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70 years of heat waves and summer climate change affecting Italian small ruminant populations

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Climate change and heat stress pose significant challenges to livestock. Local breeds, particularly small ruminants, are gaining importance due to their adaptability to harsh climates. However, the extensive system they are commonly reared in leaves them exposed to the effects of climate change. This study aims to describe the distribution and climate-related challenges faced by registered Italian sheep and goat breeds over the past seven decades. Geolocalized data from all registered small ruminant farms were combined with climatic information retrieved from the "ERA-5-Land hourly data from 1950 to present" dataset. These data were used to calculate average daily temperature, temperature humidity index (THI), and total precipitation during summer. Additionally, THI-based heat waves (HWs) were examined, including the yearly number of HW days and mean THI during HW days. These data were analysed through linear regression models including region or breed, year, and their interaction as fixed factors. The climate data indicate a concerning trend of rising summer temperatures, THI, and HW frequency and intensity, particularly over the past three decades. Central-northern Italy, including the Po Valley and the Alpine Arch, is the most affected region, impacting breeds like Rosset and Brogne sheep, and Lariana and Frisa Valtellinese goats. This is of particular concern because these populations have not been selected for hot climates, and their already small population size exacerbates the problem. Conversely, southern Italy, characterized by hotter and drier temperatures, remained relatively stable. Breeds from this region, such as Girgentana and Nicastrese goats and Nera di Arbus sheep, might represent excellent case studies for climatic adaptation and potential resources for selection for resilience in the face of ongoing climate changes. The findings presented here are essential for

Abbreviations: d2m, 2m-dewpoint temperature; HW, heat wave. HW-THI, mean temperature-humidity index occurring during heat wave days; nDays, total number of days falling in a heat wave; summer-T, average daily summer temperature; summer-THI, average daily summer temperature-humidity index; summer-TP, average daily total precipitation; t2m, 2m-temperature; THI, temperature-humidity index; tp, total precipitation.

the development of monitoring and intervention strategies for breeds facing future vulnerabilities, as well as for designing experiments to explore environmental adaptability in small ruminants.

KEYWORDS

goats, sheep, local breeds, climate change, heat waves

Introduction

Climate change is one of the most significant challenges facing the world today. There is evidence of globally rising mean temperature (Intergovernmental Panel on Climate Change, 2012; European Environment Agency, 2019b), as well as an increase in frequency, duration, and intensity of extreme weather events, especially in heat waves (HWs) (Rowlinson et al., 2008; Intergovernmental Panel on Climate Change, 2012; United Nations Office for the Coordination of Humanitarian Affairs et al., 2018; European Environment Agency, 2019a; European Environment Agency, 2019b). Moreover, the Mediterranean areas have shown to be particularly interested by these changes (Fischer and Schär, 2010). Numerous studies have reported HWs as the weather events associated with the highest number of human deaths (European Environment Agency, 2017; European Environment Agency, 2019b), but there is also well-documented evidence of a significant increase in livestock losses during these phenomena (Gaughan et al., 2009; Morignat et al., 2014; Vitali et al., 2015).

The detrimental effect of heat stress on ruminants encompass various aspects of animal health, welfare, and production, and has been extensively documented (European Environment Agency, 2017; Rojas-Downing et al., 2017). Even though sheep and, even more, goats are considered more thermotolerant than cows (Silanikove, 2000; Al-Dawood, 2017; Sarangi, 2018; Lima et al., 2022), they experience negative effects of high temperatures as well. These include a variety of metabolic and immunologic changes leading to reduced feed intake, decreased milk and meat production and quality, metabolic and immunologic impairment, pest and disease outbreaks, and increased animal mortality (Marai et al., 2007; FAO, 2015; Ribeiro et al., 2018; Sarangi, 2018; European Environment Agency, 2019a; Berihulay et al., 2019; Thornton et al., 2021). Several studies demonstrate that highly productive animals are more susceptible to heat stress and that, on the other hand, local and more rustic populations are more resilient to harsh climates, thanks to several morphological and genetic adaptations to the environment in which they developed (FAO, 2015; European Environment Agency, 2017; Rojas-Downing et al., 2017; Thornton et al., 2021; Wankar et al., 2021; Ramachandran and Sejian, 2022). However, these local breeds are often reared in extensive systems, leaving them vulnerable to changes in their environment, and farmers may not have the resources to implement sufficient technology to protect them from excessive heat or other adversities (Rowlinson et al., 2008; FAO, 2015; European Environment Agency, 2017).

Small ruminant farming holds a significant place within Italy's agricultural landscape, boasting a rich historical legacy dating back centuries (Trentacoste et al., 2018; Iommelli et al., 2022). Despite enduring fluctuations in headcounts, there has been a clear trend of reduction in overall small ruminant farm numbers over the past century, with the exception observed between 1970 and 1990 (Paoletti and Aceto, 2007; ISTAT, 2015). Presently, while the population appears relatively stable, with approximately six million sheep and one million goats, a conspicuous decrease in the number of farms is notable, particularly in small-scale, family-operated farms (Anagrafe Nazionale Zootecnica, 2022; ISTAT, 2022). The traditional extensive or semi-extensive farms, despite still being the predominant type for sheep and goats, face challenges such as the abandonment of less profitable activities, shrinking grazing lands, and the wool market crisis (Battaglini et al., 2014; Bigi and Zanon, 2020; De Luca, 2021; Ismea, 2022; Ismea, 2023a; Ismea, 2023b). However, this decline has been partially compensated by the emergence of large, modernized farms, notably in the dairy sheep sector. A substantial portion of the small ruminant population, exceeding two-thirds, is indeed concentrated within a mere five percent of such farms, mainly located in Sardinia (Anagrafe Nazionale Zootecnica, 2022; Ismea, 2022).

Currently, the small ruminant sector constitutes approximately 1.1% of Italy's total agricultural output. The vast majority of small ruminants are raised for milk or mixed production purposes, positioning Italy as the third-largest producer of sheep and goat milk and cheeses in Europe (Ismea, 2022; Ismea, 2023a). Notably, a significant proportion of milk is utilized in the production of designated origin products, such as the Pecorino cheese, which enjoys both domestic and international demand, notably in the United States (Pulina et al., 2018; Ismea, 2019; Ismea, 2023a). Additionally, small ruminant meat, predominantly sourced from lamb, holds seasonal significance, with consumption peaking during Easter and Christmas periods (Ismea, 2023b).

Despite constituting a modest fraction of the Italian agricultural economy, the social, cultural, and environmental role of small ruminant farming is pivotal, particularly in maintaining and safeguarding unproductive territories. While on a national scale, sheep and goats represent approximately 10% of the total ruminant population in Italy, they are the predominant or exclusive type of livestock in certain marginal, unproductive, and inaccessible areas. In these territories, they serve as vital components of land management strategies, facilitating ecosystem preservation and biodiversity conservation (Paoletti and Aceto, 2007; Claps et al., 2020; CREA, 2022; Iommelli et al., 2022; Ismea, 2022). Traditional practices such as transhumance—seasonal migration of flocks between mountainous and lowland pastures—are recognized as intangible cultural heritage by UNESCO (UNESCO, 2023). Furthermore, Italy stands as a reservoir of small ruminant biodiversity: with 64 sheep breeds and 41 goat breeds officially recognized,[1] the country ranks third globally in terms of goat breed diversity and sixth for sheep breeds.[2] These breeds originated due to geographic barriers, which hindered communication and the exchange of animals between farms, typically situated in the valleys, whereas in more recent times they have been recognized and selectively bred (Fabbri and Bonacini, 1983). This rich genetic heritage underscores the importance of small ruminant farming in preserving and promoting genetic diversity within livestock populations, thereby contributing to the resilience and adaptability of agricultural systems in the face of evolving environmental challenges. Therefore, the purpose of the present study is to describe the distribution of Italian small ruminant breeds and assess their exposure to the variation in summer environmental conditions occurred over a 70-year period, with the final aim of assisting in the management of the populations most threatened by the climate change.

Material and methods

Environmental data

Italian 2m-dewpoint temperature (d2m), 2m-temperature (t2m), and total precipitation (tp) from 1st January 1950 to 30th September 2022 were obtained from “ERA-5-Land hourly data from 1950 to present” dataset (Muñoz Sabater, 2019). Using these parameters, we calculated hourly relative humidity $[RH = e^{\frac{17.625*d2m}{243.04+d2m}}/e^{\frac{17.625*t2m}{243.04+t2m}}$, according to Lawrence (2005)], and temperature-humidity index ($THI = 0.8*t2m + RH*(t2m + 14.4) + 46.4$).

