EXTERNAL SCIENTIFIC REPORT

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Analysis of wild ungulate-livestock interface in Europe: preliminary results

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Abstract

The ENETWILD consortium (www.enetwild.com) aims at progressively defining the spatial interface between wild ungulates and livestock in Europe, which is essential to evaluate the risk for shared diseases. This is to provide preliminary risk maps of possible wild-domestic interfaces at European scale using relatively similar sized regions by compiling, for the first time, comprehensive data for both groups, wild and domestic ungulates in the continent. We spatially represented (i) the richness of species (livestock and wild ungulates), (ii) their specific occupancy and abundance (the latter for livestock), and finally, (iii) their spatial overlapping over Europe. Species richness in animal communities, including wildlife and domestic hosts, may moderate pathogen transmission and disease outcome.. As a first step, we should characterize the diverse assemblages of animal communities at large scale to better understand possible scenarios for further assessment of shared infection dynamics. About 90% of Europe land area hosts from one to five species of wild native ungulates. Therefore, the interface between livestock and wildlife is wide spread over the European continent. Native wild boar, roe deer and reed deer are widely distributed species, present in most possible assemblages of wild/domestic communities over Europe. The richness of ungulate species is high in Central Europe, from West to East, from the Alps (where the presence of mountain ungulates adds richness), extending to countries with important big game tradition and presence of introduced species, and finally, to Eastern Europe (where also typically northern species such as bisons appear)... To sum, we described by pair of species a wide diversity of potential interfaces, which had variable distribution areas.. While the analysis presented herein is purely spatial and at administrative level, the interface between wild and domestic ungulates is influenced by livestock husbandry (e.g., enclosed, herded or free-ranging, level of biosecurity), landscape and land uses, and wildlife management practices, among other factors, operating locally. Therefore, there is need for a more detailed picture of the interface at European scale.

Key words: distribution, wild ungulates, interface, livestock, Eurostat, risk assessment, spatial modelling.

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Summary

The ENETWILD consortium (www.enetwild.com) aims at progressively defining the spatial interface between wild ungulates and livestock in Europe, which is essential to evaluate the risk for shared diseases between wild and domestic. ENETWILD has provided several spatial distribution model updates of wild boar with new data from gap areas, continuously verifying and validating the methodological approach, including a model of wild boar hunting yield predictions downscaled to a 2x2 km grid, which was already used as a starting point to analyse the potential areas of overlap between wild boar and domestic pig across Europe (ENETWILD consortium 2020a, 2020b). Recently, first models for wild ruminants based on presence data were presented by ENETWILD (ENETWILD consortium 2021) and efforts continue to refine them, so as to incorporate hunting statistics. In this report we present an analysis of the spatial overlapping between the distribution of livestock and wild ungulates at highest possible and relatively similarly sized administrative level to date. This is to provide a general picture of Europe (using relatively similar-sized regions), or preliminary risk maps of ungulate species asemblages and possible interfaces, compiling for the first time, comprehensive data for both groups. We spatially represented (i) the richness of species (livestock and wild ungulates), and (ii) their specific occupancy and abundance (the latter for livestock) for administrative units (at spatial resolution of similarly sized administrative regions (NUTS 2 or higher resolution). Finally, (iii) we depict their spatial overlapping over Europe for pair wildlife-domestic species. Species richness in animal communities, including wildlife and domestic hosts, may moderate pathogen transmission and disease outcome. The result depends both on patterns of host species biodiversity, and on the specific composition of reservoir hosts, livestock husbandry and wildlife ecology and management. As a first step, we should characterize the diverse assemblages of animal communities at large scale to better understand possible scenarios for further assessment of shared infection dynamics.

Data: As for livestock, overall, data is usually available aggregated at large administrative level, but we found exceptions for some species in certain areas, which impeded full assessment over Europe (important data gaps). The present Europe-wide livestock census distribution information is generally restricted to a spatial resolution of NUTS 2 (province level), although downscaling modelling frameworks developed to disaggregate livestock data up to 1 km grid level (Gridded Livestock of the Word by FAO, GLW) need be validated for ruminants. Overall, land-related, and climatic factors can only, to a certain extent, explain the current spatial domestic livestock distribution in Europe and, therefore, determining the real distribution (having reliable complete data on distribution and abundance, and metadata, at high resolution) rather than modelling it, is needed. Reliable and accessible information on the distribution and abundance of livestock in Europe at higher possible resolution is needed for analyses of the risk at livestock/wild ungulate interface. However, abundance and distribution data for livestock seem to be even less accessible than for wild ungulates. When attending to national sources of data in Europe for livestock, there is a mosaic of data from different spatial resolutions, time periods, and classification of farming production systems. Livestock are produced throughout the EU on several types of farms with considerable variations between Member States. Extensive farming regions can be risky areas for interaction with wildlife. To date, the exact and complete distribution of housing types (outdoor vs indoor, extensive vs intensive) of the livestock are unobtainable. It is not possible to differentiate between backyard and outdoor production systems (backyard herds do not have a complete fence, and the livestock are not enclosed). To interpret livestock farming patterns, there is a need to aggregate standardized data describing the types and numbers of animals raised in an area, being optimal detailed geographical coordinates. At European scale (covering the whole continent), only reliable predictive models are available for wild boar distribution and abundance, and first models are being developed for ruminant species. This will allow depicting the livestock/wild ungulate interface more reliably, complete (in spatial terms) and at higher resolution. Therefore, the ENETWILD initiative is essential to create central databases of

parameters in this endeavour, but there is a need to centralize and unify the collection of livestock data.

Assessment of the interface (proxy to) at European scale: the analysis of the spatial overlapping between the distribution of livestock and wild ungulates at highest possible administrative level, to date, provided a general picture of Europe (using relatively similar sized regions). Since 90% of Europe's land area hosts from one to five species of wild native ungulates, the interface, in whatever form and composition between livestock and wildlife, can be considered almost continuous over the European continent. Native wild boar, roe deer and reed deer are widely distributed species, present in most possible assemblages of wild/domestic communities over Europe. Mountain ungulates, mostly native, add diversity locally in mountainous areas. The introduced species tended to have more limited distributions, although a few areas have up to four sympatric species and some are relatively widespread (namely, fallow deer and mouflon). For several species, the distribution was linked to protected areas, which are crucial points for the study of the interface and shared diseases, so as to develop control options.

The assessment of epidemiology and transmission of shared pathogens in Europe should rely on previous characterization of the prevalent ungulate community assemblages (specific pair or multiple-species), whose spatial distribution is, for the first time, shown in this report. A wide diversity of potential interfaces is possible, since species had highly variable distribution areas. The richness of ungulate species is high in Central Europe, from West to East, from the Alps (where the presence of maintain ungulates add biodiversity), extending to countries with important big game tradition and presence of introduced species (Hungary, Czech Republic, Germany), to Poland (where also typically northern species, such as moose or bison, appear). However, presence of medium to high richness also occurs sparsely in certain administrative regions all over Europe due to the effect of different causes at local scale (presence of mountain ungulates, introduced species, or northern species such as reindeer). Cattle, beef, and dairy present relatively similar distributions patterns, being more abundant in central Europe (France, Germany, Northern Italy, countries nearby to Poland, and in Turkey). However, national patterns may differ internally (for both typologies of cattle, respectively). The other bovine, buffalo, is mainly distributed East to the Balkans (Bulgaria, Romania, Turkey), in Italy, and to a less extent, in other countries. Overall, goats and sheep predominate in the Mediterranean regions, being remarkable exceptions such as sheep in the British Isles, and goats in the Netherlands.

While this analysis is purely spatial and at administrative level, the interface between wild and domestic ungulates is influenced by livestock husbandry (e.g., enclosed, herded or free-ranging, level of biosecurity), landscape and land use, and wildlife management practices, among other factors, operating locally. Sheep, goats, and beef cattle (but also pigs and horses in several regions) are extensively grazing in different pastureland systems, which may have the greatest interface. It is noteworthy that ungulate species present clear distribution pattern within administrative units, for instance, mountain ungulates tend to be present only in mountainous areas within each administrative region. Therefore, there is need for a more detailed picture of the interface at European scale. The distribution and abundance of wild ungulates in Europe is dynamic and, in general, increasing. For that reason, mapping their distribution and interfaces with domestic ungulates should be a continuous activity. There exists special concern for certain introduced species about their expansion, and for different reasons (e.g., conservation issues). For instance, Asian deer species introduced into central Europe and the UK.

Next steps: concerning data on livestock distribution and census at European level, next steps are (i) to harmonize and collect data at the highest possible spatial resolution for all European Countries, and (ii) to collect data that allow to differentiate intensive from extensive types of production (and outdoor from indoor, at least in certain phases of the production system). As for the wild ungulates, and namely wild ruminants, (iii) efforts to develop reliable abundance models focused on hunting yield and occurrence data will be addressed (deliverable by Dec 2021 and continued later). This will allow (iv) describing the multiple interfaces and scenarios established by livestock and wildlife more reliably and at highest spatial resolution.

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1. Introduction

1.1. Background and Terms of Reference as provided by the requestor

This contract was awarded by EFSA to Universidad de Castilla-La Mancha, contract title: Wildlife: collecting and sharing data on wildlife populations, transmitting animal disease agents, contract number: OC/EFSA/ALPHA/2016/01-01. The terms of reference for the present report (deliverable D5.2, SC8) were to update the model of interface between wild and domestic ungulates. Report and extractable and updatable raster files of wild and domestic ungulates interface at level of presence, abundance (overlapping) to show potential risk of contact all over Europe.

1.2. Scope of the report

The ENETWILD consortium (www.enetwild.com) implemented an EFSA funded project whose current main objective is to collect information regarding the geographical distribution and abundance of wildlife throughout Europe to subsequently create geospatial tools to be used in further risk assessment of diseases, such as ASF in wild boar and pigs. ENETWILD consortium has provided several spatial distribution model updates of wild boar with new data from gap areas, continuously verifying and validating the methodological approach. Recently, first models based on occurrence data were presented for wild ruminants.

According to the availability and quality of livestock data, the output of this report will be a risk map/s of possible spatial interaction between wild ungulates and livestock species (ungulates). As a necessary first step for ruminants (a previous report addressed wild boar/pig interface in detail, which are also included in the present report), this report presents an analysis of the spatial overlapping between their distribution and wild ungulates at highest possible administrative level to date. This is to provide a general picture of Europe (using similar sized regions), or preliminary risk maps of possible interfaces, compiling for the first time, comprehensive data for both groups. We spatially represented (ii) the richness of species (livestock and wild ungulates), (ii) their specific occupancy and abundance (the latter for livestock) for administrative units, and finally, (ii) their spatial overlapping over Europe. Outputs will guide future spatial description and modelling of the data collection within SC9 time scope. First models based on hunting statistics will be developed at high resolution for wild ruminants, which will be a starting point to analyse the potential areas of overlap between all wild ungulates (wild boar plus ruminants) and domestic livestock (ungulates) at higher resolution, and quantitatively.

Current scientific debate addresses how species richness in animal communities moderates pathogen transmission and disease outcome (e.g. Barasona et al. 2019). Transmission and persistence of a specific pathogen, vector in a given host community depends both on patterns of host species biodiversity, and on the specific composition of reservoir hosts, livestock husbandry and wildlife ecology and management. This has practical consequences, for instance, to redirect scarce animal, public health, wildlife management or conservation resources, it is critical to understand the relationship between host richness, specific assemblages (pair or multiple-species) and disease risk. However, in most cases, we are unaware of the spatial distribution of host communities, including both wild and domestics (their interface). Therefore, as a first step, we should characterize the diverse assemblages of animal communities at large scale in Europe to better understand possible scenarios for further assessment of shared infection dynamics.

2. Data

2.1. Study area

The study area spans 11,538,932 km^2. It comprises all countries in mainland Europe, approximately delimited by the Ural Mountains at the Eastern boundary, which is also likely to act as a geographical barrier, and includes Mediterranean islands as well as the UK and Ireland.

2.2. Wild ungulate distribution

2.2.1. GBIF data

Presence of ungulates species was downloaded using the rgbif 3.6.0 package (Chamberlain et al. 2021) on 12/11/2021 to know the current occurrence of ruminant species in Europe. Ruminant species considered were those that appear in Table 1, so as wild boar.

However, as data download from the rgbif package is limited to 100000 registers, roe deer data had to be download from the website, as presence records were more than the allowed download. Downloaded data should contain coordinates, no geospatial issues, be in Europe and belong to the 2000-2021 period.

The downloaded data seemed to show a good distribution for Alpine chamois, Pyrenean chamois, Alpine ibex, Iberian ibex, whereas an underrepresentation of the distribution of more common species such as roe deer and red deer, particularly in Eastern Europe, was observed (Figure 2). In other cases, GBIF data could add information to previous distribution of the species (e.g., wild reindeer; Linnell et al 2020) or, on the contrary, not provide any information for a few species (e.g., Siberian ibex, Chinese water deer).

