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Patterns of brown bear damages to agro-livestock activities in North-Eastern Italy across 15 years

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Livestock predations along with damages to croplands and beehives, are some of the main drivers of human-bear conflicts in shared landscapes. In the North-Eastern Italian Alps, the only brown bear *Ursus arctos* breeding population persists in the Autonomous Province of Trento, reintroduced via the LIFE *Ursus* program (1999–2004), while in Friuli Venezia Giulia (FVG) few dispersing males are detected annually. Both areas report damages mainly to agro-livestock activities near human settlements. This study aimed to: (i) describe bear-related damages to livestock (sum of preyed, injured, and missing individuals), agriculture, beehives, and structures using 15 years of claims data; (ii) assess temporal trends in damages near human settlements; and (iii) evaluate the spatial expansion of damages. We analysed official compensation claims from 2009 to 2023 in the Autonomous Province of Trento and FVG. Generalized Additive Models assessed proximity trends, while spatial expansion was analysed using 5 × 5 km grid-based hotspot analysis. Findings revealed that livestock and structural damages occurred significantly closer to human settlements across years; but a significant spatial expansion of damages was observed only in the Autonomous Province of Trento. Results highlight the need for effective prevention to reduce conflicts and support human-bear coexistence.

Keywords Agriculture, Beehives, Livestock, Grazing practices, Human-bear conflict, Human-carnivore coexistence

Where humans and large carnivores (henceforward, carnivores) share the same habitats, the real or perceived threat posed by predators to human safety and economic security may lead to negative attitudes among local communities towards these species[1–3]. This, in turn, may jeopardize the long-term survival of carnivore populations and the preservation of traditional human practices[4], particularly in regions where such practices represent the primary source of livelihood for local people[5–7]. Extensive agro-livestock activities, particularly in mountainous areas, provide essential ecosystem services to humans, including carbon sequestration, nutrient recycling, food production, and biodiversity and landscape preservation[8–10]. Similarly, in certain contexts, carnivores contribute to ecosystem services by offering public health benefits[11], controlling the presence of invasive alien species[12], and regulating the abundance and distribution of species at lower trophic levels through top-down ecological effects, thereby enhancing ecosystem stability[13]. Given the ecological and cultural significance of both carnivores and traditional human practices, fostering coexistence is a critical conservation and management priority.

Ursids, felids, and canids are frequently involved in negative interactions with humans[14–16]. However, compared to conflicts involving felids and canids, human-bear conflicts (HBCs) have received less attention, especially in Europe[14]. As a consequence of state-sponsored extermination campaigns and overhunting[17–19], the brown bear *Ursus arctos* (henceforward, bear) experienced a dramatic population decline in the past. Additionally, increasing habitat loss and fragmentation due to human settlement expansion, road construction, and forest exploitation have further reduced suitable wilderness habitats for bears. This, in turn, has brought the species into closer contact with humans, leading to the emergence of HBCs[20–23]. In recent years, thanks to conservation efforts, the bear has begun recolonising its former distribution range in many European countries[24]. However, in shared landscapes, conflicts with humans arise due to livestock predations, as well as damages to agriculture and beehives[25,26], which, in turn, generate resentment among livestock farmers[1,3,14].

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In the North-Eastern Italian Alps (and more broadly across the entire Italian Alpine range) the only extant and reproducing bear population is located in the Autonomous Province of Trento[25,27]. This population was re-established through a translocation program carried out between 1999 and 2004, supported by the European Union via LIFE Nature funding (LIFE *Ursus*) in collaboration with the Autonomous Province of Trento and the Institute for Environmental Protection and Research (ISPRA). The project aimed to prevent the extinction of the few remaining bears and restore a minimum viable population of 40–60 individuals within a few decades. To achieve this goal, between 1999 and 2002, ten bears (seven females and three males) were translocated from Slovenia to the 'Adamello Brenta' Natural Park and surrounding areas, as the Slovenian population was genetically similar to that of Trentino[25,27,28]. Conservation efforts have been highly successful, and the current population is estimated to range between 86 and 120 individuals[29]. Conversely, in the Friuli Venezia Giulia (henceforward, FVG) Region, between one and seven bears (exclusively males dispersing from the Autonomous Province of Trento and/or the Dinaric-Balkan-Pindos population) are genetically identified each year[30,31]. However, only a few of these individuals have shown stationary behaviour and have been re-sampled over multiple years. In this area, no reproductive events have been recorded after 1988. Therefore, the population cannot be considered viable[27]. As for the Veneto Region, a limited influx of individuals originating from Trentino and/or FVG has been observed over the years, but no stable presence has been recorded to date.

At the European level, the bear is included in Annex II of the Bern Convention (1979), which classifies the species among the "Strictly Protected Species". Conversely, under the 'Habitat' Directive (92/43/CEE), it is listed in Annexes II and IV, which include species of Community Interest requiring, respectively, the designation of Special Areas of Conservation and Strict Protection[27]. In Italy, the species is protected under National Law 157/92, and the Interregional Action Plan for the Conservation of the Brown Bear in the Central-Eastern Alps (PACOBACE) establishes criteria for assessing the hazard level posed by individual bears, based on which the selective removal of problematic individuals may be considered[27]. Since the inception of the LIFE *Ursus* project, the Forest and Wildlife Service of the Autonomous Province of Trento has been actively engaged in implementing prevention and mitigation measures to reduce bear-related impacts on human activities. Their efforts also include emergency management (i.e., problematic individuals) and educational initiatives designed to promote safe human-bear coexistence[29,32,33]. After a fatal attack on a runner in 2023, the Autonomous Province of Trento approved a draft law in 2024 establishing that the maximum number of problematic individuals (as defined by PACOBACE) allowed for culling will be determined annually based on the species' demographic growth. This growth is continuously monitored across years through field-based activities (e.g., camera-trapping) and/or genetic analyses. This decision will be based on technical and scientific assessments and will require approval from ISPRA. The purpose of this draft law is to reduce the risk of negative interactions with humans and/or human activities.

The presence of bears in the North-Eastern Italian Alps has been gaining increasing attention from conservation, socio-economic, and political perspectives. Research aimed at identifying the main factors driving HBCs is thus crucial to elaborate effective prevention and mitigation interventions. This study aimed to: (i) characterize bear-related damages to human activities (i.e., livestock husbandry, agriculture, beekeeping) and related structures using 15 years of official claims data, (ii) assess whether, over time, the frequency of bear damages near human settlements has increased, and (iii) identify conflict hotspot and cold spot areas. Given the continuous expansion of the bear range over the years, especially in the Autonomous Province of Trento, we expected to observe a corresponding increase in bear-related damages in close proximity to urban areas over time. Moreover, since the bear population is more established in the Autonomous Province of Trento than in the FVG Region, we also expected to detect more conflict hotspot areas in the former than in the latter.

Results

Overall bear population trend

From 2009 to 2023, the bear population significantly increased ($p < 0.001$), with an estimated proportional annual increase of 10.9% (Fig. 1). However, no significant association was found between increasing bear population and overall number of damages, except for structural damages (Fig. 1).

Overall bear damages to agro-livestock activities according to study area and seasonal period

The trend of bear-related damages to agro-livestock activities (including livestock, agriculture, beehives) and related structures along with the corresponding post-damage compensation payments (Euros - €) recorded in the FVG Region and the Autonomous Province of Trento during the study period (2009–2023) is reported in Fig. 2. As for post-damage compensation payments, the lack of data recorded for 2020 in the Autonomous Province of Trento (Fig. 2) is likely attributable to factors such as unclaimed damage events or, more plausibly, the COVID-19 outbreak. In fact, although some farmers may refrain from submitting compensation claims due to the complex bureaucracy involved in the process[3], it is likely that the significant reduction in movements during the pandemic also played a role.

As for damages on livestock, the overall number of preyed, injured, and missing individuals divided by seasons and livestock category was summarized in Table 1.

With regards to damages to crops, during spring and summer, $n = 463$ bear damages to agricultural crops were registered: $n = 451$ (97.4%) on single crops, while $n = 12$ (2.6%) simultaneously on more crops. Conversely, during autumn and winter, $n = 141$ bear damages to agricultural crops were registered: $n = 133$ (94.3%) on single crops, while $n = 8$ (5.7%) simultaneously on more crops. The seasonal number of bear damages per crop (damages involving multiple crops were separated by individual crop) is summarized in Table 2.