The average daily temperature, THI, and total precipitation recorded during summer (hereafter called summer-T, summer-THI, and summer-TP, respectively), i.e., from 1st May to 30th September, were calculated.

We relied on the Climatological EURO-CORDEX definition of HW (“a period of at least three consecutive days on which the daily maximal temperature exceeds the 99th percentile of the daily maximal temperatures of the May to September season of the control period”) (Jacob et al., 2014). However, given the wide use of the THI as a measure of heat stress in livestock, we substituted the daily maximal temperature with the daily maximal THI. Moreover, we chose the 30-year period from 1950 to 1979 as the control period. Therefore, we defined a heat wave as a period of at least 3 days, between May and September, with a maximum daily THI exceeding the 99th percentile of the reference period (1950–1979) at the same geographic coordinates.

For each location, we calculated the mean THI occurring during HW days (HW-THI) and the total number of days falling in a HW (nDays) in all years from 1950 to 2022.

R packages and ESRI ArcGis Pro 3.0.2 were used for computation and graphical representation of data.

The selection of these variables is driven by their dual significance: they not only exert a substantial impact on livestock production but also stand out as key climatic variables undergoing rapid change. Heat stress, exacerbated by rising temperatures and THI, stands out as a primary concern, directly impacting animals by reducing feed intake, impairing reproductive and productive performance, and compromising animals’ immune system. Furthermore, extreme weather events, such as heat waves, can drastically increase animal morbidity and mortality. Indirect consequences of both temperature and precipitation changes are also to be considered, including shifts in crop and forage quantity and quality, diminished water availability, and alterations in the distribution of pests, parasites, and thus vector-borne diseases (Marai et al., 2007; FAO, 2015; Rojas-Downing et al., 2017; Ribeiro et al., 2018; Sarangi, 2018; Cheng et al., 2022).

Small ruminant geolocalization data

The geolocalization of all the registered currently (31st December 2022) operational farms were provided the Italian Sheep and Goat Breeders Association (Asso.Na.Pa, 2024) for 41 goat and 47 sheep populations (Tables 1, 2). These data were paired with the environmental information described above.

In this manuscript, we have chosen to utilize Asso.Na.Pa. data due to their reliability in accurately documenting breed locations. It is important to note that, according to European and Italian law [D.Lgs 11/05/2018 n.52 and Regulation (EU) 2016/1012], a breeding animal is considered purebred only if registered with a breeding book overseen by an authorized breed society; in Italy, Asso.Na.Pa. stands as the sole authorized entity managing sheep and goat breeding books. Additionally, farms breeding local breeds are incentivized to register to receive subsidies related to autochthonous population conservation. A first census of Italian small ruminant populations, which also led to the recognition of several of them, was carried out between the 70s and the 80s and published in 1983 (Fabbri and Bonacini, 1983). Although precise geolocation data for past periods are

1 www.assonapa.it

2 www.fao.org/dad-is

TABLE 1 Number of farms and mean ± standard deviation of Summer-T, Summer-THI, and nDays during the first and last 30 years of the analysed period for each goat breed.

Goat breed	N. farms	Summer-T		Summer-THI		nDays	
		1950–1985	1986–2022	1950–1985	1986–2022	1950–1985	1986–2022
ALPINA	7	14.93 ± 4.32	16.28 ± 4.31	58.06 ± 6.48	59.99 ± 6.28	1.16 ± 2.54	3.76 ± 5.35
ARGENTATA DELL'ETNA	103	20.17 ± 1.19	20.90 ± 1.24	66.01 ± 1.72	66.98 ± 1.80	0.43 ± 1.23	2.24 ± 4.44
BIANCA MONTICELLANA	14	18.91 ± 1.26	19.94 ± 1.36	64.28 ± 1.88	65.71 ± 2.00	0.96 ± 2.29	4.07 ± 5.85
BIONDA ADAMELLO	79	13.48 ± 3.00	14.68 ± 3.02	56.04 ± 4.70	57.89 ± 4.64	0.96 ± 2.46	3.35 ± 4.70
CAMOSCIATA DELLE ALPI	230	16.02 ± 3.91	17.24 ± 3.90	59.82 ± 6.01	61.57 ± 5.87	0.95 ± 2.24	3.88 ± 5.21
CAMPOBASSO GRIGIA MOLISANA	3	18.31 ± 0.92	19.27 ± 0.99	63.06 ± 1.21	64.38 ± 1.29	0.63 ± 1.59	2.75 ± 3.41
CAPESTRINA	19	18.93 ± 1.27	19.99 ± 1.36	64.23 ± 1.90	65.68 ± 2.00	0.98 ± 2.25	3.95 ± 5.73
CILENTANA FULVA	13	19.21 ± 1.45	20.14 ± 1.48	64.62 ± 2.28	65.94 ± 2.35	0.68 ± 1.73	3.73 ± 5.03
CILENTANA GRIGIA	11	19.24 ± 1.17	20.12 ± 1.14	64.58 ± 1.81	65.85 ± 1.83	0.70 ± 1.72	3.29 ± 4.46
CILENTANA NERA	32	19.27 ± 1.11	20.14 ± 1.10	64.64 ± 1.70	65.90 ± 1.73	0.66 ± 1.64	3.38 ± 4.63
CIOCIARA GRIGIA	12	18.56 ± 1.31	19.60 ± 1.40	63.69 ± 2.02	65.12 ± 2.14	1.00 ± 2.27	3.90 ± 5.73
DELL'ASPROMONTE	102	20.98 ± 1.37	21.70 ± 1.42	67.08 ± 1.96	68.08 ± 2.05	0.46 ± 1.31	2.87 ± 5.10
DI BENEVENTO VALFORTORINA	6	18.63 ± 0.89	19.62 ± 0.86	63.42 ± 1.10	64.74 ± 1.08	0.83 ± 1.97	2.75 ± 3.97
DI MONTECRISTO	1	18.24 ± 0.85	19.35 ± 0.90	62.85 ± 1.09	64.31 ± 1.14	0.80 ± 1.81	2.79 ± 5.06
DI POTENZA	45	19.16 ± 1.67	19.94 ± 1.66	63.71 ± 2.16	64.76 ± 2.16	0.51 ± 1.18	3.18 ± 5.01
FRISA VALTELLINESE	48	10.06 ± 3.77	11.38 ± 3.81	50.56 ± 5.94	52.64 ± 5.87	0.87 ± 2.20	3.29 ± 4.59
FULVA DEI MONTI PICENTINI	1	19.07 ± 0.83	19.67 ± 0.76	63.96 ± 0.95	64.82 ± 0.92	0.49 ± 1.25	1.92 ± 4.08
GARFAGNANA	16	17.65 ± 1.82	18.70 ± 1.85	62.50 ± 2.73	64.02 ± 2.73	0.77 ± 2.02	3.19 ± 5.12
GARGANICA	32	19.93 ± 1.55	20.87 ± 1.61	65.15 ± 2.12	66.32 ± 2.17	0.47 ± 1.27	3.21 ± 4.60
GIRGENTANA	23	21.19 ± 1.18	22.00 ± 1.15	67.14 ± 1.59	68.16 ± 1.56	0.54 ± 1.46	2.49 ± 4.27
GRIGIA VALLE LANZO FIURINA	34	14.09 ± 3.43	15.35 ± 3.55	56.98 ± 5.32	58.86 ± 5.37	1.17 ± 2.50	3.56 ± 5.27
JONICA	3	19.85 ± 1.88	20.71 ± 1.83	64.86 ± 2.66	65.95 ± 2.56	0.57 ± 1.29	2.94 ± 4.44
LARIANA O DI LIVO	34	13.64 ± 0.73	14.96 ± 0.87	56.35 ± 1.15	58.37 ± 1.28	1.16 ± 2.48	4.11 ± 5.25
MALTESE	33	18.30 ± 2.71	19.47 ± 2.68	63.23 ± 3.93	64.84 ± 3.76	0.88 ± 2.23	3.55 ± 5.16
MESSINESE	107	20.18 ± 1.17	20.92 ± 1.20	66.04 ± 1.68	67.02 ± 1.76	0.44 ± 1.26	2.26 ± 4.47
NAPOLETANA	3	20.44 ± 0.85	21.47 ± 0.89	66.68 ± 1.12	68.13 ± 1.16	1.19 ± 1.91	5.57 ± 6.53
NICASTRESE	72	20.16 ± 1.52	20.79 ± 1.58	65.94 ± 2.21	66.88 ± 2.30	0.47 ± 1.24	2.82 ± 4.96
OROBICA O DI VAL GEROLA	98	13.11 ± 2.07	14.38 ± 2.13	55.50 ± 3.29	57.48 ± 3.30	1.04 ± 2.51	3.82 ± 4.93
PEZZATA MOCHENA	35	14.49 ± 3.99	15.53 ± 3.89	57.56 ± 6.00	59.15 ± 5.80	0.85 ± 2.19	3.09 ± 4.31
POMELLATA	5	19.04 ± 1.49	20.05 ± 1.52	64.38 ± 2.38	65.69 ± 2.47	0.99 ± 2.59	3.16 ± 5.14
ROCCAVERANO	31	17.05 ± 2.02	18.29 ± 2.06	61.54 ± 3.09	63.35 ± 3.07	1.20 ± 2.58	4.05 ± 5.43
ROSSA MEDITERRANEA	17	20.01 ± 1.60	20.81 ± 1.58	65.49 ± 2.46	66.55 ± 2.44	0.42 ± 1.20	2.46 ± 4.40
RUSTICA DI CALABRIA	113	19.91 ± 1.61	20.54 ± 1.66	65.30 ± 2.30	66.22 ± 2.40	0.47 ± 1.21	2.70 ± 4.85
SAANEN	152	16.81 ± 3.76	18.03 ± 3.74	60.96 ± 5.65	62.68 ± 5.49	0.92 ± 2.28	3.65 ± 5.14
SARDA (C)	146	20.44 ± 1.32	21.51 ± 1.37	66.00 ± 1.82	67.29 ± 1.86	0.81 ± 2.38	2.34 ± 4.09