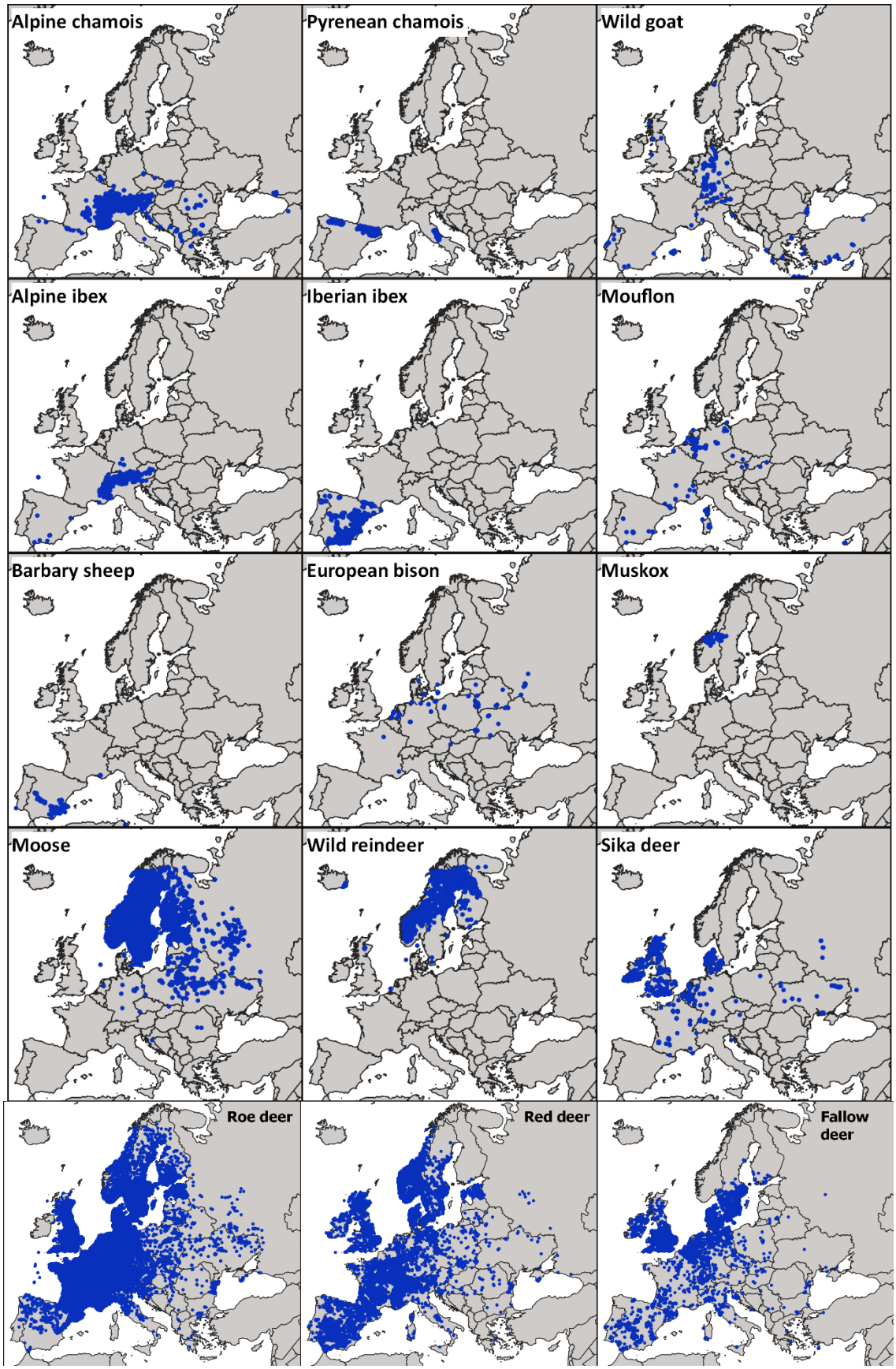
The differences observed to find an occurrence record on this platform depend on the species, but also in the country, as some countries are more propense to upload data than others.

Table 1. Wild ungulate species data idownloaded using rgbif 3.6.0 package (Chamberlain et al. 2021) on 12/11/2021 from GBIF.

	English name	Scientific name	Downloaded data
1.	Alpine chamois	*Rupicapra rupicapra*	40,490
2.	Pyrenean chamois	*Rupicapra pyrenaica*	12,024
3.	Wild goat	*Capra aegagrus*	319
4.	Alpine ibex	*Capra ibex*	51,812
5.	Iberian wild goat	*Capra pyrenaica*	8,962
6.	Mouflon	*Ovis orientalis subsp. musimon*	1,527
7.	Barbary sheep	*Ammotragus lervia*	1,059
8.	Siberian ibex	*Capra sibirica*	No registered data in GBIF
9.	Red deer	*Cervus elaphus*	87,043
10.	Roe deer	*Capreolus capreolus*	557,971[1]
11.	Fallow deer	*Dama dama*	41,330
12.	Axis deer	*Axis axis*	6
13.	White-tailed deer	*Odocoileus virginianus*	1,912
14.	Muntjac deer	*Muntiacus reevesi*	15,138
15.	Chinese water deer	*Hydropotes inermis*	No registered data in GBIF
16.	Moose	*Alces alces*	61,726

17.	Wild reindeer	*Rangifer tarandus*	25,055
18.	European bison	*Bison bonasus*	747*
19.	Muskox	*Ovibos moschatus*	5,157
20.	Non ruminant species: Wild boar	*Sus scrofa*	94,889

[1] GBIF.org (12 November 2021) GBIF Occurrence Download https://doi.org/10.15468/dl.bkwnhz * Mostly placed in Bialowieza N. Park (Poland).



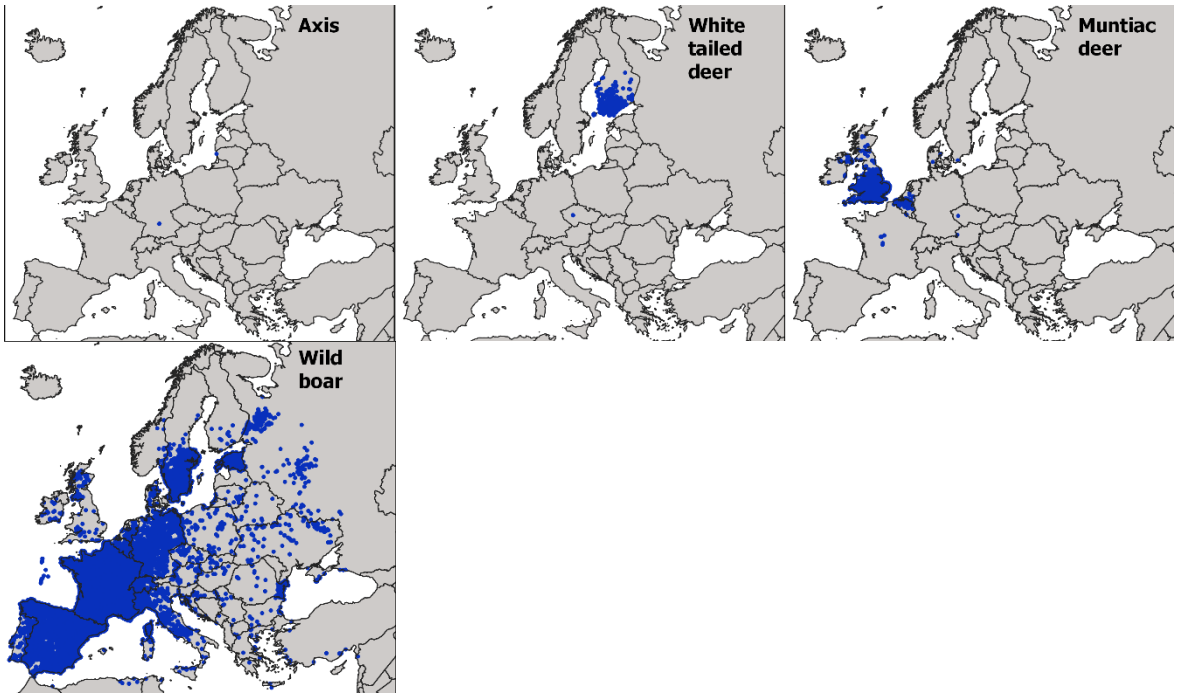


Figure 1: Map of ungulates species distribution in Europe according to GBIF downloaded data.

To represent ruminants' and ungulates' richness in Europe, presence data for each species was registered as 1 in each grid of 50x50km, and then, all presences were summed. The downloaded 100x100km grid from the European Environment Agency (EEA) was split into 4 equal parts to transform the grid into a 50x50km cell area (Figure 2).

The maximum ungulates' richness value if all species were found in a 50x50km cell was 19. However, summing cell values indicated that the maximum cell value for ungulates' richness reached 9, meaning that it is difficult to find more than 47% of ungulate species together in one place, according to GBIF data. Species co-occurrence more repeated when higher values of ruminant richness (*i.e.* 7-9) is reached by: red deer, roe deer, fallow deer and wild boar (always present), sika deer (53%), wild goat and alpine chamois (41%), Alpine ibex and mouflon (35%), Iberian wild goat (29% present), muntjac deer (24%), Pyrenean chamois (18%), barbary sheep, European bison, moose (12%). The high proportion of cells where no species are reported (53.97% of European cells) is noteworthy, particularly in Eastern Europe, which is due to underreporting. As commented below, a recent study revealed that 90% of Europe is home to at least one species of wild native ungulates (Linnell et al. 2020).

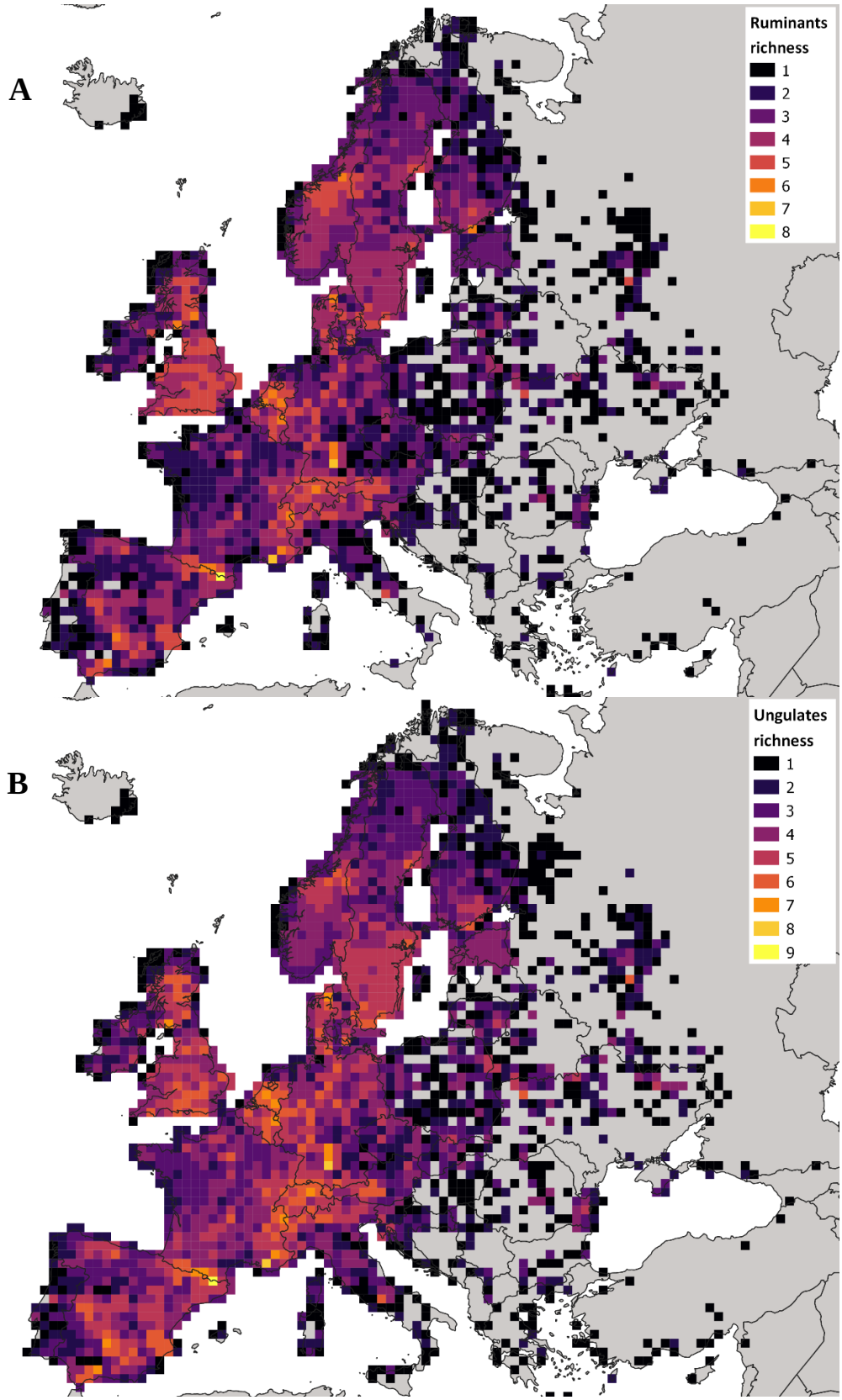


Figure 2: Map of wild ruminants richness (A) and wild ungulates richness (B) in Europe according to GBIF downloaded data.