The G-test revealed a significant difference in terms of agricultural habitat use during spring/summer ($G = 1486.5$, $p < 0.001$) and autumn/winter ($G = 320.7$, $p < 0.001$). Specifically, during spring and summer, bears

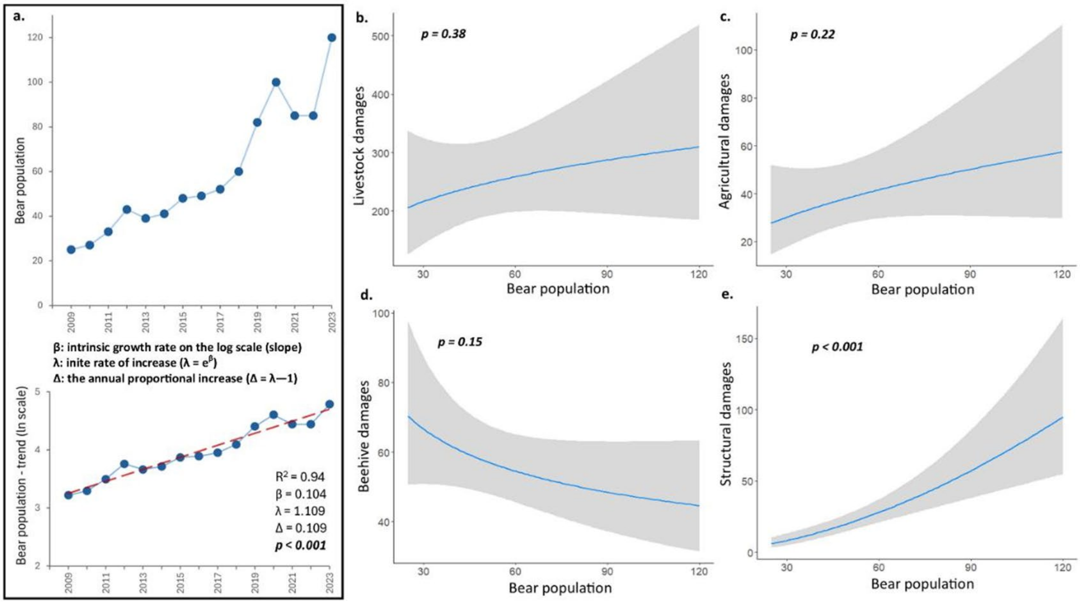

Fig. 1. Trend of bear population as function of years (2009–2023 - **a**), and trends of livestock damages (sum of preyed, injured, and missing individuals) (**b**), agricultural damages (**c**), beehive damages (**d**) and structural damages (**e**) as function of bear population. The grey area represents the confidence interval (95%). For details about the models, see Table S.1–2.

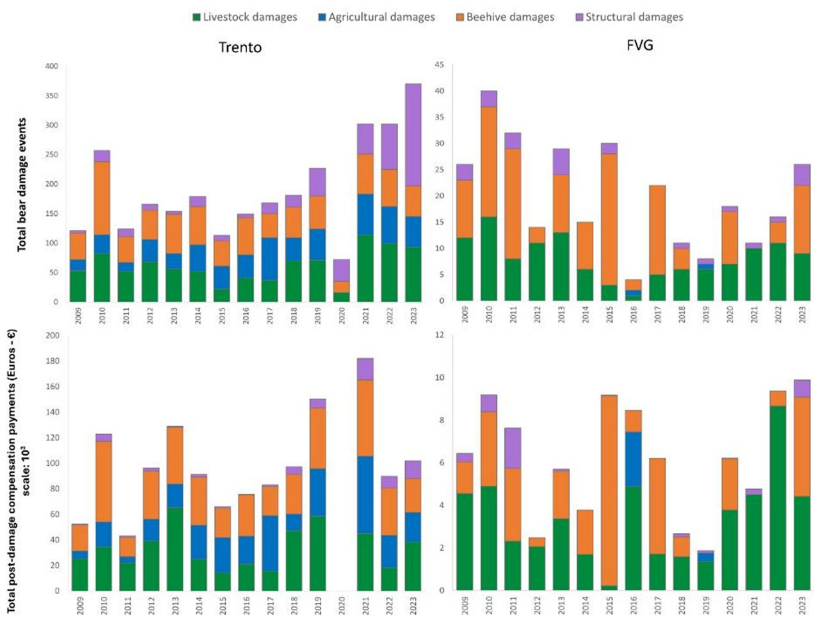

Fig. 2. Bear damages to livestock (sum of preyed, injured, and missing individuals), agriculture, beehives, and structures as well as corresponding post-damage compensation payments (Euros - €) across the study areas during the period 2009–2023. Abbreviations: FVG = Friuli Venezia Giulia.

showed selection for vineyards ($D = 0.97$) and orchards ($D = 0.51$), while underuse of croplands ($D = -0.80$) (Fig. 3a). With regards to autumn and winter, bears showed selection for vineyards ($D = 0.98$) and underuse of croplands ($D = -0.38$). Conversely, orchards were used according to their availability ($D = 0.29$) (Fig. 3b).

As for beehive damages, $n = 874$ (87.0%) damages were registered during spring and summer, while $n = 131$ (13.0%) during autumn and winter. For what concerns structural damages, $n = 353$ (66.4%) damages were recorded during spring and summer, while $n = 179$ (33.6%) during autumn and winter.

The number of damage events significantly increased ($p < 0.001$; Table S.3) during the spring and summer seasons across all categories. This effect was less pronounced for structural damages (Fig. 3a) and most

Seasons	Affected domestic category	*n*	%
Spring/Summer	Camelid	2	0.1
	Canid	1	0.03
	Cattle	97	2.8
	Cervid	5	0.1
	Equine	110	3.1
	Small-sized species	2,213	62.8
	Sheep and goat	1,089	30.9
	Swine	7	0.2
Total		3,524	100
Autumn/Winter	Camelid	4	0.6
	Canid	1	0.2
	Cattle	13	2.0
	Cervid	0	0.0
	Equine	15	2.4
	Small-sized species	368	58.0
	Sheep and goat	234	36.9
	Swine	0	0.0
Total		635	100

Table 1. Livestock damages (sum of preyed, injured, and missing individuals) by bears divided by seasons and affected domestic category. Small-sized species includes poultry, rabbits, and fish.

pronounced for beehive damages (Fig. 4a). During the spring and summer seasons, this increase was significantly and positively related with the year ($p < 0.05$; Fig. 4a), whereas no significant variation was observed during the autumn and winter seasons (Fig. 4a). Notably, the number of livestock and structural damages significantly increased ($p < 0.05$; Fig. 4b) over the years, with a particularly sharp rise from 2018 onwards.

The number of livestock damages increased significantly during spring and summer (autumn/winter: 5–24; spring/summer: 30–111; $p < 0.01$), reflecting the trend of events. The number of damages during spring and summer also showed a significant positive increase over the years ($p < 0.01$; Fig. 5a). This increase was particularly pronounced for the 'sheep and goats' category (autumn/winter range: 6–16; spring/summer range: 31–66) and the 'small-sized species' category (autumn/winter range: 4–17; spring/summer range: 37–117), which also accounted for the highest number of damages (sheep and goats range: 31–66; small-sized species range: 37–117; $p < 0.001$; Fig. 5a). Conversely, cattle and equids experienced the lowest and similar levels of damages (equids: 4–9; cattle: 5–15; Fig. 5a). Among the categories, only the 'small-sized species' category displayed a significant increase in damages over the years, with a notable surge starting in 2018 ($p < 0.01$; Fig. 5b).

The occurrence of bear damages within urban areas accounted for 4% of the total events ($n = 130$ out of 3,180), with variations observed across damage categories and seasons. Structural damages were the most frequent within urban areas ($n = 49$, 38%), with a notable increase during spring and summer ($n = 41$, 84%) compared to autumn and winter ($n = 8$, 16%). Damages on beehives and livestock occurred at similar frequencies within urban areas with, respectively, $n = 34$ (26%) and $n = 39$ cases (30%), distributed across the two seasonal periods, i.e., beehive damages: $n = 3$ (8.8%) in autumn and winter, $n = 31$ (91.2%) in spring and summer; livestock damages: $n = 4$ (10.3%) in autumn and winter, $n = 35$ (89.7%) in spring and summer. Conversely, agricultural damages showed the lowest occurrence within urban areas, with only $n = 8$ cases (6%), and revealing a minimal variation between seasons, i.e., spring/summer: $n = 6$ (75%); autumn/winter: $n = 2$ (25%).