(Continued on following page)

TABLE 1 (*Continued*) Number of farms and mean ± standard deviation of Summer-T, Summer-THI, and nDays during the first and last 30 years of the analysed period for each goat breed.

Goat breed	N. farms	Summer-T		Summer-THI		nDays	
		1950–1985	1986–2022	1950–1985	1986–2022	1950–1985	1986–2022
SARDA PRIMITIVA	66	19.90 ± 1.24	20.89 ± 1.30	65.60 ± 1.81	66.88 ± 1.91	0.87 ± 2.59	3.11 ± 5.14
SCREZIATA	1	17.63 ± 0.85	18.11 ± 0.76	61.82 ± 1.01	62.52 ± 0.95	0.31 ± 1.08	1.97 ± 4.03
SEMPIONE	3	8.66 ± 0.89	10.11 ± 0.95	48.31 ± 1.45	50.64 ± 1.50	1.01 ± 2.55	3.19 ± 4.03
VALDOSTANA	9	14.05 ± 4.94	15.27 ± 4.71	56.73 ± 7.55	58.59 ± 7.13	1.09 ± 2.40	3.76 ± 5.34
VALLESANA	20	11.93 ± 4.09	13.21 ± 4.10	53.55 ± 6.45	55.54 ± 6.35	1.11 ± 2.52	3.19 ± 4.56
VERZASCHESE	9	14.51 ± 1.60	15.87 ± 1.71	57.70 ± 2.49	59.74 ± 2.57	1.10 ± 2.44	4.27 ± 5.57

unavailable, dedicated literature describes the distribution of numerous populations (Fabbri and Bonacini, 1983; Portolano, 1987; Bigi and Zanon, 2008; Bigi and Zanon, 2020). From these sources, it is evident that for the majority of breeds, changes in distribution over time have been minimal. Also, it is noteworthy that most breeds are named after the geographic area where they originated, and the current distribution indicates that they are still being raised in the same regions.

Statistical analysis

For each location, a linear regression was fitted between the year and summer-T, summer-THI, summer-TP, HW-THI, or nDays, in order to calculate the mean yearly change of the parameter.

Moreover, using JMP® Version 16 (SAS Institute Inc., Cary, NC, 1989–2023), two different linear regression models were fitted to these parameters, in order to explore the differences among Italian regions and sheep or goat populations, respectively:

$$Y = m + year + region + year{*}region + e$$
$$Y = m + year + breed + year{*}breed + e$$

In these models, Y is the climatic parameter, m is the mean, and e is the random residual. The breed-related model was performed for sheep and goat separately and was weighted for the number of subjects of a particular breed that were present in the farm.

Results

Climatic data

As shown in Figure 1, average Italian Summer-T and Summer-THI had a similar trend, with an initial decrease followed by an evident increase after 1980; 2003 and 2022 presented the hottest summers. On the other hand, average yearly Summer-TP did not show a clear trend in the considered period. The number of HW days (nDays) exhibited an obvious increase in the last 25 years; it is worth noting that the years 1983, 2003, and 2015 were characterized by an abnormally high number of HW days when compared to the period. Lastly, the mean THI occurred during HW events appeared to be very variable, but with a growing trend after 2000.

As reported in Figure 2, the greatest increase in Summer-T and Summer-THI occurred in the same regions, namely, central-northern Italy, with special emphasis on the Po Valley and the Alpine Arch, even though the latter corresponds to the region with the lowest mean Summer-T and THI, as expected. The linear regression model (Supplementary Table S1) taking into account the effect of the region and the year*region interaction confirmed that Apulia, Sicily, and Calabria present the highest mean Summer-T and THI values, but also the lowest yearly increase, whereas the opposite is true for Lombardy and Valle d'Aosta. Overall, a negative correlation between the region's mean value and slope was observed.

Average Summer-TP was characterised by a south-to-north gradient, with the lowest values in Sicily and Sardinia and the highest in Friuli-Venezia-Giulia and Trentino Alto Adige. Its variation over the studied period showed a variable distribution, with the highest slopes in the northern regions (Valle d'Aosta and Trentino) and the lowest ones in central Italy (Toscana and Lazio); however, an increase in total precipitation was also observed along the southern Apennines Area, particularly in Calabria.

It is evident that the number of HW days (nDays) has dramatically increased in the second half of the studied period. Overall, the regions with the highest mean nDays corresponded to those with the highest yearly increase, and *vice versa*. Particularly, Lombardy and Friuli-Venezia-Giulia appeared to be the regions at higher risk of experiencing an HW, whereas Sicily and Sardinia, despite presenting mean higher Summer-THI as mentioned before, experienced fewer HW events. An evident increase in nDays was observed along the

 10.3389/past.2024.12848

TABLE 2 Number of farms and mean ± standard deviation of Summer-T, Summer-THI, and nDays during the first and last 30 years of the analysed period for each sheep breed.