2.2.2. Wild ungulate distribution maps: Linnell *et al.* (2020)

A recent study by Linnell et al. (2020) summarized the knowledge about wild ungulate distribution in Europe and drew from a wide range of sources distribution maps of European wild ungulates, revealing results showing that 90% of Europe is home to at least one species of wild native ungulate, with roe deer and wild boar occupying 74% and 64% of Europe, respectively. Interestingly, 75% of wild ungulate distribution is located outside protected areas, where uses such as extensive farming are common.

Before this research, the only detailed wild ungulate range maps available are the ones published by the Global Mammal Assessment Group in 2008 and hosted by the IUCN Red List of Threatened Species (https://www.iucnredlist.org/), and updating them was relevant for a variety of uses, such as incorporating new information. Moreover, the IUCN species range maps lack precision at local scales (Ficetola et al., 2014). Therefore, Linnell et al. (2020) produced recent continent-wide distribution maps of all native species of wild ungulates. This includes the following species: red deer, roe deer, moose, wild reindeer, European bison, Alpine ibex, Iberian wild goat, Northern chamois, Pyrenean chamois, and wild boar. Other species such as fallow deer were also included, whose native status is unclear and discussed (Chapman and Chapman, 1980; Lever, 1985), and species that are without doubt introduced, such as white-tailed deer, sika deer, Chinese water deer, Reeves's muntjac, muskox, and barbary sheep. Feral or extensively grazed free-ranging livestock such as horses and semi-domestic reindeer were not included. Data on distribution were drawn from many sources. The three volumes on ungulate management in Europe (Apollonio et al., 2010; Putman et al., 2011a; Putman and Apollonio, 2014) were central starting points. In addition, authors added data from national mammal atlases, hunting statistics, citizen science databases, vehicle collisions, scientific papers that provided the location of their study sites or which reviewed the status and distribution of various species and populations, and expert assessments. Full details are provided in the online Appendix (Linnet et al. 2020, https://ars.els-cdn.com/content/image/1-s2.0-S0006320719318312-mmc1.pdf). Data were digitalized and represented on a 10×10 km grid, bearing in mind that the real resolution of some underlying data may have been coarser. For example, some data were only available as polygon data representing counties, hunting grounds or other administrative units (Figure 3). From the 10×10km grid Linnell et al (2020) derived a spatial dataset containing 48,499 observations that were used to carry out GIS analysis and visualize the results.

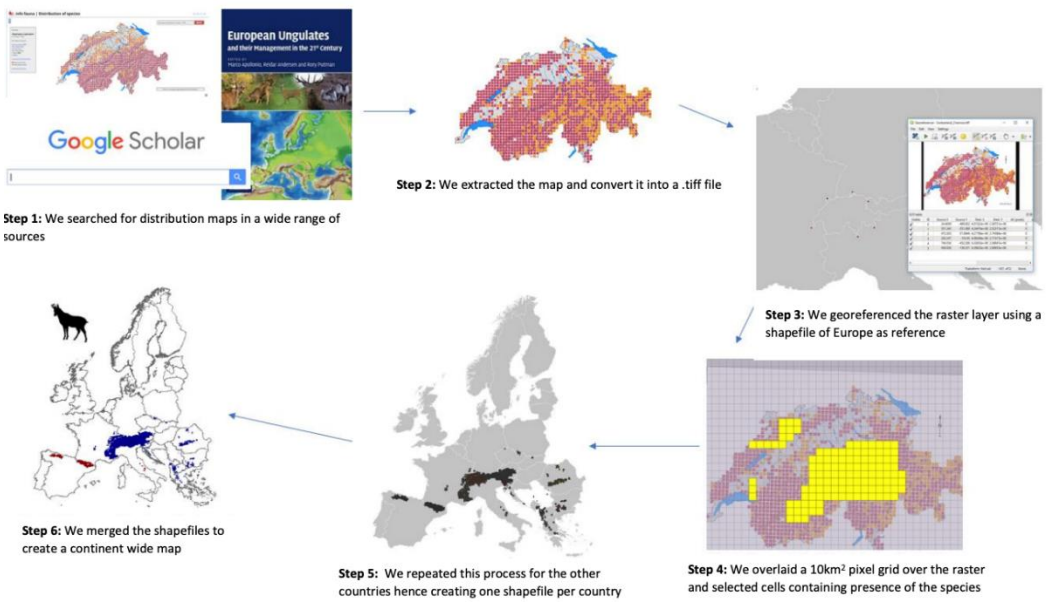


Figure 3: Process of producing the wild ungulate species distribution maps by Linnell at al. (2020). Image Under a Creative Commons license.

Figures 4 and 5 display the distribution maps for wild native and introduced ungulates, respectively, in Europe (Linnell et al. 2020).

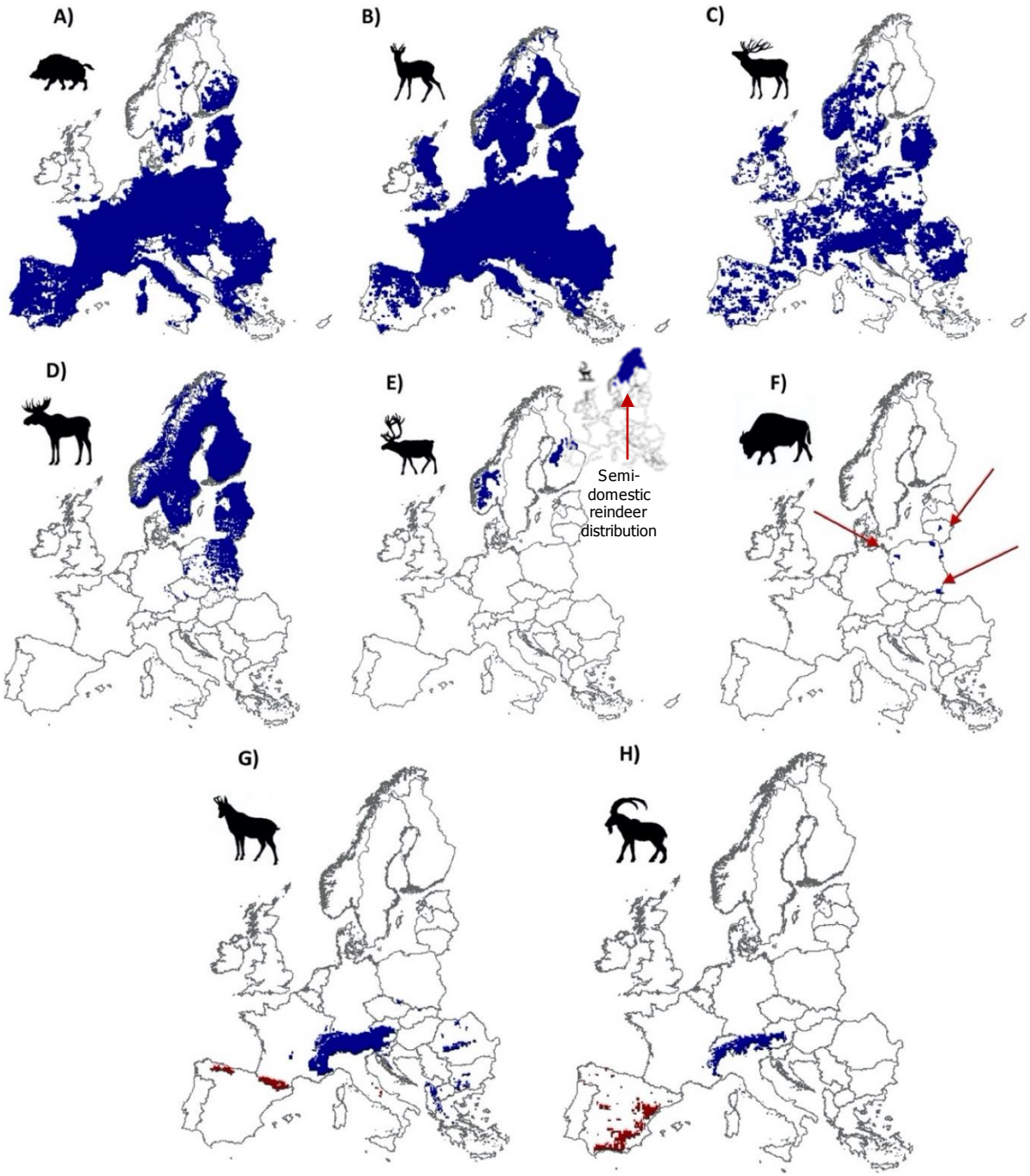


Figure 4: Distribution maps for wild native ungulates in Europe. A) wild boar, B) roe deer, C) red deer, D) moose, E) wild reindeer, F) European bison, G) northern chamois (in blue) and Pyrenean chamois (in red), H) alpine ibex (in blue) and Iberian wild goat (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of Linnell et al. 2020). Image Under a Creative Commons license (Linnell et al. 2020).

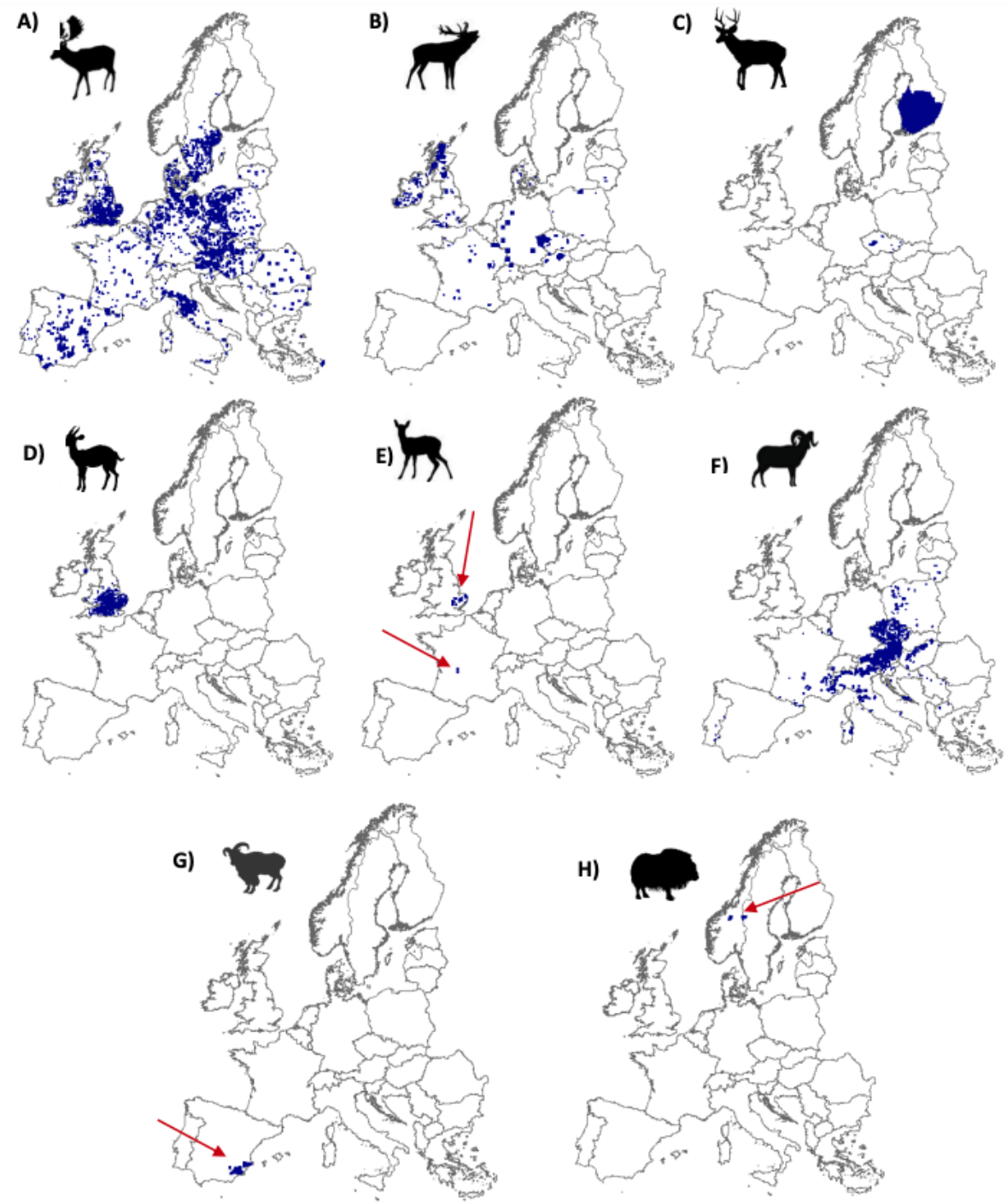


Figure 5: Introduced ungulates distribution in Europe. A) Fallow deer, B) sika deer, C) white-tailed deer, D) Reeves's muntjac, E) Chinese water deer, F) mouflon, G) barbary sheep, H) muskox. Image Under a Creative Commons license (Linnell et al. 2020).