The single categories of damages showed significant differences in terms of minimum distances from urban areas ($p < 0.001$ - Fig. 6a), where structural damages were the most distant ranging between 1.9 and 2.5 km, followed by livestock with a range between 1.7 and 2.2 km, and agricultural damages with a range between 1.7 and 2.0 km. Conversely, beehive damages were the closest to urban areas ranging between 1.5 and 1.9 km (Fig. 6a). Both livestock and structural damages showed significant variations across years, i.e., livestock: $p < 0.001$; structural: $p < 0.01$, where the latter significantly decreased from 2020 (Fig. 6b). No significant differences ($p = 0.12$) were instead detected between seasons and across years, although both livestock and beehive damage distances from urban areas tended to decrease during autumn and winter (Fig. 6a).

Bear damages experienced a significant range of expansion, increasing from $n = 73$ (31.3%) to $n = 141$ (60.5%) grid cells out of the $n = 233$ cells considered during the research period. This expansion varied yearly depending on damaged category and seasons, reflecting trends in grid cell usage (Fig. 7). Among damaged categories, structural damages involved the fewest grid cells per year and significantly differed from the other categories, i.e., agricultural damages range: 6–8; livestock damages range: 5–8; beehive damages range: 5–7; structural damages range: 3–5 ($p < 0.001$; Fig. 7a). The area of grid cells with almost one damage event was significantly larger during spring and summer than during autumn and winter (range of cells with almost one damage event: autumn/winter 5–7; spring/summer 27–33; $p < 0.001$), with no significant differences observed across years. During autumn and winter, the lowest numbers of used grid cells were consistent across type of damages, with both livestock (range of cells with almost one damage event: autumn/winter 5–8; spring/summer 18–26) and beehive

Seasons	Crop category	Crop type	*n*	%
Spring/Summer	Vineyard	Grape	117	24.4
	Orchard	Apple	37	7.7
		Apricot	10	2.1
		Cherry	189	39.5
		Chestnut	0	0.0
		Medlar	1	0.2
		Nut	3	0.6
		Peach	15	3.1
		Pear	9	1.9
		Plum	54	11.3
		Strawberry	1	0.2
	Cropland	Chicory	0	0.0
		Hay	16	3.3
		Maize	25	5.2
	Olive grove	Olive	2	0.4
Total			479	100
Autumn/Winter	Vineyard	Grape	37	26.2
	Orchard	Apple	40	28.4
		Apricot	0	0.0
		Cherry	2	1.4
		Chestnut	1	0.7
		Medlar	1	0.7
		Nut	1	0.7
		Peach	1	0.7
		Pear	5	3.5
		Plum	1	0.7
		Strawberry	0	0.0
	Cropland	Chicory	1	0.7
		Hay	20	14.2
		Maize	31	22.0
	Olive grove	Olive	0	0.0
Total			141	100

Table 2. Seasonal number of bear damages per crop, in the period 2009–2023. Crop category was defined based on habitat re-classification obtained from the 2018 CLC shapefile.

damages (range of cells with almost one damage event: autumn/winter 5–7; spring/summer 27–33) showing the highest differences ($p < 0.001$; Fig. 7a). In contrast, agricultural (range of cells with almost one damage event: autumn/winter 6–8; spring/summer 11–15) and structural damages (range of cells with almost one damage event: autumn/winter 3–5; spring/summer 6–10) exhibited smaller absolute differences (Fig. 7a).

The hotspot analysis revealed a significant clustering based on type of damage and seasons in terms of total events (Fig. 8; Table S.7). Hot areas were more prevalent during spring and summer compared to autumn and winter (Table S.8), aligning with the observed increase in grid cell use during spring and summer (Fig. 8). Notably, no common hot areas were identified across type of damage, indicating distinct spatial patterns for each type of damage within the area. Hot areas were exclusively located in the Autonomous Province of Trento, where corresponded to the 46% of its total cells ($n = 74$ out of $n = 160$), while areas in FVG were classified as either insignificant or cold spot (Table S.9). The constant hot areas between the two seasonal periods per type of damage accounted less than 10% of the total areas (range: 11–15 out of $n = 233$ - Fig. 8). Specifically, the percentage of observed constant hot areas were 6% for livestock damages ($n = 14$ - 7 exclusively for the type of damage - out of $n = 233$), 4% for agricultural ($n = 11$ - 1 exclusively for the type of damage - out of $n = 233$), 7% for beehive damages ($n = 15$ - 4 exclusively for the type of damage - out of $n = 233$), and 6% for structural damages ($n = 13$ - 7 exclusively for the type of damage - out of $n = 233$ - Fig. 9). The hotspot analysis revealed that most hot areas underwent classification changes between the two seasonal periods, with variation depending on the type of damage (Fig. 9). Specifically, livestock damages changed classification in 17% and 21% of cases from spring/summer to autumn/winter and vice versa ($n = 16$ and 20 out of 233, respectively); agricultural damages in 9% and 17% of cases ($n = 12$ and 22); beehive damages in 11% and 15% ($n = 12$ and 16); and structural damages in 6% and 20% ($n = 5$ and 21).

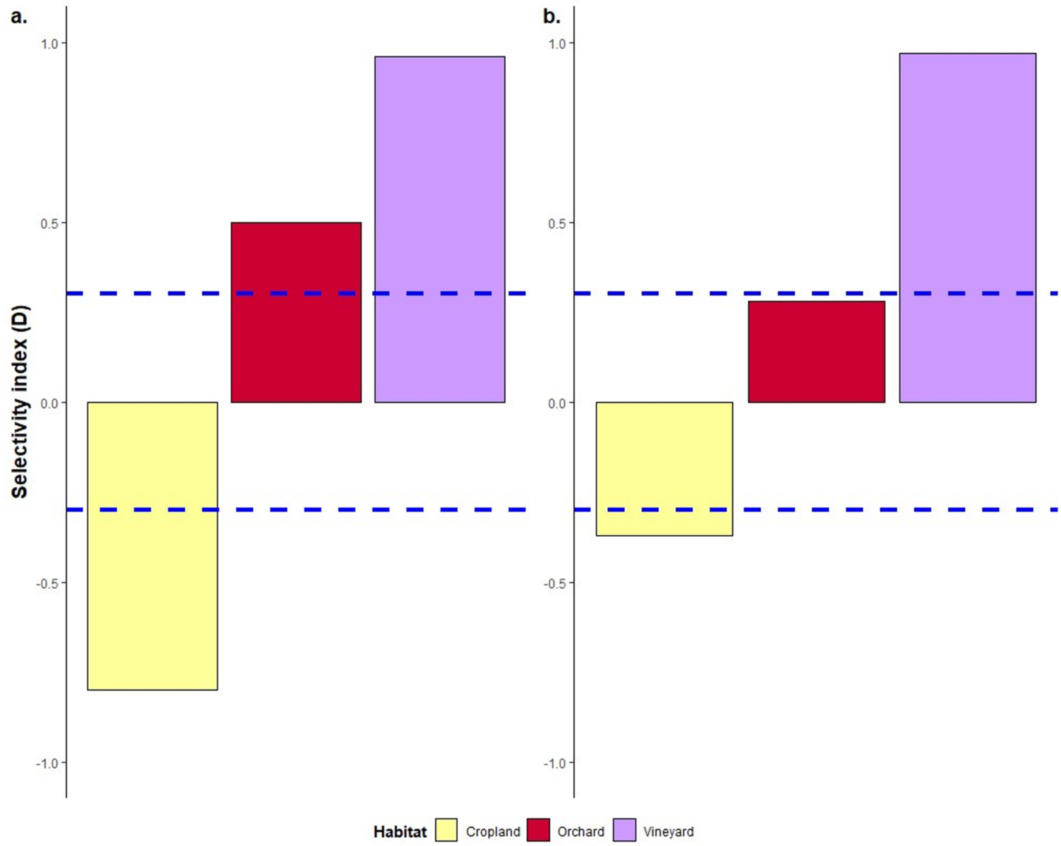

Fig. 3. Agricultural habitat selection (Jacobs' Selectivity Index - D) by bears during spring and summer (**a**) as well as autumn and winter (**b**). Positive (> 0.3) or negative (< -0.3) values (dashed blue lines) indicate selection or underuse, respectively, towards a specific habitat.