Sheep breed	N. farms	Summer-T		Summer-THI		nDays	
		1950–1985	1986–2022	1950–1985	1986–2022	1950–1985	1986–2022
ALPAGOTA	47	14.62 ± 2.53	15.73 ± 2.65	57.83 ± 3.92	59.50 ± 3.97	0.81 ± 2.24	4.43 ± 5.06
ALTAMURANA	10	20.65 ± 1.18	21.59 ± 1.13	66.26 ± 1.55	67.50 ± 1.52	0.45 ± 1.25	3.09 ± 4.96
APPENNINICA	134	18.85 ± 1.55	19.95 ± 1.64	63.96 ± 2.28	65.43 ± 2.37	0.87 ± 1.92	3.26 ± 4.93
BAGNOLESE	119	18.75 ± 1.29	19.72 ± 1.33	63.74 ± 1.91	65.07 ± 1.97	0.75 ± 1.86	3.31 ± 4.75
BARBARESCA	17	20.05 ± 1.59	20.89 ± 1.62	65.83 ± 2.21	66.95 ± 2.23	0.57 ± 1.53	2.65 ± 4.39
BERGAMASCA	52	17.76 ± 2.65	18.82 ± 2.74	62.34 ± 3.88	63.79 ± 3.93	0.80 ± 1.90	2.94 ± 4.11
BIELLESE	14	17.98 ± 2.28	19.27 ± 2.32	62.75 ± 3.31	64.53 ± 3.27	0.98 ± 2.24	3.79 ± 5.39
BRIANZOLA	24	17.19 ± 1.48	18.63 ± 1.64	61.84 ± 2.21	63.84 ± 2.29	1.20 ± 2.50	4.87 ± 5.91
BRIGASCA	4	15.32 ± 2.52	16.38 ± 2.54	59.11 ± 4.09	60.78 ± 4.11	0.80 ± 2.09	2.90 ± 4.85
BROGNE	40	17.68 ± 1.95	18.96 ± 2.10	62.51 ± 2.85	64.27 ± 2.96	0.99 ± 2.32	4.80 ± 5.55
COMISANA	60	20.27 ± 2.25	21.10 ± 2.24	65.70 ± 3.20	66.81 ± 3.19	0.61 ± 1.52	2.73 ± 4.58
CORNELLA BIANCA	4	18.08 ± 1.69	19.32 ± 1.78	62.79 ± 2.34	64.48 ± 2.39	0.88 ± 2.14	3.30 ± 4.80
CORNIGLIO	14	17.49 ± 2.30	18.73 ± 2.44	61.96 ± 3.30	63.64 ± 3.38	1.01 ± 2.25	3.65 ± 4.90
DELL'AMIATA	57	18.97 ± 1.05	20.08 ± 1.10	64.06 ± 1.50	65.53 ± 1.56	0.89 ± 1.84	3.52 ± 5.52
DELLE LANGHE	31	17.60 ± 0.97	18.83 ± 0.97	62.35 ± 1.39	64.11 ± 1.37	1.23 ± 2.58	3.94 ± 5.42
FABRIANESE	33	18.44 ± 1.50	19.52 ± 1.62	63.23 ± 2.17	64.67 ± 2.29	0.80 ± 1.81	2.98 ± 4.02
FRABOSANA	45	15.05 ± 2.66	16.29 ± 2.74	58.44 ± 4.10	60.31 ± 4.14	1.18 ± 2.54	3.35 ± 4.96
GARESSINA	1	20.20 ± 0.74	21.26 ± 0.79	66.31 ± 0.96	67.78 ± 1.07	0.89 ± 2.18	4.32 ± 5.58
GARFAGNINA BIANCA	28	18.21 ± 2.07	19.24 ± 2.11	63.35 ± 3.14	64.84 ± 3.16	0.88 ± 2.13	3.79 ± 5.65
GENTILE DI PUGLIA	36	20.36 ± 1.95	21.27 ± 1.98	65.68 ± 2.69	66.86 ± 2.71	0.47 ± 1.30	2.81 ± 4.47
ISTRIANA-CARSOLINA	6	17.95 ± 1.14	19.12 ± 1.19	63.13 ± 1.73	64.77 ± 1.74	1.07 ± 1.89	5.52 ± 5.98
LAMON	23	14.28 ± 2.07	15.30 ± 2.14	57.34 ± 3.26	58.92 ± 3.29	0.84 ± 2.28	3.92 ± 4.66
LATICAUDA	60	18.96 ± 1.16	19.95 ± 1.14	63.83 ± 1.57	65.14 ± 1.57	0.82 ± 1.97	2.62 ± 3.64
MASSESE	85	18.69 ± 1.72	19.77 ± 1.77	63.96 ± 2.57	65.47 ± 2.61	0.84 ± 2.06	3.63 ± 5.43
MERINIZZATA ITALIANA	130	18.19 ± 1.93	19.00 ± 1.95	62.50 ± 2.59	63.60 ± 2.61	0.52 ± 1.35	2.82 ± 4.39
MOSCIA LECCESE	17	19.34 ± 4.38	20.33 ± 4.23	64.55 ± 6.45	65.95 ± 6.13	0.61 ± 1.71	3.63 ± 5.64
NERA DI ARBUS	98	20.36 ± 1.31	21.50 ± 1.37	65.92 ± 1.84	67.31 ± 1.90	0.68 ± 2.09	1.78 ± 3.61
NOTICIANA	1	22.62 ± 0.59	23.33 ± 0.67	70.01 ± 0.75	70.96 ± 0.88	0.66 ± 1.59	3.95 ± 5.82
PECORA CIUTA	17	10.32 ± 3.15	11.64 ± 3.15	50.99 ± 5.02	53.09 ± 4.94	0.95 ± 2.43	3.20 ± 4.55
PECORA DI CORTENO	15	11.45 ± 2.14	12.86 ± 2.19	52.75 ± 3.30	54.95 ± 3.21	0.97 ± 2.64	3.03 ± 4.29
PINZIRITA	20	21.87 ± 1.05	22.68 ± 1.07	68.65 ± 1.55	69.68 ± 1.57	0.68 ± 1.66	3.50 ± 6.06
PLEZZANA	4	15.37 ± 1.27	16.52 ± 1.31	59.02 ± 1.95	60.73 ± 1.96	0.99 ± 2.14	4.40 ± 5.14
POMARANCINA	34	19.58 ± 0.92	20.66 ± 0.95	65.22 ± 1.36	66.70 ± 1.42	0.73 ± 1.83	3.55 ± 5.47
ROSSET	74	9.67 ± 1.92	11.07 ± 1.92	49.96 ± 3.18	52.18 ± 3.10	1.19 ± 2.58	3.37 ± 4.70
SAMBUCANA	59	14.16 ± 3.19	15.42 ± 3.27	57.00 ± 4.99	58.92 ± 5.01	1.11 ± 2.51	3.10 ± 4.62

(Continued on following page)

TABLE 2 (*Continued*) Number of farms and mean ± standard deviation of Summer-T, Summer-THI, and nDays during the first and last 30 years of the analysed period for each sheep breed.

Sheep breed	N. farms	Summer-T		Summer-THI		nDays	
		1950–1985	1986–2022	1950–1985	1986–2022	1950–1985	1986–2022
SARDA (O)	648	20.18 ± 1.30	21.32 ± 1.34	65.64 ± 1.87	67.05 ± 1.89	0.78 ± 2.24	2.21 ± 4.04
SAVOIARDA	6	16.20 ± 3.00	17.57 ± 3.16	60.16 ± 4.53	62.09 ± 4.61	1.11 ± 2.45	4.04 ± 6.00
SCHWARZNASENSCHAF	23	13.78 ± 3.54	15.04 ± 3.66	56.45 ± 5.49	58.33 ± 5.52	0.96 ± 2.35	3.45 ± 4.62
SCIARA-MOSCIA CALABRESE	5	19.45 ± 1.26	20.08 ± 1.32	64.89 ± 1.81	65.85 ± 1.91	0.37 ± 1.05	2.69 ± 4.65
SOPRAVISSANA	56	18.33 ± 2.00	19.39 ± 2.14	63.13 ± 3.03	64.55 ± 3.18	0.86 ± 1.93	3.18 ± 5.04
TACOLA	102	15.02 ± 3.24	16.35 ± 3.31	58.38 ± 4.99	60.33 ± 4.95	1.12 ± 2.45	3.71 ± 5.37
TRIMETICCIA DI SEGEZIA	1	17.92 ± 0.93	18.82 ± 0.87	62.21 ± 1.13	63.43 ± 1.08	0.43 ± 1.24	2.34 ± 3.35
TURCHESSA	5	19.91 ± 0.98	20.97 ± 1.00	65.56 ± 1.37	67.00 ± 1.42	0.98 ± 2.06	3.67 ± 4.70
VALLE DEL BELICE	248	21.47 ± 1.23	22.29 ± 1.23	67.43 ± 1.88	68.44 ± 1.91	0.63 ± 1.55	2.48 ± 4.49
VICENTINA-FOZA	13	17.05 ± 2.44	18.24 ± 2.63	61.57 ± 3.68	63.25 ± 3.82	0.87 ± 2.25	4.84 ± 5.53
VILLNOESSER SCHAF-FIEMMESE	33	12.34 ± 2.68	13.42 ± 2.75	54.32 ± 4.24	56.00 ± 4.30	0.91 ± 2.26	2.95 ± 4.03
ZERASCA	20	16.86 ± 0.96	17.99 ± 1.01	61.35 ± 1.45	62.98 ± 1.50	1.05 ± 2.36	3.49 ± 4.85

Tyrrhenian coasts. As expected, the HWs were overall characterized by higher THI in southern Italy (Apulia and Sicily), but the highest increase in HW intensity was observed in the northern regions, especially Valle d'Aosta and Trentino Alto Adige, as well as the coasts.