2.2.3. Livestock distribution and abundance: Data sources and characteristics

2.2.3.1. Eurostat

Eurostat data browser have the animal populations by NUTS 2 regions. Data is available from 1977 to 2020 and at three resolution scales (*i.e.* NUT0, NUT1 and NUT2). Animal populations are measured as a thousand heads (animals) and are categorised in 47 categories. There are four general categories: i) live bovine animals, ii) live swine, domestic species iii) live sheep, iv) live goats, which comprises the sum of animal populations that are also sub-grouped in specific/detailed categories (Table 2). However, Eurostat's animal population does not register information about equids, and the information provided is sometimes not up-to-date for each country. For example, sheep registers by Eurostat in Poland from 2013-2020 are 0, while this information is available in the Polish local data bank. For this reason, as well as because Eurostat data do not include European countries outside of the European Union (such as Norway, Belarus, Ukraine, and Russia), agriculture statistics for these countries were searched.

Table 2. Eurostat data on domestic animal populations are measured as a thousand heads (animals) and are categorised in 47 categories. There are several general categories used in this report, namely for ruminants: i) live bovine animals, ii) live swine, domestic species iii) live sheep, iv) live goats, which comprises the sum of animal populations that are also sub-grouped in specific/detailed categories.

Code	Livestock type	Code	Livestock type	Code	Livestock type
A2000	**Live bovine animals**	A2010	Bovine animals, less than 1 year old	A2010B	Bovine animals, less than 1 year old, for slaughter
				A2010C	Bovine animals, less than 1 year old, not for slaughter
		A2020	Bovine animals, 1 to less than 2 years old		
		A2030	Bovine animals, 2 years old or over		
		A2110C	Male calves, less than 1 year old, not for slaughter		
		A2120	Male bovine animals, 1 to less than 2 years old		
		A2130	Male bovine animals, 2 years old or over		
		A2230_A2330	Female bovine animals, 2 years old or over	A2210C	Female calves, less than 1 year old, not for slaughter
		A2220	Heifers, 1 to less than 2 years old	A2220B	Heifers, 1 year old, for slaughter
				A2220C	Heifers, 1 year old, not for slaughter
		A2230	Heifers, 2 years old or over	A2230B	Heifers, 2 years old or over, for slaughter
				A2230C	Heifers, 2 years old or over, not for slaughter
		A2300	Cows	A2300F	Dairy cows

				A2300G	Non dairy cows
		A2400	Buffaloes	A2410	Breeding female buffaloes
				A2420	Other buffaloes
A3100	**Live swine, domestic species**	A3110	Piglets, live weight of under 20 kg		
		A3120_3133	Breeding pigs		
		A3120	Breeding sows, live weight 50 kg or over	A3120K	Covered sows
				A3120KA	Sows covered for the first time
				A3120L	Sows, not covered
				A3120LA	Gilts not yet covered
		A3131	Pigs, from 20 kg to less than 50 kg		
		A3132	Fattening pigs, live weight 50 kg or over	A3132X	Fattening pigs, from 50 kg to less than 80 kg
				A3132Y	Fattening pigs, from 80 kg to less than 110 kg
				A3132Z	Fattening pigs, live weight 110 kg or over
		A3133	Breeding boars		
A4100	**Live sheep**			A4110K	Ewes and ewe-lambs put to the ram
				A4110KC	Milk ewes and ewe-lambs put to the ram
				A4110KD	Non milk ewes and ewe-lambs put to the ram
		A4120	Other sheep		
A4200	**Live goats**			A4210K	Goats mated and having already kidded
				A4210KA	Goats mated for the first time
				A4210KB	Goats having already kidded
		A4220	Other goats		

2.2.3.2. Other sources of livestock data

As commented, Eurostat information does not include European countries which do not belong to the European Union. In addition, the spatial resolution of administrative units is quite variable. Therefore, we identified other sources of data to homogenize as much as possible the spatial scale of administrative units for comparisons, and searched for livestock abundance and distribution data in Member and non-Member States:

Statistics Norway is a website where information since 1876 from Norwegian statistics can be found. Statistics are divided into different categories such as business and technology, where the subcategories for agriculture, forestry, hunting, and fisheries can be found. The category on agriculture contains information about livestock husbandry. The information, which can be downloaded, comprises domestic animals by kind from 1998-2021. The information is available at counties spatial scale.

State Statistics Service of Ukraine has also published documents of agriculture, forestry, and fishery in the economic statistics category, where numbers of agricultural animals are available from 2001 to 2021. However, detailed information about livestock categories is only easily understandable for 2017-2021, where agricultural holding, enterprise, and households quantities can be found, and for 2008-2011, where thousands of heads quantities are registered. Other documents available at the statistics website are written in Ukrainian language. Both type of information is at NUT1 resolution.

National Statistical Committee of the Republic of Belarus also has information on the main livestock population in agricultural organisations by regions (NUTS1) for 2021 in the agriculture, forestry, and fishery group at the economic statistics. However, information by region only comprises three category classes: cattle, cows and pigs, not registering information on sheep, goats, or equids; although numbers of livestock and poultry are available for 1995, 2000, and 2005-2020 at country level (NUT0).

Statistics of Moldova website has information about livestock in households by localities from 2016-2021. That means that livestock households are recorded at commune level (*i.e.* second level of Moldova regional division). However, spatial information has not been found at that spatial resolution, so information was aggregated at district level (*i.e.* first level of Moldova regional division).

Presidency of Turkish Statistical Institute (TURKSTAT) is the organism in charge to collect and disseminate agriculture data, where livestock statistics can be found. If databases are needed, the central dissemination system website provides livestock statistics that can be downloaded for eight categories from 2004-2019 by region. Region scale can also be chosen from NUT0 (country level) to NUT3 (province level).

The Institute of Statistics of Albania (INSTAT) has an agriculture and fishery theme, which comprises agriculture, livestock, fishery, and forest. The livestock category has databases where numbers of livestock by municipalities can be consulted and downloaded for 12 types of livestock from the last three years (*i.e.* 2018-2020).

The National Statistics Office of Georgia registered household survey databases from 2009-2020, where numbers of domestic animals and poultry are recorded for 13 categories (*i.e.* cow, bull, buffalo, young cattle, donkey, horse, pig, sheep, goat, rabbit, bee hive, poultry, others). Although information is available for each household, location is not available due to the confidentiality-policy, so upscaling of spatial statistics to NUTS level was not possible. On the other hand, they publish an annual statistical yearbook, where information about livestock is provided at country level from 2002-2019.

The State Statistical Committee of the Republic of Azerbaijan has public information about numbers of animals and poultry at country level from 1997-2020. Moreover, they have detailed livestock data for regions from 2005-2019. The information provided can be used at three levels of spatial resolution (country, economic region[2], and region level).

The Statistical Committee of Republic of Armenia provides on its website two datasets of livestock. The first one is the annual exhaustive livestock Census, which is conducted in all households of the republic by local governmental bodies (jointly with the Marz Administrations). The census comprises 2006-2021 and its eleven regions. Almost the same period (2007-2021) is available at the Livestock by regions, types and years in the ArmStatBank databases. However, it must be noticed that this last dataset has less categories than the previous one (four categories vs ten) and data has been rounded. On the other hand, the information in the annual exhaustive livestock Census is given in PDF format and cannot be transformed easily into a table for managing statistics.

[2] https://en.wikipedia.org/wiki/Economic_regions_of_Azerbaijan

The Statistics showcase of Russia has information about livestock and poultry at regional level (NUT1 resolution). The data series found , together with Norway, starting in 1999 and ending in 2020. However, there is a difficulty to note when looking for this information, as the website is not translated into English, and only searches in Russian can be done, as well as data downloaded is in Russian.

The Swedish Board of Agriculture's official statistics provides numbers of animals by municipality from 1981-2020 at NUT0 and NUT3 level.

The Natural Resources Institute Finland in its Statistics Database gives the numbers of Livestock by municipality from 2014 to 2020 for 18 categories.

Latvia official statistics gives the numbers of livestock and poultry by region at the end of the year from 1990-2020 for five categories. There is also another database which registers data from 1915 to 2020 with 41 categories of livestock and poultry at the end of the year. However, country instead of region is the spatial resolution.

In the indicator section of the **Official Statistics Portal of Lithuania** there is registered information about numbers of animals and poultry at the beginning of the year with three spatial resolutions of the data (*i.e.* NUT1, NUT2 and NUT3) and a total of 39 livestock categories for a time series from 1991 to 2021.

Statistics of Estonia gives information about 47 categories of livestock and poultry by county from 1980 to 2021 in the agriculture livestock production section. The information is divided by quarters of the year, and the used information for this report correspond to the 4th quarter, that is at 31st of December.

The database section of **Dastatis Statistisches Bundesamt** gives information about 42 categories of livestock at the spatial resolution of **Germany** (NUT0) and its sixteen federal states (NUT1) from 1951 to 2021.

Statistics in the **French Ministry** reports data of number of livestock by head for department (NUT3) for twenty years (2000-2020). However, it must be noticed that multiple selection of categories or years is not allowed due to restriction of data selection, which make the process of data download cumbersome.

The **Spanish Ministry of Agriculture, Fisheries and Food** is the one in charge to provide livestock statistics, which can be downloaded per year from 2002 to 2020 and for four categories at NUT0, NUT2 and provinces spatial resolution.

The **Italian Statistics** provides information about livestock in the agriculture section of its web page, where data can be consulted and downloaded for a total of 33 categories for the years 2016-2020 at NUT0, NUT1 and NUT2 spatial resolution.

Poland livestock statistics are in the agriculture, forestry and hunting category at the Local Data Bank. The information is given for a total of 40 categories and can be consulted and downloaded from 2005 to 2020 and for NUT0, NUT1 and NUT2 spatial resolution.

Romanian livestock data depend on the Ministry of Agriculture and Rural Development, and they only have available information for 26 categories for 2017 at NUT3 spatial resolution.

The **Statistical Office of Check Republic** has (https://vdb.czso.cz/vdbvo2/faces/en/index.jsf?page=vystup-

objekt&pvo=ZEM07B&z=T&f=TABULKA&skupId=2746&katalog=30840&c=v3~2__RP2002MP03DP01&&str=v97) for nine categories from 2002-2021 at NUT0 and NUT3 spatial resolution.

Livestock statistics of Netherland can be found at the Statistics Netherland's database. Open data ranges from 2000-2020 for NUT0, NUT1, NUT2 and NUT3 spatial resolution.

Austrian livestock statistics are in the Agriculture and Forestry category of the Statistics Austria web page. Information is available for five categories at NUT0 and NUT1 spatial resolution, and available from 1946-2020, except for equids that are available until 2003. A total of 38 categories are given in their statistics database for Farm Structure Survey, however, temporal resolution is only available for 2010, 2013 and 2016. Data used for this report correspond to the database of more categories available, although it has lower temporal resolution.

Denmark Livestock by county, unit and type can be consulted and downloaded from the Statistics of Denmark web page. There are a total of 144 categories from 2006 to 2020 at NUT1, NUT2 and NUT2 spatial resolution.

Hungarian livestock statistics are available for four categories (cattle, pig, sheep, poultry) from 2000-2020 by NUTS0, NUTS1 and NUTS3 spatial resolution

Croatian Bureau Statistics has information about livestock numbers of a total of 40 categories from 2000-2020 at NUTS0 and NUTS2 (Continental Croatia and Adriatic Croatia) spatial resolution.

Bosnia and Herzegovina livestock numbers are found in the Agriculture category of the Agency for Statistics. Information contains 54 categories, from 2010 to 2020 and at at NUTS0 (country level) spatial resolution.

In the Agriculture, Livestock and Fishery category of the **Hellenic Statistical Authority**, information about livestock is recorded. There are two subsections, which contain information about livestock: i) census of agricultural and livestock holdings, which consists of census for two years (2000 and 2009) with nine categories of animal types registered by NUT0, NUT2 and NUT3 spatial resolution; ii) Livestock/crop surveys, which have information about a total of 32 categories, from 2002 to 2019 for NUTS0 and NUTS2 spatial resolution. However, until 2016 cattle and pigs categories are not available, and no data from equids are on the survey. The information used for this report correspond to the series of livestock surveys.

The **Statistical Office of the Republic of Serbia** contains in the Agriculture, forestry and fishery section of its database information about the numbers of livestock for a total of 48 categories from 2006 to 2020 at NUTS0, NUT1 and NUT2 spatial resolution.

The **Republic of North Macedonia** has in its State Statistical Office information about (https://makstat.stat.gov.mk/PXWeb/pxweb/en/MakStat/MakStat__Zemjodelstvo__DobitocnoProizvodstvo/175_DobPro_Reg_DobZivPc_ml.px/?rxid=46ee0f64-2992-4b45-a2d9-cb4e5f7ec5ef) for seven categories, from 2007 to 2020 for NUTS0 spatial resolution.