Discussion

This study provides a long-term assessment of bear-related damages in the area, with particular attention to the proximity of these events to urban infrastructures. By addressing this previously underexplored aspect, the research offers valuable insights into the dynamics of human-bear interactions in the study site. The high number of damages recorded near urban areas, combined with the ongoing expansion of the bear range, suggests an increasing likelihood of human-bear encounters in the near future. Given the expanding bear range in the North-Eastern Italian Alps, particularly within the Autonomous Province of Trento, the findings presented here can support the development of effective prevention and intervention strategies to mitigate HBCs while simultaneously safeguarding bear populations and protecting human activities in shared landscapes. Bear incursions into urban environments pose significant challenges, potentially leading to adverse social and conservation outcomes[34–36]. When residents experience fear due to such encounters, their perceptions of bears may become increasingly negative[37,38]. This shift in attitude can undermine educational campaigns designed to inform the public about the ecological importance of bears and strategies for safe coexistence.

The consistently higher number of bear-related damages to livestock, agriculture, beehives, and structures, as well as the corresponding post-damage compensation payments observed in the Autonomous Province of Trento compared to the FVG Region, aligns with the differing bear population sizes in these areas. Bear damages predominantly occurred during spring and summer, with a significant increase observed over the years. This pattern is influenced by the presence of livestock in mountainous grasslands during the transhumant period (i.e., from May/June to September/October[39,40]), the ripening stage of certain crop categories (e.g., maize, cherries, plums, apples), as well as beekeeping activities concentrated during the warmest months[25,26]. Additionally, bears hibernate during the coldest seasons[41], in turn reducing or nullifying the risk of damages. Small-sized livestock (i.e., poultry, rabbits, fish) and sheep and goats, were the most affected categories. According to the latest census conducted by the National Institute of Statistics (ISTAT 2022)[42], poultry represents the most abundant livestock in both the Autonomous Province of Trento and the FVG Region. In the Autonomous Province of Trento, poultry density stands at 104.8 ind./km^2, followed by cattle (7.6 ind./km^2), sheep (7.6 ind./km^2), and goats (1.7 ind./km^2). Similarly, in the FVG Region, poultry density is 834.5 ind./km^2, with cattle at 9.6 ind./km^2, sheep at 2.9 ind./km^2, and goats at 0.8 ind./km^2. Poultry, rabbits, and fish are often confined within enclosures or fences, which may also explain the high number of structural damages observed. Furthermore, although we were unable to explore bear selection towards specific livestock categories due to the absence of detailed information for each affected farm, it is well-documented that sheep and goats are frequently targeted by large predators[5,15,43,44].

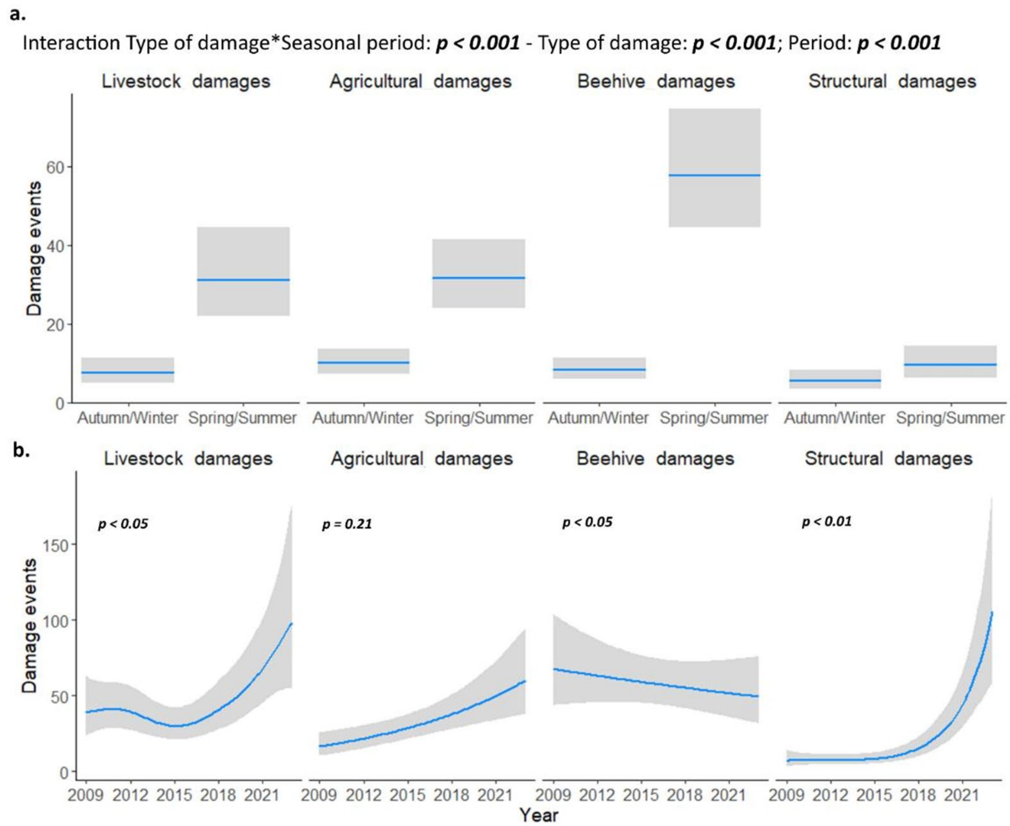

Fig. 4. Damage events of bear in relation to the type of damage (livestock damages, agricultural damages, beehive damages, and structural damages) and seasons (autumn/winter and spring/summer - **a**) and trends of damage events during the period 2009–2023 in relation of type of damage (**b**) The grey area represents the confidence interval (95%). For details about the models, see Table S.3.

This susceptibility is attributed to their smaller size, poor defensive adaptations, and limited anti-predatory behaviours. A previous study conducted in the Autonomous Province of Trento[25] showed that sheep and goats accounted for 93% of the overall livestock preyed upon by bears. Similarly, research conducted in Slovenia[45] revealed that sheep represented 97% of all registered bear predation events.

As for agricultural damages, the preference shown by bears for both orchards and vineyards, especially during spring and summer, aligns with other studies conducted in Eastern Europe[46,47], which revealed that fruits, due to their high caloric content, constitute an important part of the overall bear diet. Croplands, such as maize, also represents a significant component of the bear diet, especially during summer[47]. However, in our case, the avoidance of croplands by bears compared to the overall available agricultural surfaces suggests that they shift their attention to other profitable food resources, such as fruits.

The presence of hotspot conflict areas (particularly during spring and summer) exclusively in the Autonomous Province of Trento is in line with our initial hypothesis, and reflects the differing abundance and range expansion of the species in the two areas. Nevertheless, despite the increasing bear damages observed in the Autonomous Province of Trento over the years, along with the associated rise in bear population and range expansion[29], our findings revealed no significant association between the growing bear population and damages to human activities. This result suggests that bear-related damages may be linked to the presence of problematic individuals[48] rather than being driven by the overall bear population size. This contrasts with observations from a previous study conducted in the same area[25], where a significant positive relationship between the number of damages and bear abundance was reported. However, the authors also affirmed that most damages were attributed to problematic individuals identified by DNA analyses, in turn highlighting the impact that problematic bears may have on agro-livestock practices. Additionally, although we were unable to investigate this effect due to data limitations, a further possible explanation may relate to the increasing adoption of prevention measures over the years, especially in the Autonomous Province of Trento where the presence of species is consolidated[29]. Further research incorporating the genetics of damaging bears, as well as the implementation of prevention measures, is needed to provide more detailed and comprehensive insights.