Italian sheep and goat distribution and model

All the analysed goat and sheep farms have been plotted in Figure 3. It should be noted that the present study only considered farms that were registered to Asso.Na.Pa. and resulted still in activity at the end of 2022. All the analysed breeds originated in Italy, with the exception of the Saanen goat, which has Swiss origins. However, it was included due to its widespread breeding in Italy, thus constituting an important component of the Italian goat breeding landscape.

With a total of 1,349 farms and 124,524 animals, goat breeding is highly represented in the northern part of Italy and, to a lesser extent, in the South -particularly in Calabria and Basilicata- and the two main islands, i.e., Sicily and Sardinia. A different distribution was observed for the 315,204 sheep, reared in 2,363 farms that are more evenly distributed along the Italian peninsula, they being especially numerous in the central-southern regions, in the very northern Italy, and in the two isles.

A model was performed to analyse the climate changes related to the different sheep and goat breeds, according to the locations of the farms they are reared in. Tables 1, 2 report the mean values of the three main parameters (summer-T, summer-THI, and nDays) in the first and last analysed 30 years for goat and sheep breeds, respectively, whereas the results of the models can be found in Supplementary Table S2.

Girgentana, Dell'Aspromonte, Napoletana, and Sarda were the goat breeds with the highest mean summer-T and summer-THI (breed least square means ranged from 21.26°C to 21.60°C and from 66.94 to 67.92 THI points, respectively); with regard to sheep, Noticiana, Moscia Leccese and Valle del Belice had the highest values (21.97°C–22.99°C and 68.06–70.50 THI points). The lowest mean values were observed for Sempione, Frisa Valtellinese, Valdostana, and Vallesana goats (9.26°C–12.43°C and 49.29 to 54.29 THI points), and for Rosset, Pecora Ciuta, and Pecora di Corteno sheep (10.00°C–12.24°C and 50.49–53.98 THI points). As expected, the animals reared in the northern regions usually experienced lower summer-T and THI. However, the opposite was found for slope, meaning that the breeds that have never been used to, and thus selected for, high temperature and THI, are going to live in regions becoming hotter and hotter if this trend persists. Particularly, the highest slopes were associated with Sempione, Lariana o Di Livo, Frisa Valtellinese, and Orobica goat for both summer-T and summer-THI (+0.030 to +0.03°C/year and +0.047 to +0.053 THI points/year); among the sheep breeds, Savoiarda, Brianzola, and Pecora di Corteno (+0.032 to +0.034°C/year and +0.047 to +0.050 THI points/year) had the highest slope for summer-T, and Pecora di Corteno, Rosset, and Pecora Ciuta for summer-THI. On the other hand, southern breeds live in more stable (i.e., having a lower slope) regions; this

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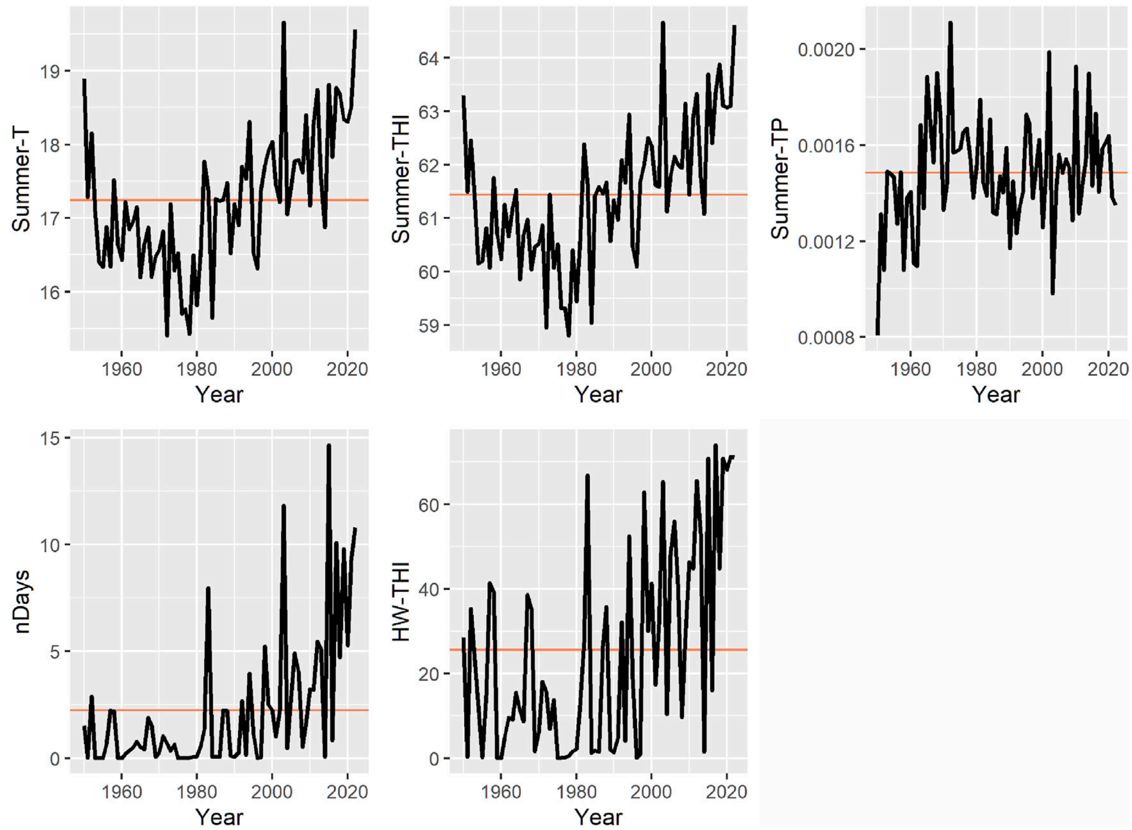

FIGURE 1
Lineplots of yearly Italian mean temperature, THI, and total precipitation during summer (Summer-T, Summer-THI, and Summer-TP, respectively), mean number of heat wave days (nDays) and average THI during heat waves (HW-THI) from 1950 to 2022. The horizontal red lines indicate the mean value when the whole studied period is considered.

was particularly true for Screziata, Fulva dei Monti Picentini, and Nicastrese goats -notably, all Calabrian breeds- (+0.009 to +0.012°C/year and +0.014 to +0.020 THI points/year) and Sciara-Moscia Calabrese and Barbaresca sheep (+0.010 to +0.016°C/year and +0.0180 to +0.022 THI points/year). Some of the breeds with the most divergent characteristics were plotted in Figure 4 (only summer THI was considered, given the similarity with summer-T maps and results).

Overall, northern breeds had the highest mean summer-TP values -such as Sempione, Orobica, and Vallesana goats (0.0025–0.0033 mm), and Lamon, Brianzola, and Tacola sheep (0.0026–0.0034 mm)-, whereas breeds reared in southern Italy and the isles, including Girgentana, Sarda, and Dell'Aspromonte goats (0.0004–0.0005 mm), and Noticiana, Valle del Belice, and Nera di Arbus sheep (0.0003–0.0005 mm), live in a drier environment. However, the differences in terms of summer-TP slope did not present a clear pattern as observed for summer-T and THI. Indeed, breeds from Calabria (Nicastrese goat and Sciara-Moscia Calabrese sheep), Veneto (Lamon and Vicentina Foza sheep), and Lombardy (Bionda dell'Adamello goat) were associated with an increase in precipitations, and others from Tuscany (Garfagnana goat and Garfagnina Bianca and Massese sheep) as well as Lombardy (Lariana o Di Livo and Orobica goat and Brianzola sheep) with decreased precipitations.

