan chamois and that the three top limiting factors shaping the suitable habitats were related to human disturbance. Most reported threats for all chamois species are indeed human-induced, including poaching, overharvesting, habitat loss and degradation, livestock grazing and related disease transmission, and disturbance from human developments, tourism and recreational activities [61]. According to the national action plan [16], all these threats also apply to the Balkan chamois in Greece, except for overharvesting as chamois hunting is banned, along with specific threats such as road construction, mining, genetic isolation, global warming, and hunting disturbance.

The most influential limiting variable was the distance to the nearest livestock pen; chamois exhibited a significant avoidance pattern away from them. Livestock presence can increase hormonal stress in chamois [62]. Livestock avoidance strategy is often a stronger driver than climate change in spatiotemporal behavioral shifts away from suitable habitats and high-quality food resources [63]. Besides competition for food resources, livestock presence is associated with disturbance from shepherds' presence and their dogs [64]. Livestock presence occurs seasonally on Mt. Oiti, from late June to September, but coincides with the warm period that chamois occupies high-altitude grasslands. In the absence of livestock activity disturbance and interspecific competition with livestock, it is possible that chamois could use more intensively the mountainous grasslands at higher elevations and present less forest-dependent behavior. Although no infected animals were observed during our surveys, we underline that livestock presence can increase the risks for disease transmission [65], which can have substantial impacts on chamois populations [66].

We also found a clear preference for chamois to be away from hunting grounds and roads, both related to human disturbance and substantially contributing to the habitat suitability model. Human disturbance does not necessarily relate to human presence per se, as the animals on another mountain (Mt. Olympus) do not avoid hikers, but rather prefer to be near hiking trails [20]. It seems to be more closely linked to the presence of anthropogenic landscapes of fear, generated by legal and illegal hunting activities that involve shotguns use and hunting dogs. For this reason, the species also showed a preference to be near escape terrains, although limited in our study area in extent, to find protection from predators and disturbance [22]. Therefore, the role of hunting and poaching in the chamois habitat selection process seems to be substantial on Mt. Oiti, as well as other mountains of the country [21]. Such disturbance is further intensified by forest roads, providing greater public access to chamois habitats, and intensifying hunting and poaching activity. The strong road avoidance pattern of the chamois population on Mt. Oiti appears widespread in Greece and is reported for other populations as well [20, 21].

Three other environmental factors significantly influence chamois habitat suitability. Given the mountainous character of the species [22], animals exhibited a preference for

higher altitudes, even though their altitudinal range of seasonal migration was limited. Chamois also favored grasslands and avoided scrublands, as also found on Mt. Timfi [21]. Grasslands offer high forage quality [67] but they are not so extensively used on Mt. Oiti as they could, due to habitat use shifts from livestock presence in the warm period, or the high forage quality inside forests, enhancing the forest-dwelling character of the population.

4.4 Renewable energy plans

Our analysis indicated that the proposed wind power station plans overlap substantially with the most suitable chamois habitat on Mt. Oiti. Habitat loss is a major threat to the Balkan chamois throughout its range [61]. Located at high-altitude grasslands (1600–2128 m), the projects are expected to pose significant threats to the local chamois population, primarily through the reduction of grazing grounds, and overall habitat loss and fragmentation. The species might exhibit a range shift away from wind turbines in the study area, probably finding shelter in the most inaccessible forest zones, given its high sensitivity to human disturbance and the adverse wind turbine effects reported for other forest-dwelling ungulates [68]. While some ungulate studies indicate that wind energy development does not increase mortality risk [69] and does not significantly affect nutrition and home ranges [70], other studies document elevated stress near large wind farms [71], strong avoidance patterns and changes in the use of movement corridors [72, 73] and even range shifts several kilometers away, outside the visibility zone of wind turbines [74]. The adverse effects are associated with both the construction and operation phases of wind turbines [73, 74].