Our findings revealed that bear damages to croplands and beehives were the closest to urban areas, as especially croplands are frequently intermixed or ubicated in the near proximity of urban infrastructures. Conversely, damages to livestock and, especially, structures were more distant. However, model results indicated that, over time, the distance of these damages from urban areas significantly decreased, thus matching with our initial hypothesis. Although bears, like other carnivore species, typically avoid humans, they are capable of roaming

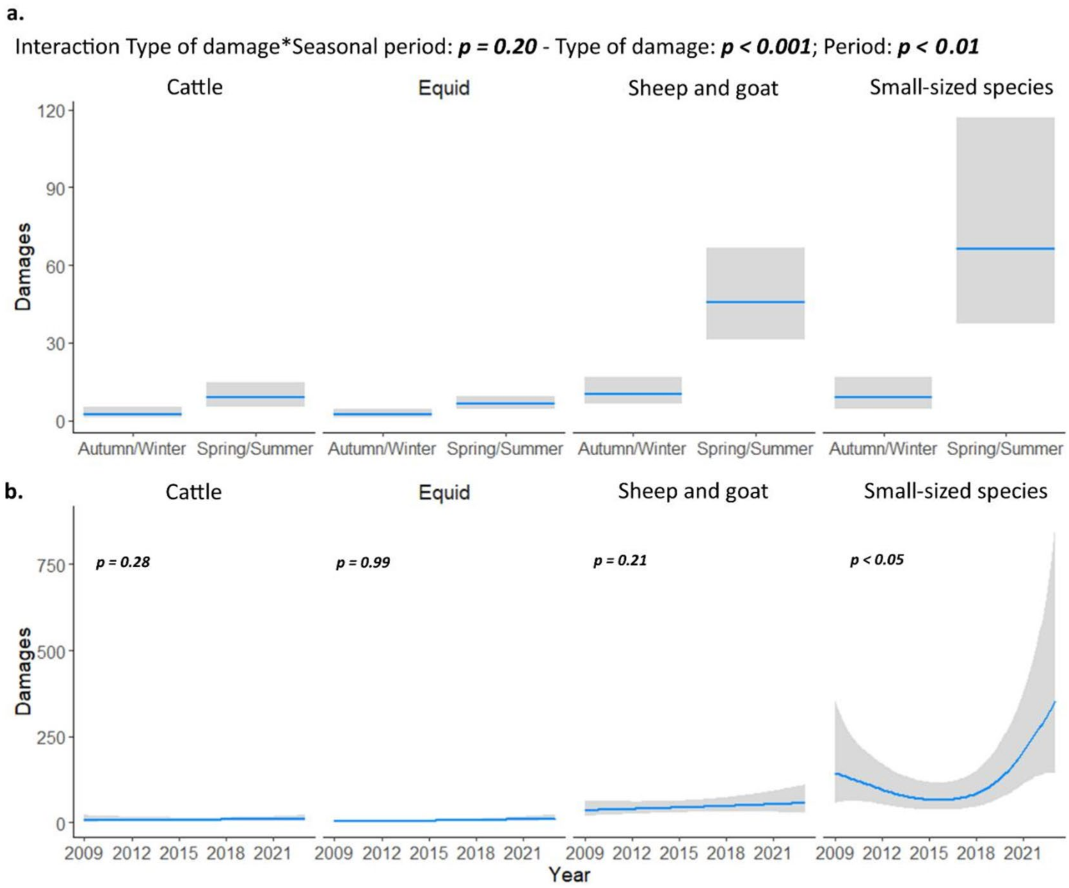

Fig. 5. Livestock damages (sum of preyed, injured, and missing individuals) of bear in relation to the type of damage (cattle, equid, sheep and goats and small-sized species) and seasonal periods (autumn/winter and spring/summer - **a**); and trends of damage events during the period 2009–2023 in relation of type of damage (**b**). The grey area represents the confidence interval (95%). For details about the models, see Table S.4.

into human-altered environments, thereby increasing the likelihood of negative interactions[49]. In North-Eastern Italy, particularly in the Autonomous Province of Trento, the bear population has been expanding its range, bringing bears into closer contact with humans[29]. Moreover, the abandonment of agro-livestock practices in mountainous areas has led to a reduction in ecotonal habitats (i.e., grasslands intermixed with patches of natural habitats), favouring forest expansion and bringing carnivores closer to human infrastructures[40]. Beyond damages to livestock and agriculture, the presence of carnivores near human settlements and infrastructures is often perceived as problematic because these animals can also attack pets. Additionally, although attacks on humans are rare, especially in Europe[50], people may experience fear and perceive their presence as dangerous[37,38]. Therefore, their close proximity to human settlements must be properly managed and monitored to reduce the likelihood of risky situations for both bears and humans[36]. In our research, the inclusion of yearly spatial data on grasslands and beehive locations would have greatly improved our ability to describe the spatial distribution of bear damages to livestock and beekeeping activities in relation to urban areas. However, given the long-time span of our study, such information was not available on a yearly basis. Further studies incorporating these data are therefore needed to provide more detailed insights.

The limited data on prevention measures did not allow us to assess their potential effect on reducing bear-related damages. However, literature shows that proper prevention/mitigation is key to reducing HBCs[51]. Electric fences are the most effective tool, achieving an 80–100% reduction in damages to livestock, beehives, and crops when correctly installed and maintained[26,51–53]. Nevertheless, their use may be impractical in harsh terrains, requiring alternative measures such as livestock guardian dogs or human guarding. Predator removal (e.g., translocation, captivity, direct killing) is also used in high-conflict areas or to manage problematic individuals[51,54–56]. Under the European Directive (Article 16.1, 'Habitat' Directive 92/43/CEE), removal may be considered when non-lethal methods fail and the species' conservation status is not at risk[55]. Yet public support for removal, especially direct killing, is low[14,56], and its long-term effectiveness is debated due to context- and species-dependent outcomes[51,54–56]. Ineffectiveness often stems from non-selective removals, short translocation distances, and rapid replacement by new individuals[51]. Since not all problematic bears will necessarily remain problematic, and human-derived food sources can promote such behaviours[57], securing anthropogenic food[58] or using aversive conditioning[59,60] may help reverse them. The presence and distribution of carnivores in human-inhabited areas must be carefully managed to prevent fear-driven support for illegal killings[37,38], which can jeopardize long-