Lastly, the variables related to HW were modelised. We observed that Napoletana, Pomellata, and Ciociara Grigia, located in Campania and Lazio respectively, had the highest mean and slope for nDays among goats (2.96–3.37 days/year and +0.12 to +0.13 days/year, respectively), whereas the Screziata, Fulva dei Monti Picentini, and Girgentana (located in Calabria, Veneto, and Sicily, respectively) the lowest values (1.18–1.37 days/year and +0.04 to +0.05 days/year). However, it should be noted that some northern breeds, such as Lariana or Di Livo, Orobica, and Camosciata delle Alpi (one of the main and most specialised dairy breeds) had rather high slopes (+0.09–0.10 days/year). Consistently with the overall summer values, the highest mean HW-THI were found for Napoletana (76.35 THI points) and other southern breeds such as Dell'Aspromonte, Argentata dell'Etna, and Sarda goats (75.55–75.96THI points), and the lowest for northern breeds including Sempione, Frisa Valtellinese, Valdostana, and Vallesana (60.90–65.73 THI points). Di Potenza goats had the

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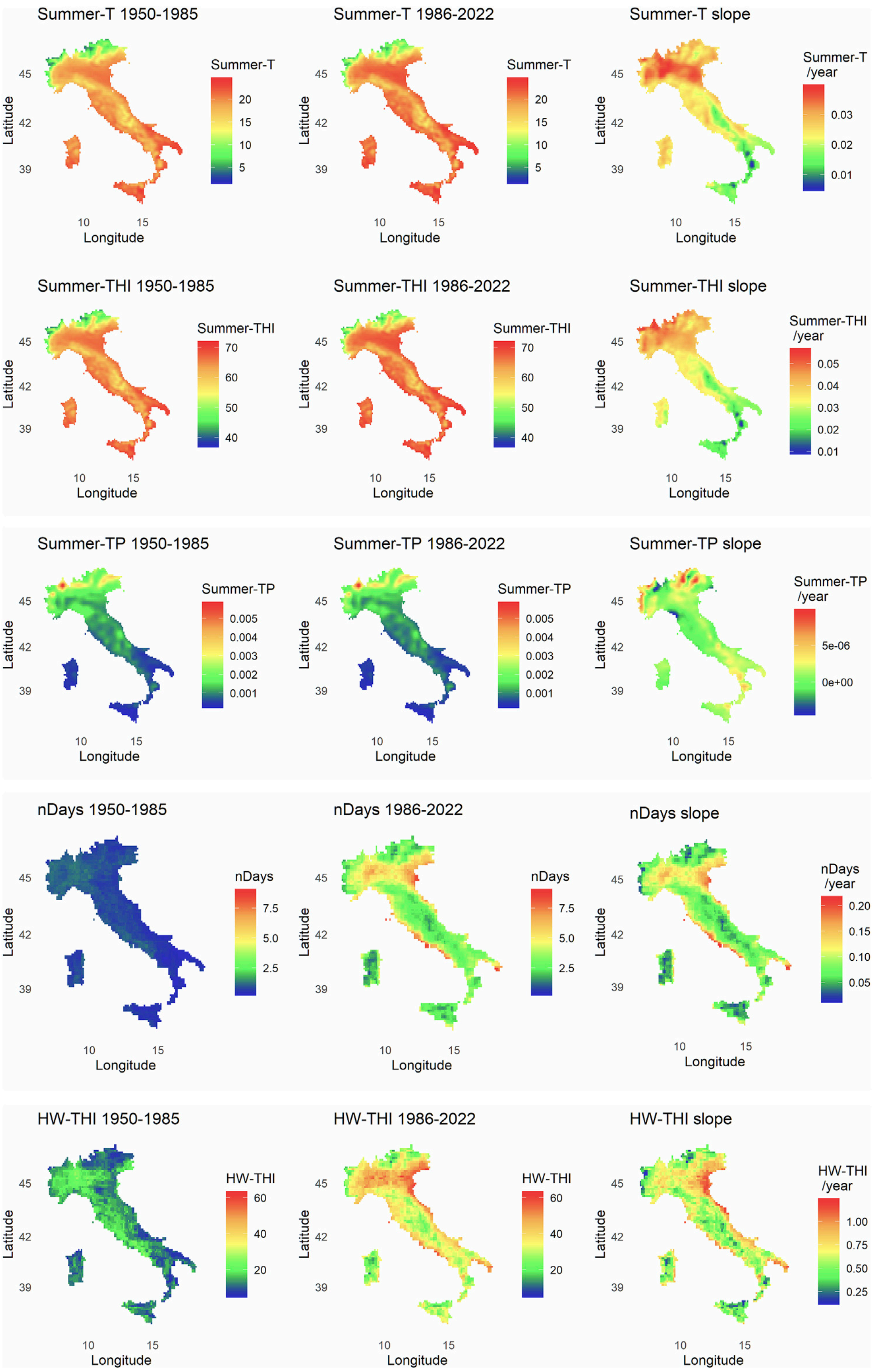

FIGURE 2
Comparison of mean temperature, THI, and total precipitation during summer (Summer-T, Summer-THI, and Summer-TP, respectively), mean number of heat wave days (nDays) and average THI during heat waves (HW-THI) in 1950–1985 and 1986–2022, and their slope along this period.

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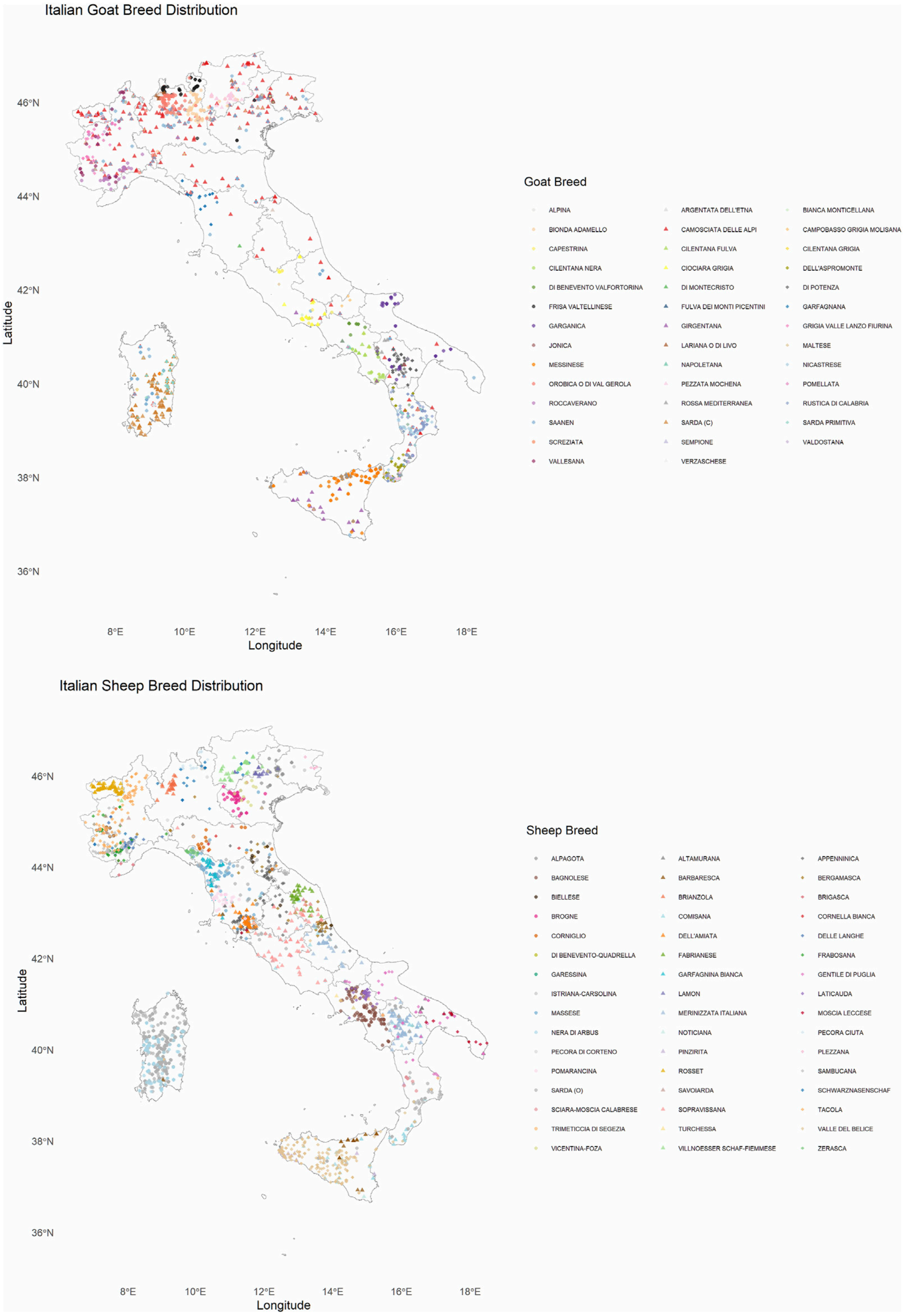

FIGURE 3
Distribution of Italian goat and sheep farms by breed.