Belgium Statistics is the organisms who shares information about livestock numbers, which can be found in the subsection of (https://statbel.fgov.be/nl/themas/landbouw-visserij/land-en-tuinbouwbedrijven/plu) inside the Agriculture and Fisheries category.

Livestock numbers correspond to starting A codes of table A, which cover a period from 1980 to 2017, for more than a hundred of livestock types and NUTS2 spatial resolution.

In the agriculture, forestry, and fisheries category of the **Statistical Office of the Slovak Republic** animal production can be found, from where livestock numbers are available for a total of eight categories from 2012 to 2020 for NUTS0, NUTS1, NUTS2, NUTS3 and NUTS4 spatial resolution.

The Statistical Office of the **Republic of Slovenia** has two data series of livestock. On the one hand, they have numbers of livestock divided into six categories and six years (2003, 2005, 2007, 2010, 2013 and 2016) by NUTS2 spatial resolution. On the other hand, they have numbers of livestock divided into 60 categories for two years (2000 and 2010) and the same spatial resolution.

3. Methodology: definition of the spatial interface between wild and domestic ungulates

3.1. The spatial overlapping between wild ungulates and livestock at European scale

We present this analysis using:

- For **livestock data**, the Eurostat database and above-mentioned other sources (section 2.2.3.2) to improve the spatial domain out of EU, and/or the spatial quality of data while keeping similarly sized administrative units (NUTS 2 tends to be large sized in areas of low human population density). The abundance of livestock, measured as number of heads, was categorized following this criterium: number of heads per livestock category were divided by area (km^2) of each territorial unit, obtaining a relative measure of density per territorial unit making the quantity of livestock comparable for different territorial sizes. Each livestock category was then classified into four density categories: low, moderate and high, according to the <33%, 33-66%, >66% percentile respectively, and NA, if values were not available for that category.
- For **wild ungulates distribution data**, the maps elaborated by Linnell et al. (2020). To establish the areas of spatial overlapping between livestock and wild ungulates distribution (which does not necessarily equate to risk of contact), we transformed the 10x10km grid into centroids and counted the number of centroids inside each territorial unit, obtaining two types of information: a) if a species was present in a territory and b) estimation of the occupied area by a species in a territorial unit. From the first type of information, we could calculate the richness of species occurrence by territory unit as the sum of number of species present in a territory. We also grouped the found richness into three categories: low richness (1-3 species), moderate richness (4-6 species), high richness (7-9 species). From the second type of information, we relativized the occupied area between the territorial unit surface, obtaining an estimated percentage of area occupied by each species for each territorial unit. Each species was then classified into five categories: low, moderate, and high, according to the <33%, 33-66%, >66% percentile respectively, not present if the species was not present and NA, if values were not available for that category from the percentage values of area occupied.

  Finally, the **overlap** between wild ungulates and livestock was calculates using two approaches:

- On one hand, an **overlapping interface** between wild ungulates occupancy and livestock density per territorial unit, which has been categorized according to the following matrix, where NA values of any of both groups make impossible to assign an overlapping category.

		Wild ungulates occupancy				
		Not present	NA	Low	Moderate	High
Livestock density per territorial unit	NA	Not overlap				
	Low	Not overlap		*	*	**
	Moderate	Not overlap		*	**	***
	High	Not overlap		*	***	****

- On the other hand, **richness overlapping areas** were determined between wild ungulates richness categories and livestock density per territorial unit, showing that special care must be taken where most wild species tend to be spatially concentrated.

		Wild ungulates richness			
		NA	Low (1-3)	Moderate (3-6)	High (7-9)
Livestock density per territorial unit	NA				
	Low		*	*	**
	Moderate		*	**	***
	High		*	***	****

3.2. Predictive accuracy validation of Gridded Livestock of the World (GLW v3)

ENETWILD consortium, 2020b reported that a true validation of the accuracy of the predictive livestock models for the world from Gridded Livestock of the World (GLM v3) would involve field observation of livestock densities in different pixels and testing those observations against predicted values. However, as this detailed information is not available at large scale, validation would have to be done on re-aggregated model predictions.

In this term, they were obtained the mean values of the DA GLW distribution models for buffaloes, cattle, goats, horses, pigs and sheep to each of the unit levels of domestic animals used for this report. Then, the obtained density means (animals per km^2) were compared to the domestic livestock density obtained for this report.

4. Results and discussion

4.1.1. Livestock: Eurostat and complementary sources

Eurostat data browser has the animal populations by NUTS 2 regions at maximum resolution for four general categories of ungulates: i) live bovine animals, ii) live swine, domestic species iii) live sheep, and iv) live goats, which comprises the sum of animal populations that are also sub-grouped in specific/detailed categories (not for equids). This is the reason why the present European-wide livestock census distribution information was used at a spatial resolution of NUTS2. However, Eurostat information does not include European countries which do not belong to the European Union, and the size of administrative units is quite variable. We therefore identified other sources of data for some Member States to homogenize as much as possible the spatial scale of administrative units for comparisons, and searched for livestock abundance and distribution data in non-Member States.

The fact that subnational census statistics are usually found in the form of numbers per administrative unit, usually NUTS2, remarks the need of developing a framework to collect data at European scale with higher resolution, in a harmonized way, and following standards to ensure data can be comparable, validated, and finally, used. There is also need to resolve definition issues regarding the type of production systems. All this results in a European mosaic of data from different spatial resolutions, periods of time, variables and metadata that prevent their availability and usage.

Figure 6 shows the domestic ungulates (livestock) distribution and abundance in categories in Europe (number heads/surface, categorized according to the <33%, 33-66%, >66% percentile respectively).

- Cattle, and particularly, beef and dairy, respectively, present relatively similar distributions patterns, being more abundant in central Europe (France, Germany, Northern Italy, Poland and nearby contries, and Turkey). However, national patterns may differ internally (for both typologies of cattle, respectively), such as in the case of Spain and France, where dairy typically occurs in the North regions.
- The other bovine, buffalo, is mainly distributed East to the Balkans (Bulgaria, Romania, Turkey), in Italy, and to a lesser extent in other countries.
- Overall, goats and sheep predominate in the Mediterranean regions, being remarkable exceptions such as sheep in the British Isles, and goats in the Netherlands.

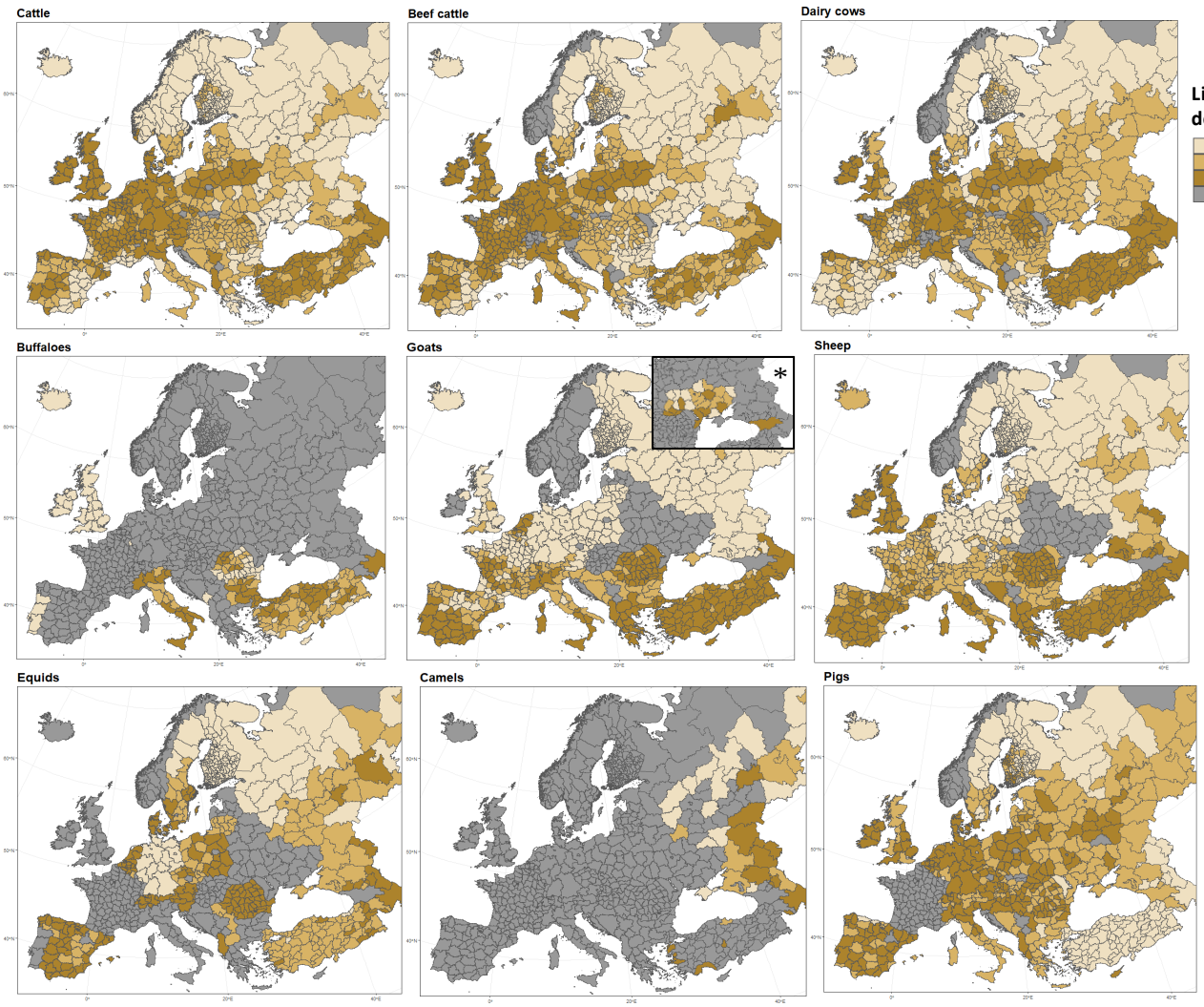
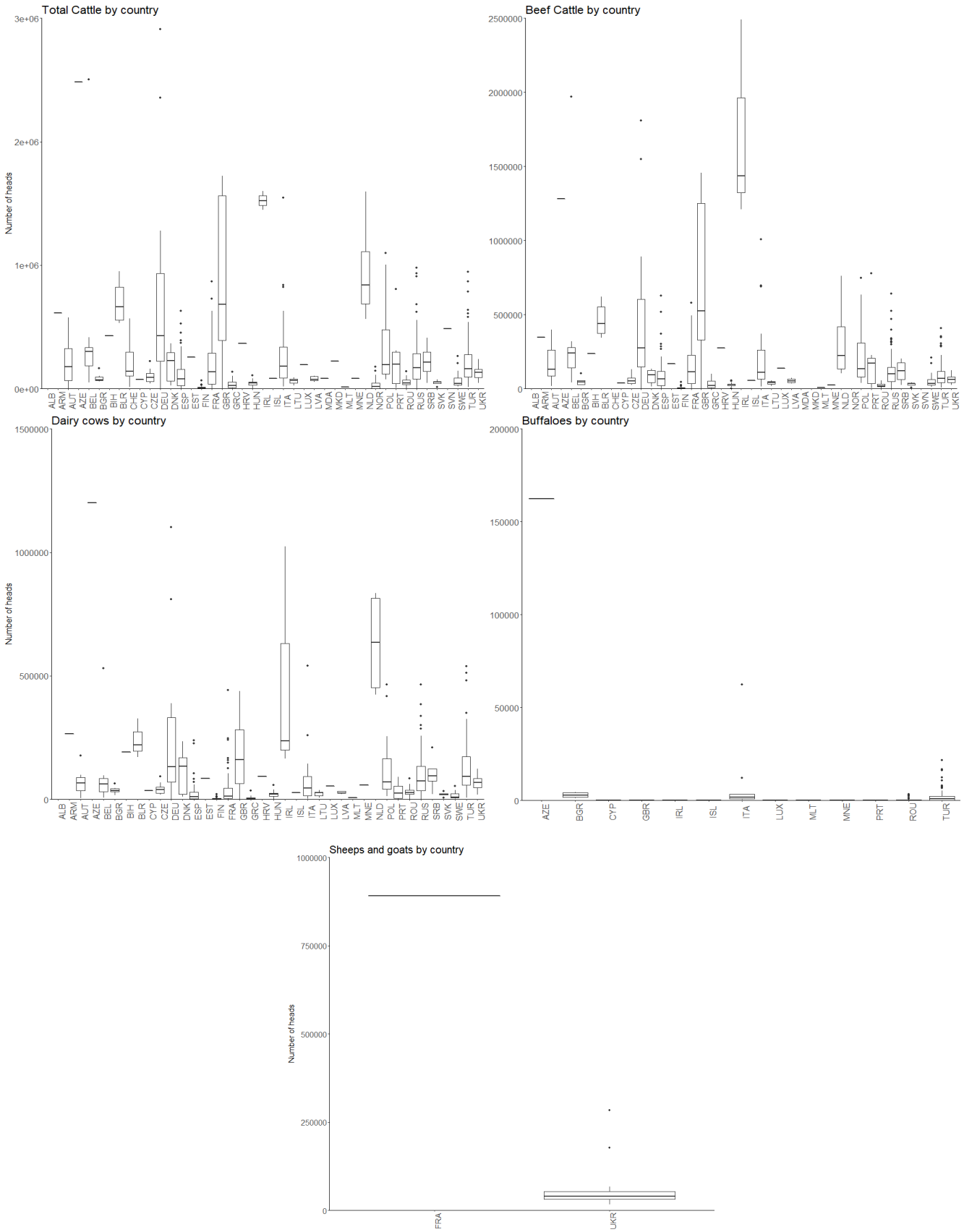


Figure 6: Domestic ungulates distribution in Europe (number heads/surface, categorized). Sheep and goats (*) are showed together for some countries where disaggregated data was not available. NA category means no data available.