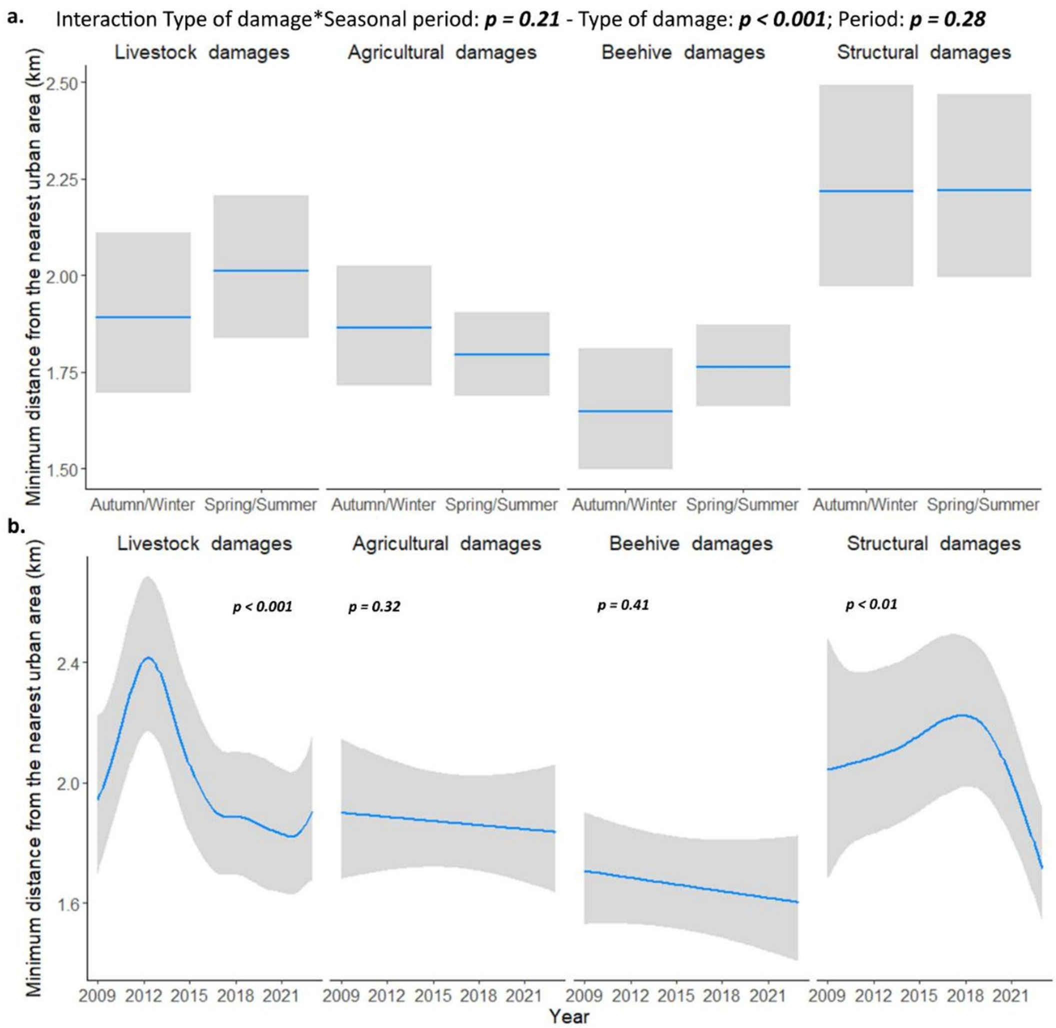

Fig. 6. Minimum distance from the nearest urban area (km) of bear damage events in relation to the type of damage (livestock damages, agricultural damages, beehive damages, and structural damages) and seasonal periods (autumn/winter and spring/summer - **a**); and trends of damage events during the period 2009–2023 in relation of type of damage (**b**). The grey area represents the confidence interval (95%). For details about the models, see Table S.5.

term conservation efforts. Effective non-lethal prevention measures should remain the primary strategy, though targeted removal of problematic individuals may be necessary in severe cases to mitigate HBCs[61], especially when animals repeatedly enter urban areas. In our study, data on prevention measures used by livestock owners were either unavailable or inconsistently reported. Moreover, the effectiveness of such measures in reducing carnivore damages has rarely been evaluated[55,56,62], and these data are often missing in large-scale studies[63,64]. This highlights the need for stronger collaboration between research bodies and environmental authorities to ensure systematic, standardised data collection on prevention effectiveness. Achieving human-carnivore coexistence requires balancing species conservation with human activities; thus, well-planned interventions are essential to protect both bears and local livelihoods in mountainous regions.

Methods

Study areas and data collection

The study was conducted across two areas totalling 14,131 km^2, i.e., Autonomous Province of Trento (6,207 km^2), and FVG Region (7,924 km^2- Fig. 10).

In the study areas, habitat composition varies with elevation. Canopy-covered (i.e., forests and shrublands) and open habitats (i.e., meadows and grasslands/pastures) are prevalent in the Alpine and pre-Alpine zones, whereas croplands and anthropogenic areas dominate the lowlands. Human density is different in the two study areas, i.e., 87.8 inhab./km^2 in the Autonomous Province of Trento, and 150.7 inhab./km^2 in the FVG Region. As for agriculture, the lowland area is characterised by both intensive and extensive cultivations (primarily maize), along with orchards, vineyards, and olive groves. Livestock grazing occurs primarily in Alpine and pre-Alpine grasslands during the spring and summer transhumance period (May/June to September/October[39,40], when

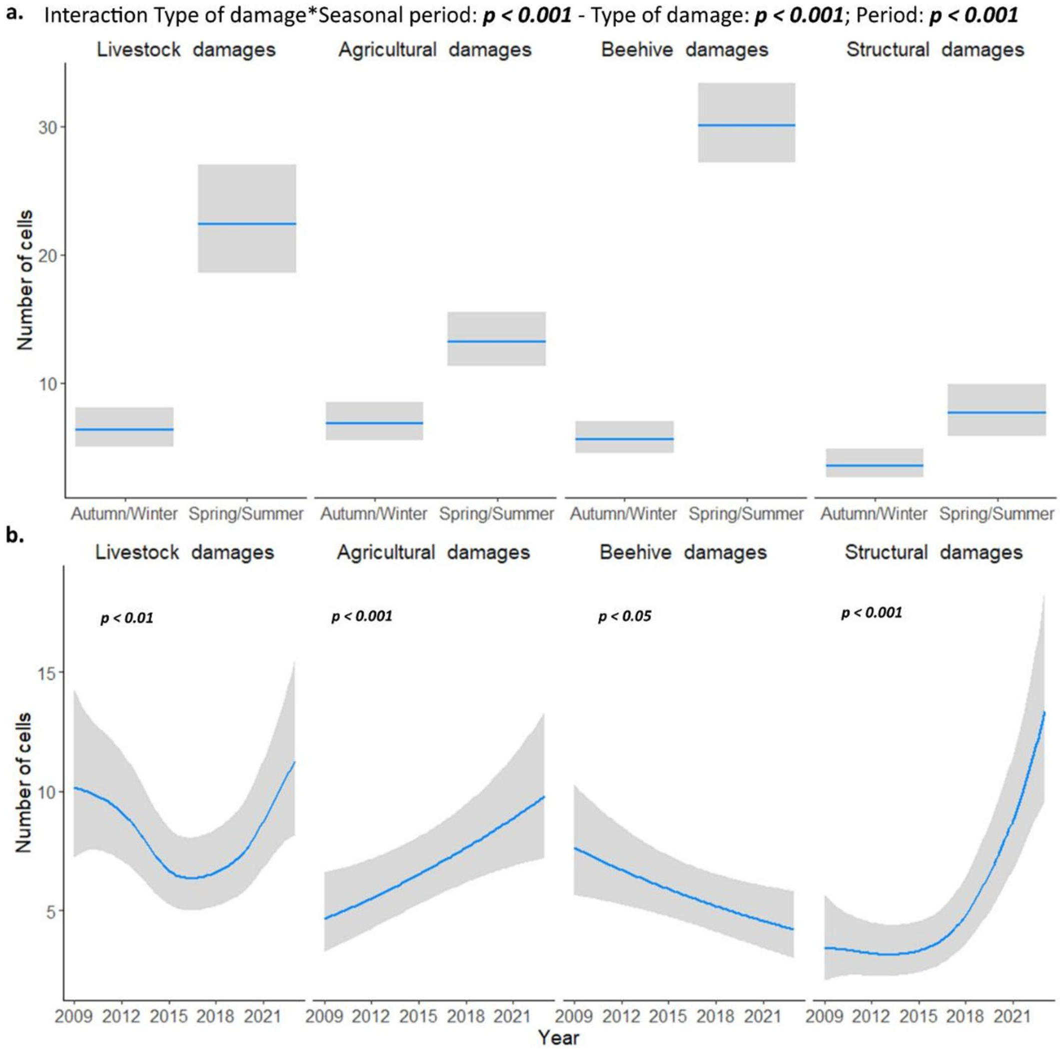

Fig. 7. Number of cells having damages of bear in relation to the type of damage (livestock damages, agricultural damages, beehive damages, and structural damages) and seasonal periods (autumn/winter and spring/summer - **a**); and trends of damage events during the period 2009–2023 in relation of type of damage (**b**). The grey area represents the confidence interval (95%). For details about the models, see Table S.6.

livestock is moved to higher elevations to graze in open areas, increasing their risk of predation by bears (and other large carnivores). The bear range of distribution across the North-Eastern Alpine arch is shown in Fig. S.1.

We analysed official claims data on bear-related damages collected from 2009 to 2023 by field operators working for the Autonomous Province of Trento and the FVG Region. Damages attributed to bears were verified through on-site inspections conducted by trained personnel, including wildlife technicians, members of the Forestry Service, and veterinarians. The responsible predator was identified based on signs such as footprints, scrapes, bite marks, and the distance between canine teeth (in the case of livestock predations). In specific instances where the responsible predator could not be conclusively identified through field-collected evidence, genetic analyses were performed for further verification. The database included the following information for each municipality: (i) municipality ID, (ii) date of the damage, (iii) coordinates of the damage, (iv) type of damage (livestock damage, agricultural damage, beehive damage, structural damage), (v) affected livestock species and total number of preyed, injured, and/or missing individuals, (vi) type of crop damaged, and (vii) post-damage compensation payments (Euros - €). The compensation system for carnivore damages varies by Region and/or Province according to local legislation: (i) in the Autonomous Province of Trento, it is governed by Article 33 bis of Provincial Law No. 24/1991; (ii) in the FVG Region, by Articles 11 and 39 of Regional Law No. 6/2008 and Regional Decree No. 162/2020. Compensation claims must be filed within 24 h in the Autonomous Province of Trento, and within 48 h in the FVG Region. Subsequently, an in-situ kill-site inspection is conducted by trained personnel (veterinarians, wildlife technicians, and members of the Forestry Service) working for the Autonomous Province of Trento or the FVG Region, with damages compensated at 100% of the verified amount.