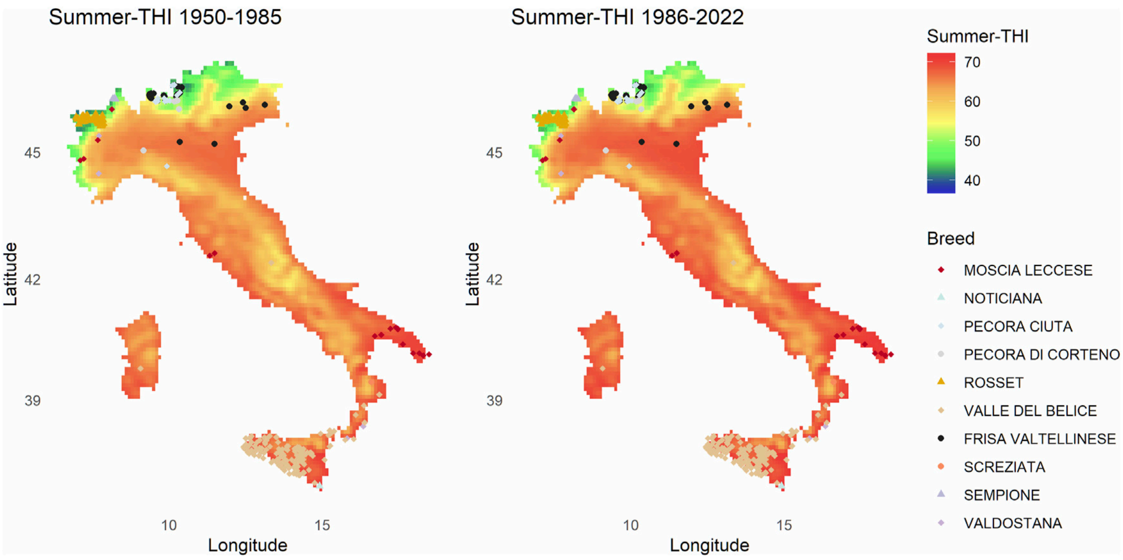

FIGURE 4
Representation of sheep and goat breeds with divergent values for summer-THI mean and slope. Southern breeds such as Moscia Leccese and Noticiana sheep and Valle del Belice and Screziata goats presented high mean summer-THI but low slopes, whereas the opposite was found for Pecora Ciuta, Pecora di Corteno, and Rosset sheep and Frisa Valtellinese, Valdostana, and Sempione goats.

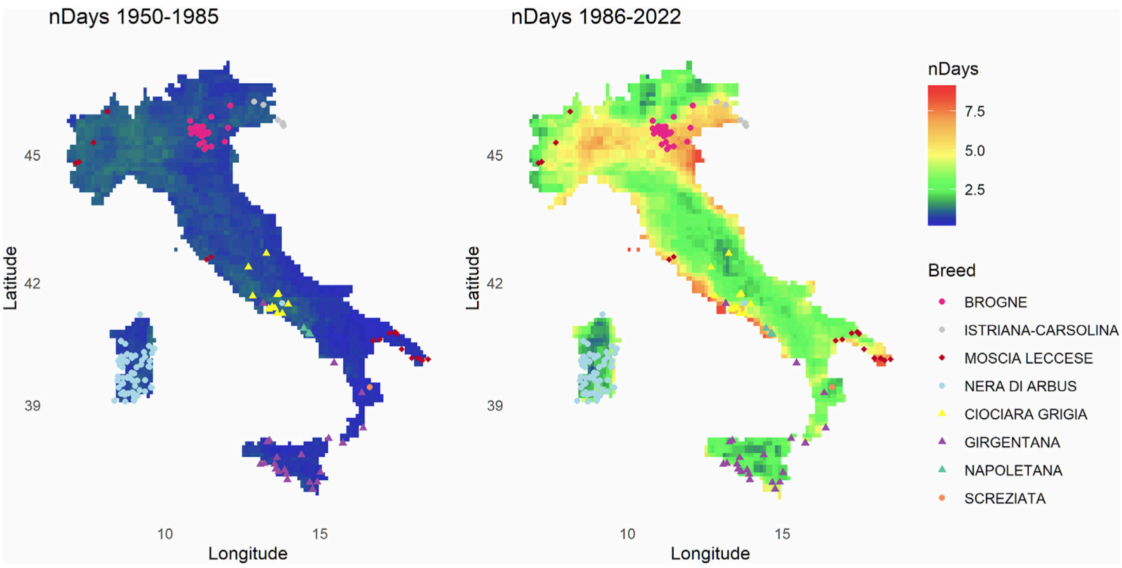

FIGURE 5
Representation of sheep and goat breeds with divergent values for nDays mean and slope. Brogne and Istriana-Carsolina sheep as well as Napoletana and Ciociara Grigia goats had both high mean and slope, whereas the opposite was true for Nera di Arbus and Moscia Leccese sheep and Girgentana and Screziata goats.

highest slope (+0.022 THI points/year), and Screziata had the lowest one (+0.004 THI points/year).

With regard to sheep, northern breeds -e.g., Istriana-Carsolina and Brogne- were characterized by both high nDays mean and slope values (2.95–3.33 days/year and +0.11 to +0.12 days/year), whereas southern breeds -e.g., Moscia Leccese and Nera di Arbus- by both low nDays mean and slope values (1.18–1.23 days/year and +0.05 to +0.06 days/

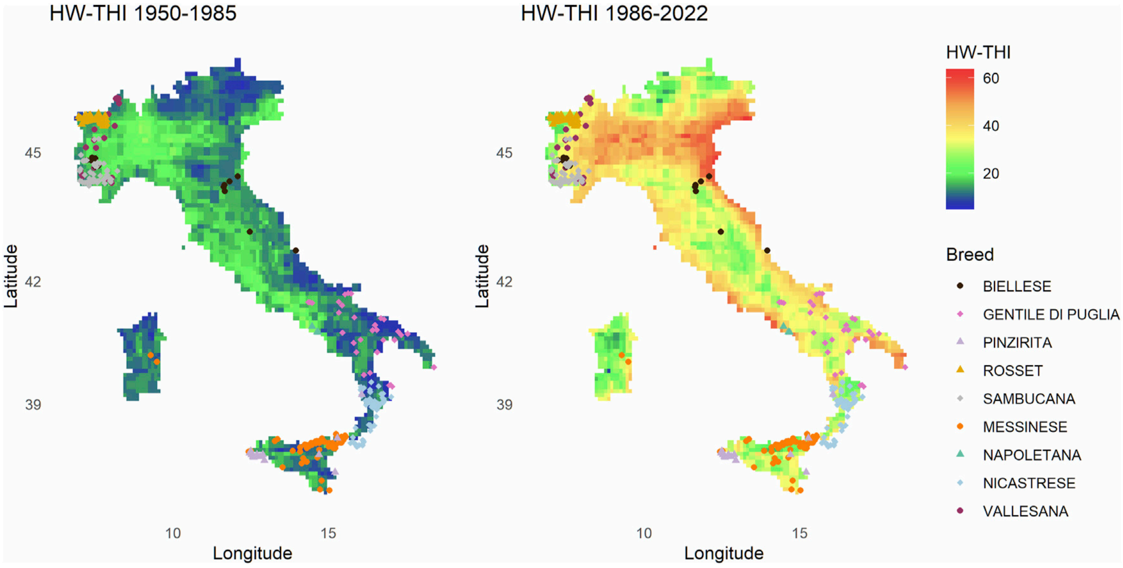

FIGURE 6
Representation of sheep and goat breeds with divergent values for HW-THI mean and slope. High mean and slope values were found for Biellese and Gentile di Puglia sheep as well as Napoletana and Nicastrese goats; the opposite was found for Rosset sheep and Vallesana goats. Moreover, Pinzirita sheep and Messinese goats had a high HW-THI mean but a low slope, whereas Sambucana sheep had a low mean but a high slope.

year). High mean HW-THI were associated with southern breeds (Noticiana, Moscia Leccese, and Pinzirita, ranging from 76.51 to 77.90 THI points), and low means to northern breeds (Rosset, Ciuta, and Fiemmese, ranging from 63.068 to 65.574 THI points), as expected. However, the highest slope was found for Gentile di Puglia breed, followed by Bergamasca (a sheep diffusely bred for meat production) and Biellese (+0.024 to +0.026 THI points/year), whereas the lowest slopes were found for Alpagota, Lamon, and Fiemmese breeds (−0.001 to +0.012 THI points/year). Some of the breeds with the most “extreme” nDays and HW-THI characteristics were represented in Figures 5, 6, respectively.