Table 1. Spatial resolution of livestock data available and used for the analysis.

Country	Spatial Resolution of data downloaded	Spatial Resolution grouped to the analysis
Albania	Municipality	NUTS0
Armenia	Municipality	NUTS0
Austria	NUTS2	NUTS2
Azerbaijan	NUTS0	NUTS0
Belarus	NUTS1	NUTS1
Belgium	NUTS2	NUTS2
Bosnia and Herzegovina	NUTS0	NUTS0
Bulgaria	NUTS2	NUTS2
Croatia	NUTS2 (2012-2020)	NUTS2 (2012-2020)
Czech Republic	NUTS3	NUTS3
Cyprus	NUTS2	NUTS2
Denmark	NUT3	NUTS2
Estonia	NUT1	NUTS0
Finland	Municipality	Regions
France	NUTS3	NUTS3
Germany	NUT1	NUTS1
Georgia	NUT0	NUTS0
Greece	NUT2	NUTS2
Hungary	NUTS3	NUTS3
Iceland	NUTS2	NUTS2
Ireland	NUTS2	NUTS2
Italy	NUT2	NUTS2
Latvia	NUTS3	NUTS3
Liechtenstein	NUTS2	NUTS2
Lithuania	NUTS3	NUTS3
Luxembourg	NUTS2	NUTS2
Macedonia	NUTS0	NUTS0
Malta	NUTS2	NUTS2
Moldova	District	NUTS0
Montenegro	NUTS2	NUTS2
Netherland	NUTS2	NUTS1
Norway	Province	Province
Poland	NUTS2	NUTS2
Portugal	NUTS2	NUTS2
Romania	NUTS3	NUTS3
Rusia	NUTS1	NUTS1
Serbia	NUTS2	NUTS2
Slovakia	NUTS3	NUTS3
Slovenia	NUTS3	NUTS0
Spain	NUTS4	NUTS4
Sweden	Municipality	Province
Swizterland	NUTS3	NUTS2
United Kingdom	NUTS2	NUTS2
Ukraine	NUTS1	NUTS1
Turkey	Province	Province



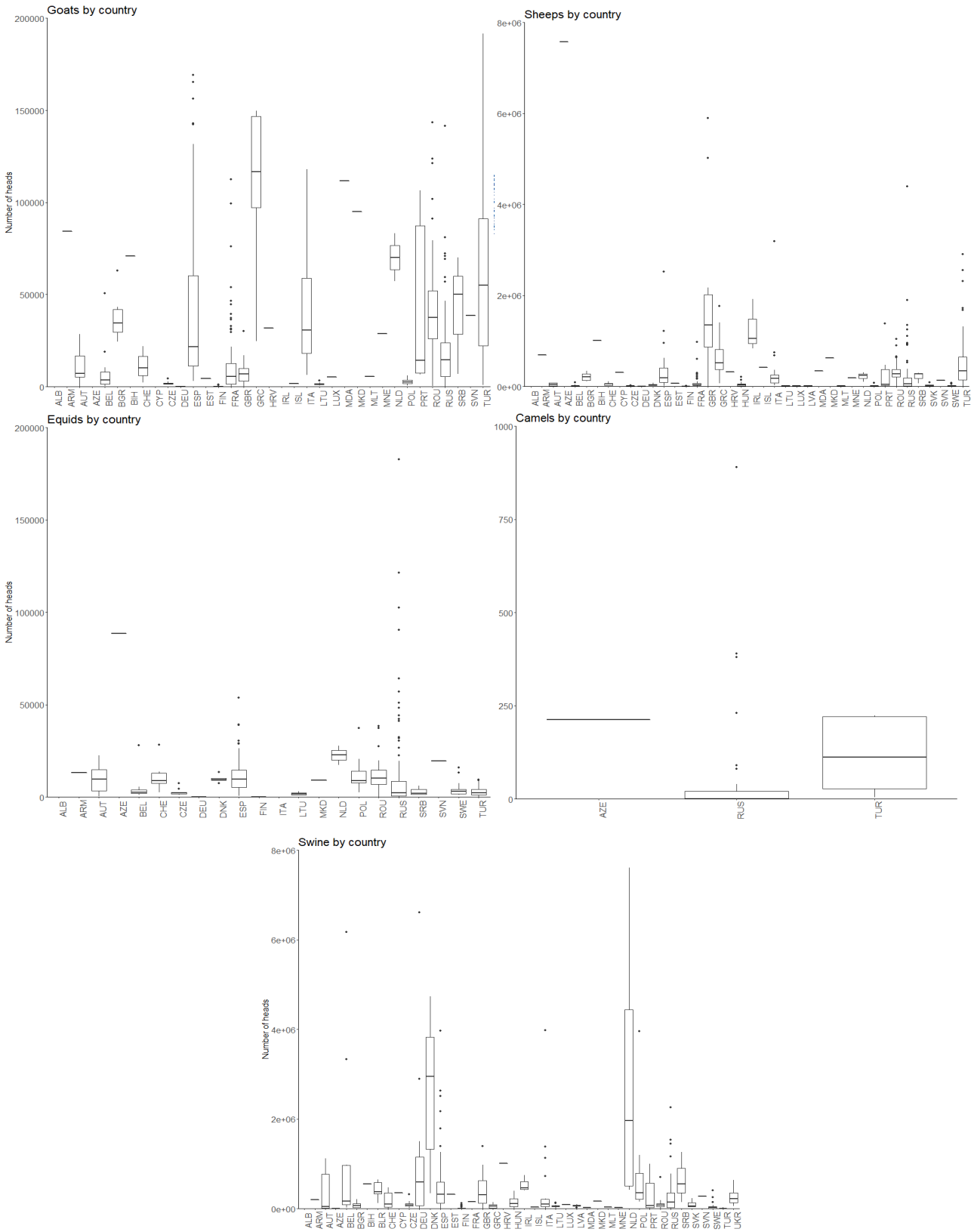


Figure 7: Domestic ungulates (number of heads) boxplots per administrative region for each European country. The box represents lower (Q1), median (Q2) and upper quartile (Q3), while data falling outside are plotted as outliers.

4.1.2. Current distribution of wild ungulates in Europe

From the pool of 18 species that Linnell et al. (2020) included, they recognised ten species as being native and eight as being introduced (Linnell and Kaltenborn 2019). The distribution maps and histograms of the number of native and introduced diversity in Europe is shown in Figures 8 and 9 (Linnell et al. 2020). About 90% of Europe's land area hosts from one to five species of wild native ungulates with mountainous areas being generally the most species-diverse. It should be noted that even though northern Scandinavia appears ungulate-free or has a low ungulate diversity, semi-domestic reindeer thrive in most of this range (Pape and Löffler 2012). The introduced species tended to have more limited distributions, although a few areas have up to four sympatric species (Figures 8 and 9). Species had highly variable distribution areas (Figure 8) with roe deer and wild boar occupying respectively 74% and 64% (more than 3 million km^2) of the continent, and mountain ungulates (i.e., Northern and Pyrenean chamois, and Alpine and Iberian Ibex) occupying 5% or less of the European land area (less than 250,000 km^2). These differences in distribution area are also reflected in differences in the extent to which distributions were linked to protected areas (Figure 10, Linnell et al. 2020). If we visualize the richness of ungulate species by administrative regions (Figure 9), a high richness is remarkable in regions in Central Europe, from West to East, from the Alps (where the presence of mountain ungulates adds biodiversity), extending to countries with important big game tradition and presence of introduced species (Hungary, Czech Republic, Germany), to Poland (where also typically northern species such as moose and bison already appear). Presence of medium to high richness also occurs sparsely in certain administrative regions all over Europe due the effect of different causes at local scale (presence of mountain ungulates, introduced species, or locally distributed species). When comparing Figures 8 and 9, it is noteworthy that ungulate species present clear distribution pattern within administrative units, for instance, mountain ungulates tend to be present only in mountainous areas within each administrative region (e.g. in the Alps).

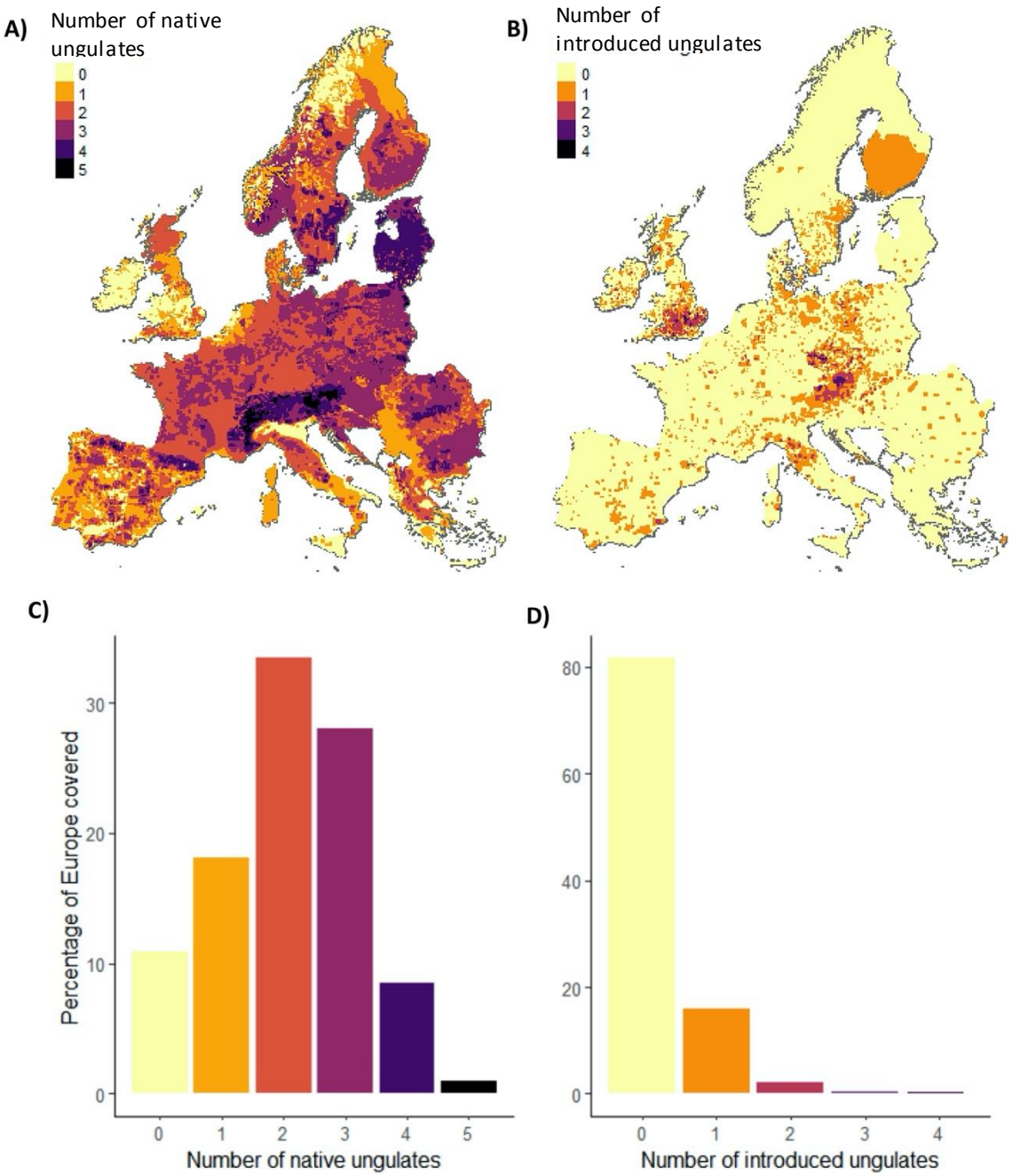


Figure 8. Distribution maps and histograms of the number of native (A) (C) and introduced (B) (D) diversity in Europe (Linnell et al. 2020). Image under a Creative Commons license.