The impact of wind energy infrastructure extends beyond habitat loss within the investment polygons (2.1 km^2), where turbines are going to be installed on cement bases. The actual land footprint is larger when accounting for other required infrastructures (transmission lines and electricity pylons, meteorological towers, operation buildings, and new and widened access roads) and the subsequent vegetation clearance required across access roads that would directly impact chamois forest habitats. In Greece, the wind industry causes a 3.5 times higher conversion of natural to artificial land than the global average, due to the tendency to plant wind turbines in remote natural areas with steeper slopes away from existing infrastructures, with access roads being an important land consumer in this process [75]. Furthermore, the whole study area exhibits high naturalness and low fragmentation, qualifying it as a wind farm-free zone in a national-scale study for sustainable wind energy planning, excluding such natural areas from wind energy investments without undermining the 2030 national energy goals achievement [29]. On the other hand, none of the nine small hydroelectric stations planned fall within chamois suitable habitats. Their impact seems minor but remains uncertain. It is not known whether the stations will affect water availability for wildlife in mountain streams and waterbodies, or the extent of land take expected from road sprawl and infrastructures required.

4.5 Conservation implications

Our findings provide strong scientific evidence informing policymaking and conservation actions at local and broad scales as follows: first, we recommend preserving the natural integrity of the study area by preventing land take and habitat fragmentation.

This includes discouraging large-scale renewable energy projects, other land-consuming developments, and associated road expansion, given their expected negative impact on the chamois population. These measures are expected to broadly benefit the biodiversity of Mt. Oiti, including endemic and globally threatened insect species that inhabit mountainous grasslands, including the area of planned wind energy investments [76]. At a broader scale, we advocate for bold policies to protect landscape naturalness and prevent further ecosystem fragmentation from roads and artificial land development. A roadless policy has already been implemented in Greece offering a strict but provisional protection status in nine remote mountains of great naturalness [77, 78], benefiting four chamois populations there. The government aspires to protect 55 mountains under target 15.4 of the Sustainable Development Goals for mountainous ecosystem maintenance [79, 80]. These measures are in line with the national action plan suggesting roadless areas expansion and modification of major construction projects through alternative solutions in the species distribution range [16].

Second, we recommend poaching mitigation measures and the expansion of wildlife refuges to increase the quiet, hunting-free areas that were found to be preferred by chamois. On a broader scale, the national legislation freely allows hunting all over the countryside (with few exceptions), including the protected areas of the Natura 2000 network or private lands when not fenced, as hunting grounds. An accurate national mapping of hunting grounds is missing. Less than 10% of the country is declared a hunting-ban zone for wildlife conservation, covering about 40% of the Balkan chamois' distribution nationwide [21], and proving their importance as chamois shelters. Besides hunting-ban areas expansion, we emphasize the need for overall spatial hunting planning, including mapping the hunting grounds, regulating hunting intensity, and implementing government-led monitoring, accounting for chamois and other protected wildlife species needs. This would reduce human-induced "landscapes of fear" and would benefit chamois populations on Mt. Oiti and nationwide.

Third, we suggest drafting and implementing sustainable livestock grazing plans accounting for biodiversity maintenance and chamois needs. Although chamois may benefit from intraspecific competition mitigation, it is still uncertain how the grassland ecosystems and biodiversity will be affected in the long term, since livestock grazing is mild on the mountain and might decrease in the future. Mapping the mountainous pastures of Mt. Oiti, their grazing capacity, livestock stocking density and temporal use, while monitoring the livestock grazing activity on an annual basis is a prerequisite to planning and implementing sustainable grazing schemes favoring both grassland ecosystems, wildlife, and the local economy, in line with the suggestions of the action plan [16].

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44353-025-00050-2.

Supplementary file 1.

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Author contributions
K.P. and V.K. conceived the study, wrote the first draft of the paper and secured funding; K.P. gathered the data and conducted data analysis. V.K. provided resources and supervision. All authors developed the methodology and reviewed and edited the manuscript.

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Data availability
The datasets generated and analysed during the current study are not publicly available due to the sensitive nature of the data following the species' strict protection status under national legislation but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Relevant permission
Fieldwork on Mt. Oiti was conducted under research permission by the Ministry of the Environment and Energy (ΥΠΕΝ/ΔΔΔ/20036/756, date: 28/03/2022).

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