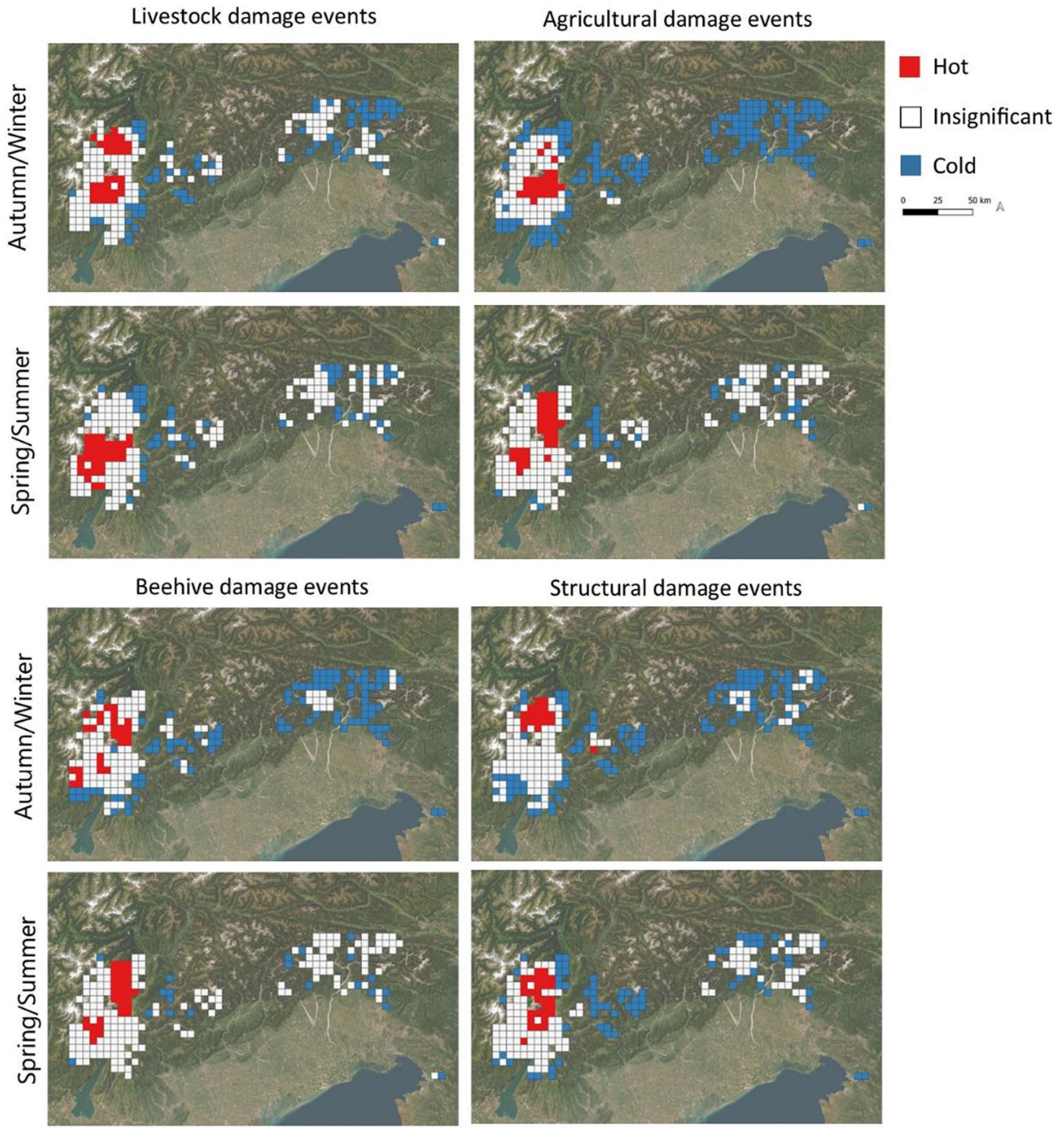

Fig. 8. Hotspot analysis of total events for each type of damage (livestock damages, agricultural damages, beehive damages and structural damages) and seasons (autumn/winter and spring/summer) in study area (red cell: hot areas - Gi > 0, $p \leq 0.05$; white cell: insignificant areas - Gi ≈ 0 and $p \geq 0.1$; blue areas: cold areas - Gi < 0, $p \leq 0.05$). The map was realised through the Software QGIS (v. 3.34 - https://qgis.org)[65].

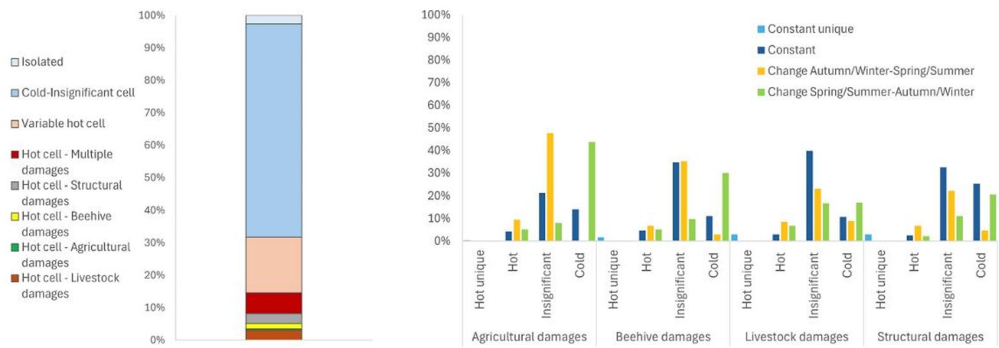

Fig. 9. Distribution of hotspot cells in the study area for each type of damage damage (livestock damages, agricultural damages, beehive damages and structural damages) and seasons (autumn/winter and spring/summer) in study area (see Table S.7–8).