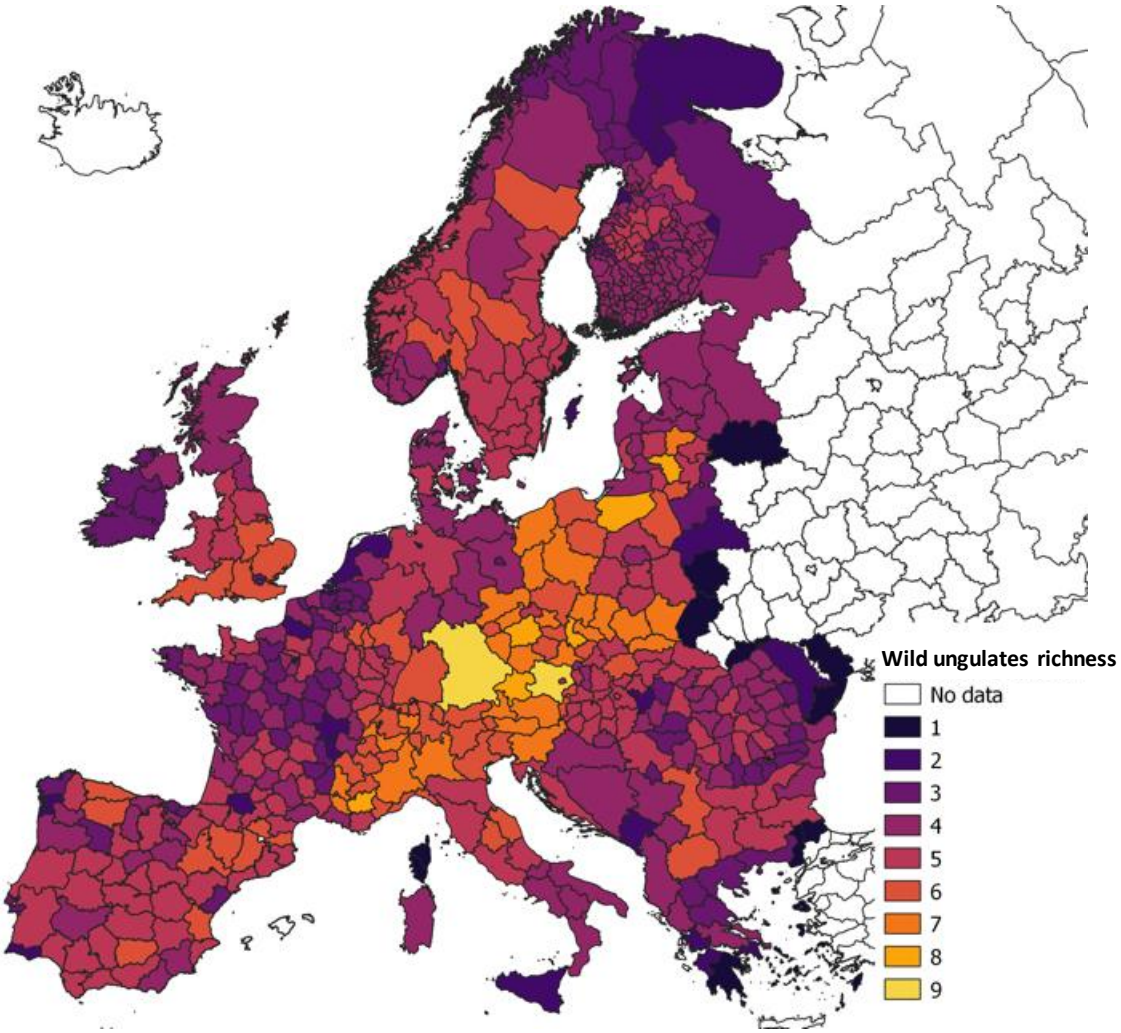


Figure 9: Wild ungulates richness (sum of number of species) distribution in Europe by NUTS administrative unit (NUTS resolution is indicated in Table 1) used in the spatial analysis of the present report.

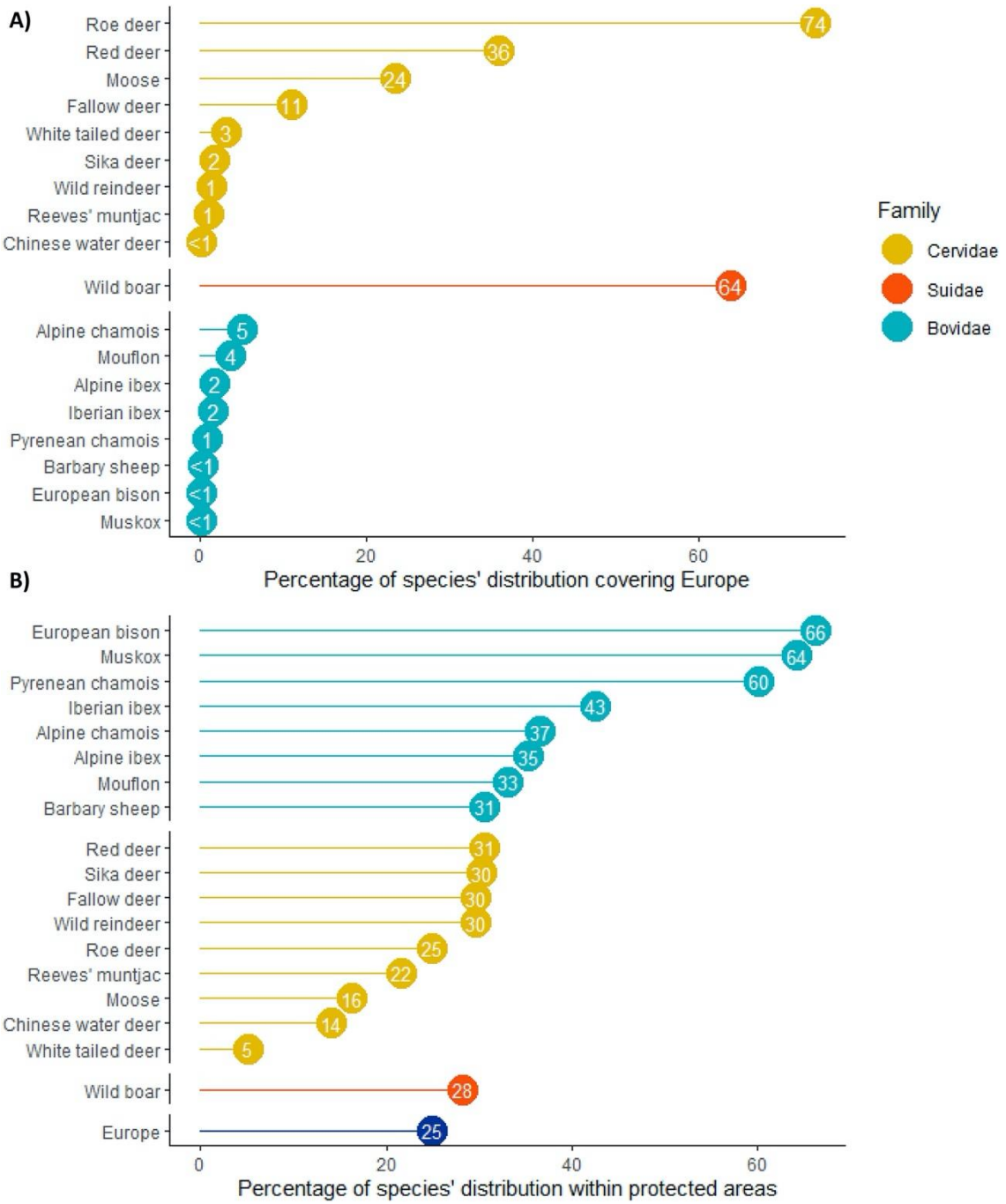


Figure 10: The area of distribution of wild ungulates in Europe (in % of total area) and B) the percentage of this distribution that is within protected areas (Linnell et al. 2020). Image under a Creative Commons license.

Literature indicates that the distribution and abundance of wild ungulates in Europe is dynamic and, in general, increasing (e.g. Apollonio et al. 2010, Massei et al. 2015, Linnet et al. 2020). Therefore, mapping their distribution and interfaces with domestic ungulates should be a continuous activity. For certain introduced species there exists special concern about their expansion for different reasons (e.g., conservation issues). For instance, Asian deer species introduced in central Europe and the UK. Linnell et al. (2020) identified the main drivers of change, which are diverse:

- Changing human pressure on the landscape through infrastructure development (transport, recreation, renewable energy production, Venter et al. 2016).
- Global change, including climate change, the re-emergence of diseases once thought to be under control, and the appearance of new diseases (Lindgren et al. 2012).
- Increased diversity of stakeholder perspectives with divergent, and often conflicting, perspectives on wild ungulate management. The increase in focus on new ideologies like animal rights and rewilding, for example, represent considerable challenges for conventional management structures that are centred around hunting as both an objective and a tool to reach other ecosystem goals (Kennedy and Koch 2004).
- The return of large carnivores as predators on ungulates and competitors with hunters (Chapron et al. 2014).
- Constant changes in agricultural and forestry practices in response to shifting policy priorities (Persson et al.i 2016).
- The controversial impacts of the increasing densities of ungulates, and their expansion into many areas, especially urbanised areas and those with intensive agricultural production create several challenges associated with the success of their conservation (Stillfried et al. 2017).
- New knowledge about movement patterns, demography, ecological interactions, and disease processes that challenge existing management paradigms.
- Finally, the impact of shifting political directions that are currently dismantling, or restructuring, many of the wildlife management institutions that have developed during the 20th century.

4.2. The spatial overlap between wild and domestic ungulates distribution at European scale: a preliminary approach

4.2.1. Overlapping interface

Next, several figures by domestic species display the spatial overlap between wild and domestic ungulates distribution at European scale. It is shown at relatively homogeneous administrative units (mainly NUTS2) and depicts a first broad scale approach to the potential interface for cattle (Figures 11 and 12), beef cattle, (Figures 13 and 14) dairy cattle (Figures 15 and 16), goats (Figures 17 and 18), sheep (Figures 19 and 20), buffalo (Figures 21 and 22), equids (Figures 23 and 24) and pigs (Figures 25 and 26). Data are particularly complete for ruminant species.

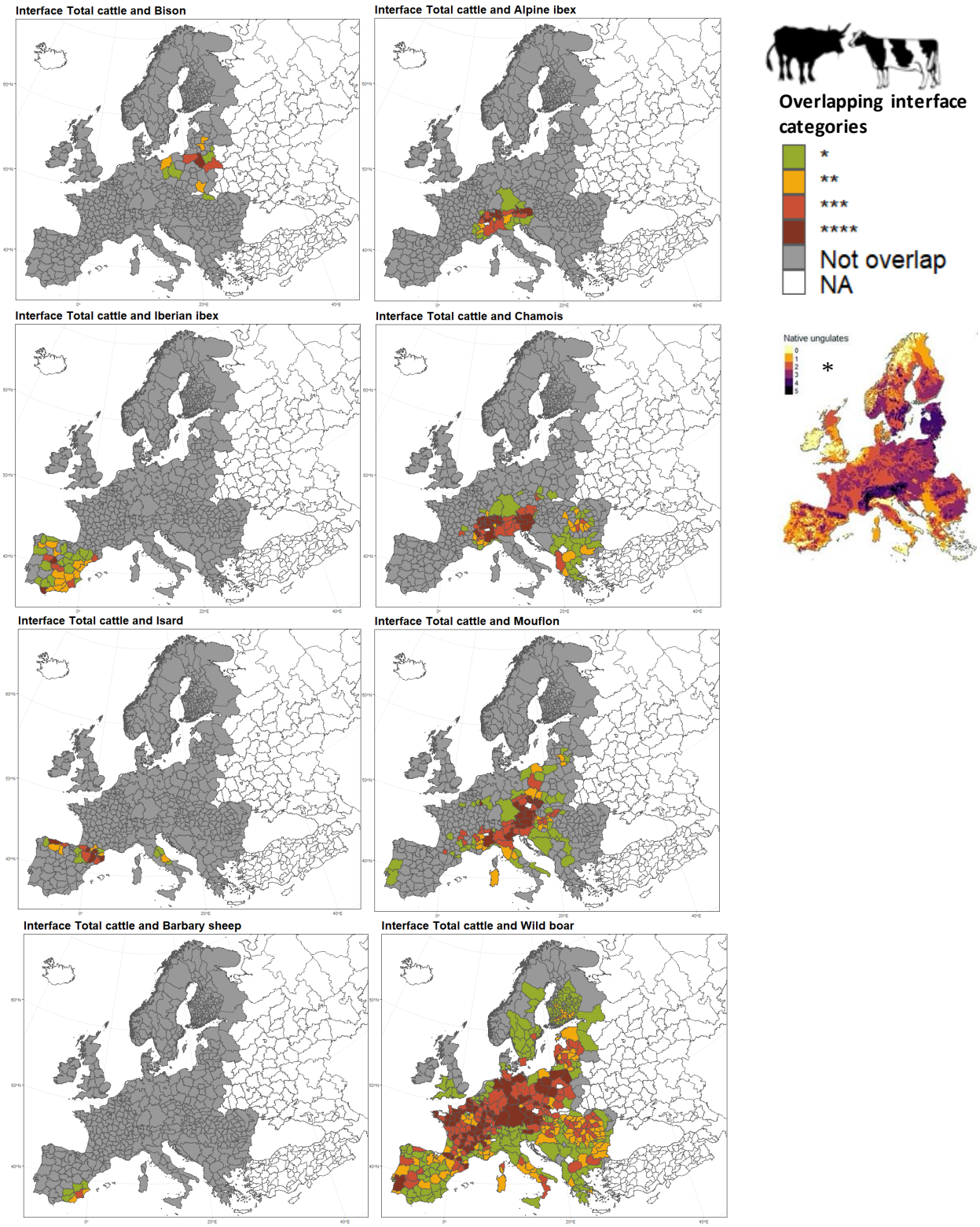
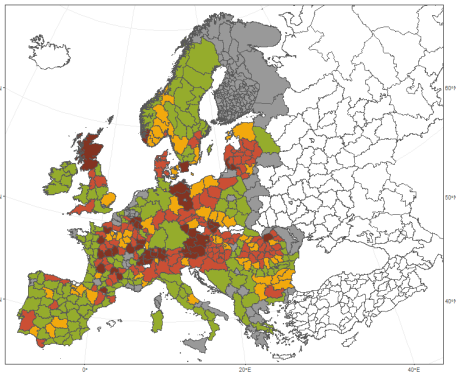
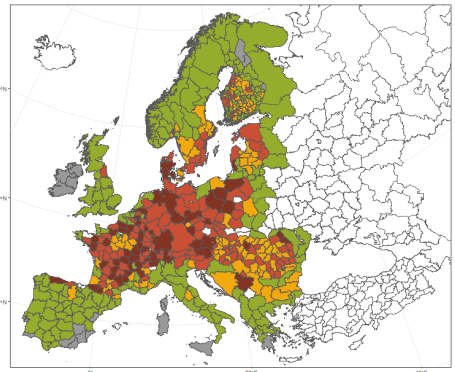