Sarda sheep, Camosciata delle Alpi, and Saanen goats are the most prevalent breeds in Italy. All of them are specialized in milk production and commonly reared in intensive or semi-intensive farming systems, reducing the impact of environmental variables. The Sarda sheep constitutes the largest ovine population, with 166,730 registered animals and 648 farms, with nearly 90% located in Sardinia. Climatic data analysis indicates that this population predominantly inhabits areas characterized by high but stable summer-T and THI, along with low summer-TP and nDays. Moreover, there is a negative slope for nDays (−0.06 days/year) over the studied period (Figure 7). Camosciata delle Alpi ranks as the most numerous goat breed in Italy, with 13,203 heads distributed across 203 farms, with over 70% of these goats bred in Northern Italian regions, particularly Lombardy. Saanen goat breed counts 12,636 registered heads across 152 farms, primarily found in Sardinia and Northern Italy. Among both the Saanen and Camosciata breeds, small farms (with fewer than 50 animals) make up more than half of the total farms, while around 28% and 16%, respectively, house over 100 animals. However, it is noteworthy that 18% of Saanen goats are concentrated in the 2% of farms with over 500 heads. Often, Saanen and Camosciata delle Alpi are reared together with other breeds (two-thirds and half of the farms, respectively). Analysis reveals an increase in summer-T, summer-THI, and nDays for both breeds during the study period (Figure 7).

Discussion

This study represents, at best of our knowledge, the first effort in comprehensively analysing the distribution of all registered and active farms of Italian sheep and goat local breeds and examining the climate changes that these populations have been subjected to in the past seven decades. Our findings is underlined by the Food and Agriculture Organization (FAO, 2024), which underscores the importance of assessing the distribution of local breeds, considered invaluable resources for confronting future climate changes, and the potential risks they face (FAO, 2015).

Our data reveal notable disparities in the distribution of goat and sheep farms across Italy. Goats are predominantly

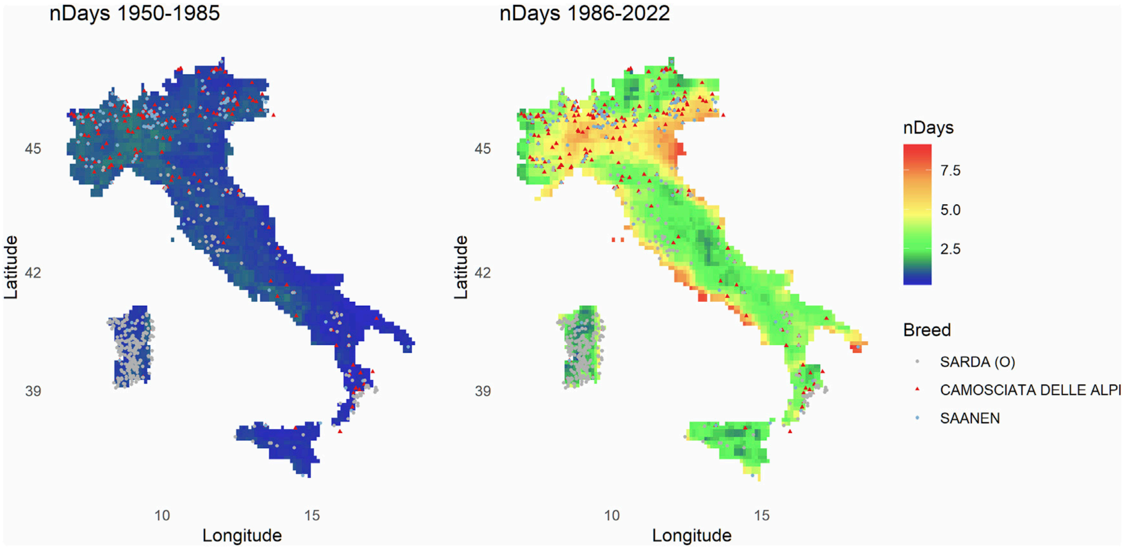

FIGURE 7
Representation of the three main sheep (Sarda) and goat (Camosciata delle Alpi and Saanen) breeds reared in intensive or semi-intensive farming systems Italy and comparison between the mean number of heat wave days (nDays) in 1950–1985 vs. 1986–2022.

concentrated in the northern regions, with a limited presence in the South, specifically Calabria and Basilicata, as well as the islands of Sicily and Sardinia. In contrast, sheep farms are more evenly distributed throughout the Italian peninsula, with higher concentrations in central-southern regions, northern Italy, and the islands. Consistently with what reported by the Italian National Institute of Statistics (ISTAT, 2022) and the National Database of Animals and Holdings (BDN) (Anagrafe Nazionale Zootecnica, 2022), Sardinia counts the majority of both farms and animals -about half of sheep and a quarter of goats-, followed by Sicily, whereas goats only are also high represented in Lombardy and Calabria. Our data also underscore the presence of several breeds with extremely restricted breeding ranges; specifically, 10 sheep and 12 goat populations were raised in fewer than ten registered farms. Conversely, our dataset also encompasses some widely distributed populations, including the Sarda sheep, as well as the Saanen and Camosciata delle Alpi goats. All of them are reared for milk and cheese production and mainly rared in intensive or semi-intensive farms.

The climate data presented in this study depict a concerning trend of increasing summer temperatures, temperature humidity index (THI), and heat wave (HW) frequency and intensity, particularly over the last three decades; most notably, we propose a definition of heatwaves that incorporates THI, a widely recognized index for assessing livestock heat stress (Herbut et al., 2018; Wijffels et al., 2021). Our findings are in accordance with the literature about climate changes occurring and foreseen in Europe and Italy (Brunetti et al., 2004; Toreti and Desiato, 2008; Christensen et al., 2015; Twardosz et al., 2021; Kotlarski et al., 2022). The regions most affected by these changes are situated in central-northern Italy, including the Po Valley and the Alpine Arch, thus interesting breeds such as Rosset and Brogne sheep, and Lariana and Frisa Valtellinese goats. This poses a challenge because livestock breeds traditionally raised in these regions have not been selected for, and thus are not adapted to, hot climates. Furthermore, the often small population size of most of the highly impacted breeds exacerbates the situation, calling for potential interventions and changes in farm structures to ensure their survival and productivity. Conversely, the relative stability observed in southern Italy, which has always been characterized by hotter and drier temperatures, positions Sicilian, Calabrian, and Sardinian breeds -e.g., Girgentana and Nicastrese goats and Nera di Arbus sheep-, especially if reared in extensive or semi-extensive systems, as excellent case studies for climatic adaptation and possible resources for future selection and breeding efforts to enhance resilience in the face of ongoing climate changes. In this regard, further evaluation of the effects of heat stress on different Italian sheep and goat populations (as in Finocchiaro et al., 2005; Peana et al., 2007), as well as the establishment of specific reference thermotolerance ranges (as in Ferreira et al., 2023), might prove beneficial.

In conclusions, this paper provides an overview of the distribution and population size of Italian small ruminants, offering valuable insights into the conditions and changes they have been subjected to over the past seven decades in terms of summer temperature, THI, and HWs. These data are instrumental for devising precise monitoring and intervention strategies for breeds that may face future vulnerabilities. By combining this information with other environmental risks, inbreeding-related concerns, and population size, it would be possible to develop comprehensive strategies to protect these invaluable genetic resources. Moreover, the data presented herein offer a foundation for designing experiments aimed at investigating the environmental adaptability of these animals, by assisting in the selection of the breeds that, having thrived and evolved in diverse environmental conditions, are the most suitable for being compared.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

AB: Methodology, software, formal analysis, writing–original draft, writing–review and editing, visualization; MC: Writing–review and editing; AN: Resources, writing–review and editing; PC: Conceptualization; methodology; validation; writing–review and editing, supervision, project administration, funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2024.12848/full#supplementary-material

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