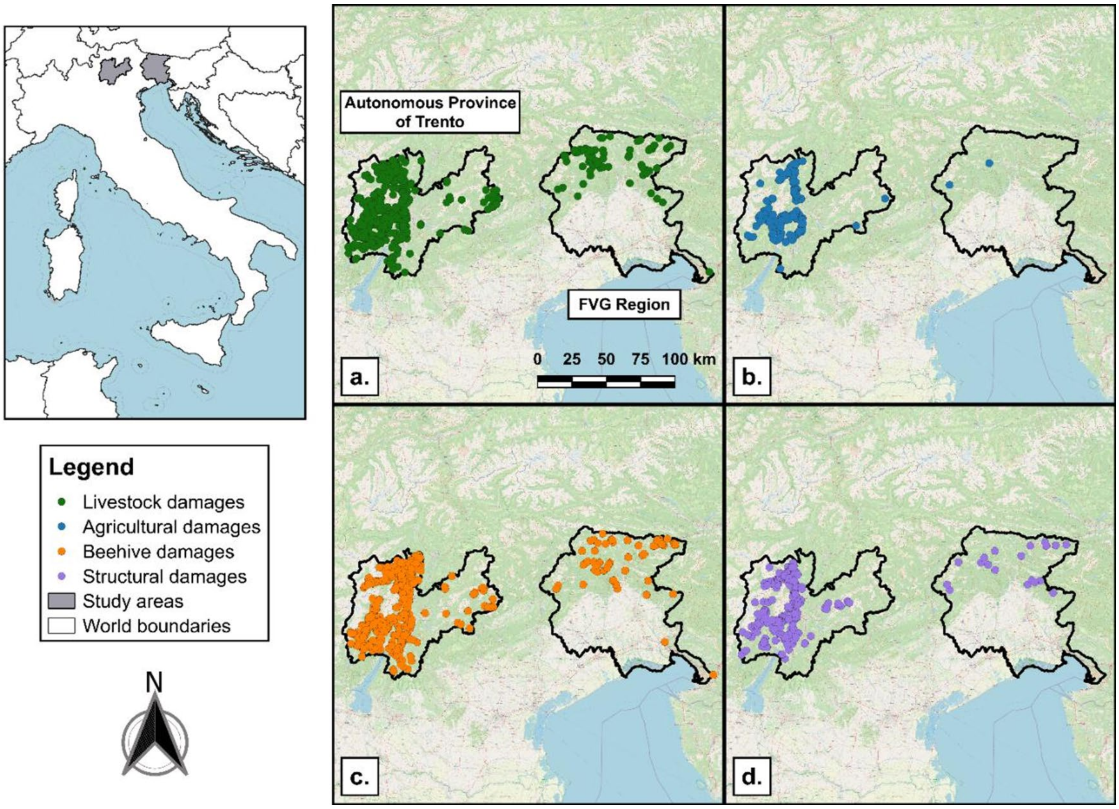

Fig. 10. Location of the study areas (inset map) and related bear damages, i.e., livestock damages (sum of preyed, injured, and missing individuals) (**a**), agricultural damages (**b**), beehive damages (**c**), and structural damages (**d**). Abbreviation: FVG = Friuli Venezia Giulia. The map was realised through the Software QGIS (v. 3.34 - https://qgis.org)[65].

Spatial and statistical analyses

We realised the spatial analyses using the Software QGIS (v. 3.34)[65], while statistical analyses using the Software R (v. 4.3)[66]. The level of significance was set at 0.05.

The trend of the bear population over the years within the Autonomous Province of Trento was analysed using a Linear Regression Model (LM) implemented with the *lm* R function[67]. The response variable was first log-linear transformed, and, following Fryxell et al. (2014)[68], the β (slope - intrinsic growth rate on the log scale) value was extracted to estimate λ (finite rate of increase; $\lambda = e^{\beta}$) and Δ (the annual proportional increase; $\Delta = \lambda - 1$). Cubs were included in the analysis, and a logarithmic transformation was applied to the data to reduce interannual variability. Additionally, the total annual events per type of damage, i.e., livestock damages, agricultural damages, beehive damages, and structural damages (e.g., fences, garbage cans, cisterns), were analysed as function of the bear population.

The variation in bear damages to livestock, agriculture, beehives, and structures as well as the corresponding post-damage compensation payments across years in the study areas, was analysed using different sets of Generalized Additive Models (GAMs)[67], using the *gam* R function implemented in the 'mgcv' R package[69]. Specifically, bear damages were analysed in relation to the total number of events considering all type of damages, and the total number of preyed, injured, missing individuals for the livestock damages only. The former model was realised considering a negative binomial family distribution to account for overdispersion among data, previously assessed using Pearson's residual coefficient[67]. The latter model was instead realised considering a normal family distribution after logarithmic transformation of the data, adopted due to the different scale of damages among the considered classes. With regards to the involved domestic species, swine, canids, camelids, and cervids were excluded due to their marginal occurrence. All models implemented the w-way interaction between seasons ("autumn-winter" - Reference Level (R.L.); "spring-summer") and type of damage ("agricultural damage" - R.L., "beehive damage", "livestock damage", "structural damage") and the spline of the year within each category of the two predictors. Seasonal periods, i.e., spring/summer and autumn/winter, were classified as follows: autumn (September 21st - December 20th), winter (December 21st - March 20th), spring (March 21st - June 20th), summer (June 21st - September 20th). Model predictive performance (i.e., *goodness-of-fit*) was evaluated using the *gam_check* R function. Since non-significant *p*-values were obtained, good predictive performance could be inferred[69]. Moreover, the temporal autocorrelation of each model was assessed using the ACF plot using the *acf_plot* R function implemented in the 'itsadug' R package[70].

Starting with the 2018 Corine Land Cover (CLC) shapefile, we reclassified habitat classes using the *case* function within the Expression Dialog of the attribute table. The reclassified data were then aggregated using the *dissolve* geoprocessing tool in QGIS, resulting in a new habitat classification: 'broad-leaved forest', 'cliffs, glaciers, and coastal areas', 'coniferous forest', 'croplands', 'grasslands', 'mixed forests', 'olive groves', 'orchards', 'shrublands', 'urban areas', 'vineyards', 'water bodies', and 'wetlands'. A 1,000 m buffer was applied around each coordinate corresponding to bear agricultural damages. Within these buffers, we extracted the associated habitat categories. The seasonal bear selection of agricultural habitats, i.e., croplands, orchards, and vineyards (olive groves were excluded from the analysis due to the low number of recorded damages - see *Results*), was then explored using the Jacobs' selectivity index[71]:

$$D = (r - p)\,(r + p - 2 \times r \times p)$$

where r is the proportion of bear damages in each agricultural habitat, and p is the proportion of agricultural habitats available within the buffer areas.

This index ranges from + 1 (strong selection) to -1 (strong avoidance), with values of 0 indicating no selectivity. Preference or underuse are considered only for values > 0.3 and < -0.3, respectively[72–75]. Before applying the index, we first assessed whether habitat use differed significantly from habitat availability by calculating observed and expected frequencies based on habitat availability within the buffers. Since expected frequencies were < 5 in more than 20% of the cases, we used the G-test implemented in the 'DescTools' R package[76].

Starting from the classification of land use associated with each damage location, we first quantified the presence of damages occurring within urban areas. For those damages located outside urban areas, we calculated the minimum spheroidal distance to the boundary of the nearest urban area using the *ST_DistanceSpheroid* function implemented in PostGIS. This minimum distance to urban areas was subsequently analysed using a GAM, which included: (i) the two-way interaction between seasons and type of damage, (ii) a spline term for the year at each level of the considered predictors, and (iii) the interaction between longitude and latitude, expressed as a tensor product smooth. To investigate spatial variations in bear damages, the study area was subdivided into a regular grid composed of cells with a resolution of 5 × 5 km. Within each grid, the total number of events was counted for each combination of type of damage and seasons. Subsequently, the trend in terms of expansion of damage was analysed using the count of cells with at least one damage event. This analysis employed a GAM, modelling the two-way interaction between type of damage and seasonal periods, alongside the spline for the year within each predictor level, using a negative binomial distribution. Subsequently, a hotspot analysis was conducted, considering the total number of events for each combination of seasonal periods and type of damage. The hotspot analysis assessed spatial clustering patterns or spatial autocorrelation for specific features, such as the total damage caused by bears, following the methods outlined by Nelson & Boots[77]. Spatial autocorrelation was evaluated through the Getis-Ord statistic (Gi), which compares the spatial lag of a feature with the sum of its values among neighbouring units[78]. According to Getis[79], spatial autocorrelation describes the degree to which a feature in one spatial unit relates to the same feature in contiguous units, indicating whether values are clustered (similar) or dispersed (dissimilar). The Gi value can thus be positive (spatial clustering) or negative (spatial dispersion). A positive Gi value indicates high feature values within a unit and its neighbouring cells, while a negative Gi value suggests low feature values. The magnitude of the Gi value reflects the strength of spatial clustering[80]. For the purpose of the hotspot analysis, grid cells with isolated events (not contiguous with others that showed no events or damages) were classified as "isolated" and excluded from the analysis. The analysis employed the *poly2nb* function implemented in the 'spdep' R package[81] to generate a neighbour matrix for each grid cell. Using the *local_g_perm* function implemented in the 'sfdep' R package[82], the statistical significance of spatial autocorrelation was evaluated with 999 permutations. Each grid cell was classified into one of four categories based on the value and significance of the Gi: "Hot" (Gi > 0, $p \le 0.05$), "Cold" (Gi < 0, $p \le 0.05$), "Insignificant" (Gi ≈ 0 and $p \ge 0.1$), and "Isolated" (i.e., not contiguous with others).

Data availability

The data presented in this study were shared by the Autonomous Province of Trento and the Friuli Venezia Giulia Region. Data are available on reasonable request from the corresponding author only in the case of previous consent obtained from the Autonomous Province of Trento and the Friuli Venezia Giulia Region. Data are not publicly available due to privacy reasons.

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