Figure 11: Distribution overlap of cattle and wild ungulates (Bovidae and wild boar) in Europe. Categories of interaction are indicated in color as detailed in section 3.1. The arena for the overlapping spatial analysis is show on top (*), and similarly applies to next figures. NA category means that there is not information about ungulates.

Interface Total cattle and Red deer



Interface Total cattle and Roe deer



Overlapping interface categories

*

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***

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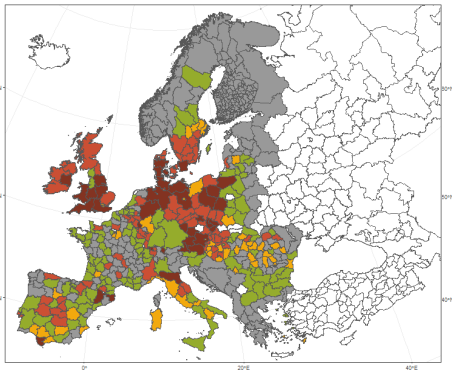
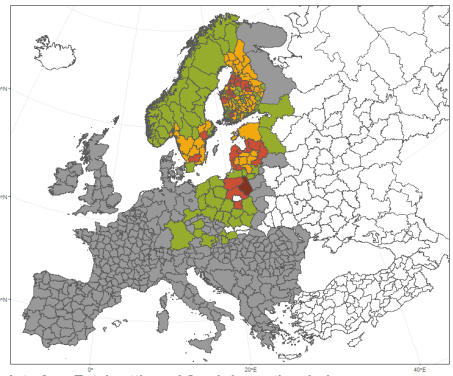
Not overlap

NA

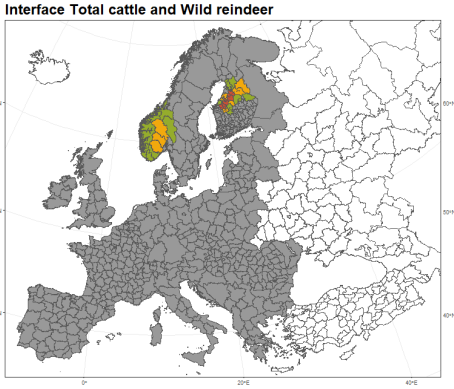
Interface Total cattle and Fallow deer



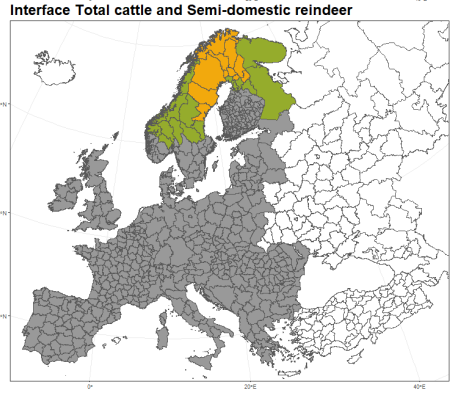
Interface Total cattle and Moose



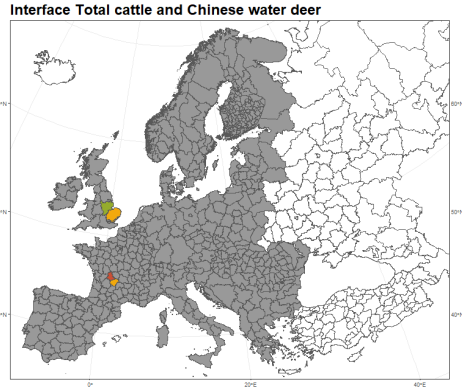
Interface Total cattle and Wild reindeer



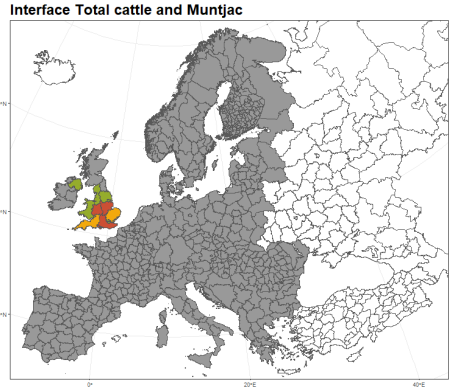
Interface Total cattle and Semi-domestic reindeer



Interface Total cattle and Chinese water deer



Interface Total cattle and Muntjac



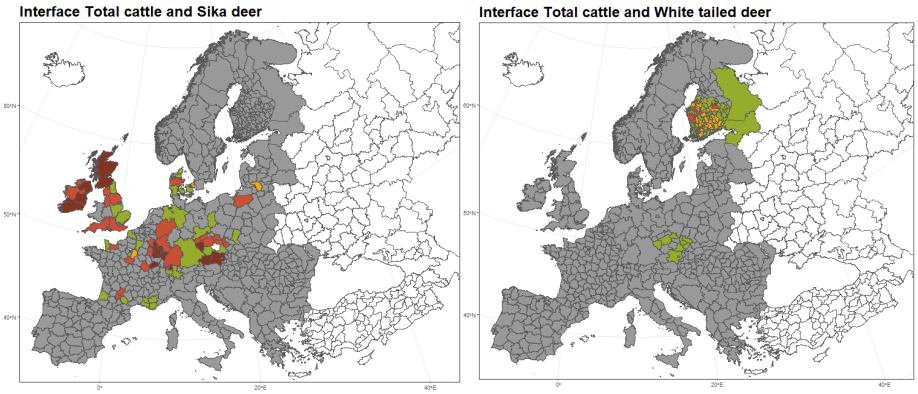


Figure 12: Distribution overlap of total cattle and wild Cervidae in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

Total cattle/wild ungulate overlapping maps at administrative unit level are shown first for Bovidae (Figure 11), wild species being appearing first from higher phylogenetic closeness. Wild boar is also shown in Figure 11. Next, Figure 12 includes Cervidae species, which are diverse across Europe (ten classes, including nine native and introduced species, reindeer is separately represented for wild and semi-domestic). This scheme to represent results is similar for other livestock species, to facilitate comparisons.

- As for ruminant Bovidae, the detected overlapping administrative units are mainly determined by where wild species, respectively, occur, since total cattle are widely farmed all over Europe.
- Regarding mouflon, the intense overlapping at administrative unit level in Central Europe, from West to East, from the Alps (where the presence of mountain ungulates adds diversity), expanding to countries with important big game tradition and presence of introduced species (Hungary, Czech Republic, South Germany), to South Poland, is remarkable.
- Regarding wild boar and most widely distributed Cervidae, red deer and roe deer (all native species), a relevant intense overlapping occurs in Central Europe, from France, towards Austria, Czech Republic, Hungary, Slovakia and to Poland. It also appears in certain regions of the Balkans and the UK (North UK for red deer). Noteworthy is the case of fallow deer, with a similar but less intense pattern in France, and high presence in co-occurrence with cattle in certain Mediterranean countries (Spain, Italy).
- As for other Cervidae, similar to mountain ungulates, co-occurrence is mainly determined by the distribution of the wild species, normally restricted to certain regions of Europe for both northern native (reindeer, moose) or introduced species. Specifically, the pattern for introduced Sika deer is relevant, indicating that it occurs widely in the British Isles, and is scattered in many regions of different central Europe countries.

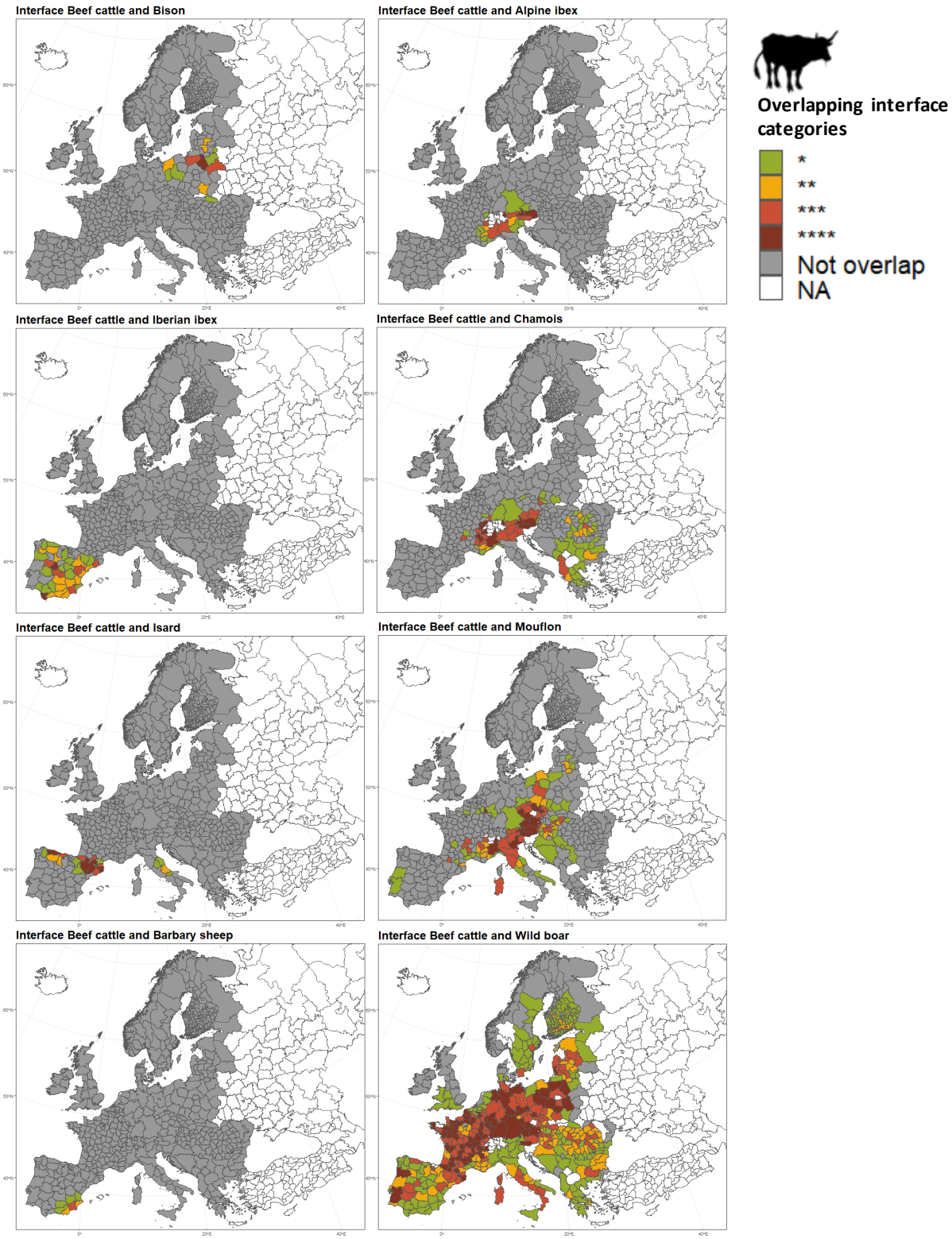
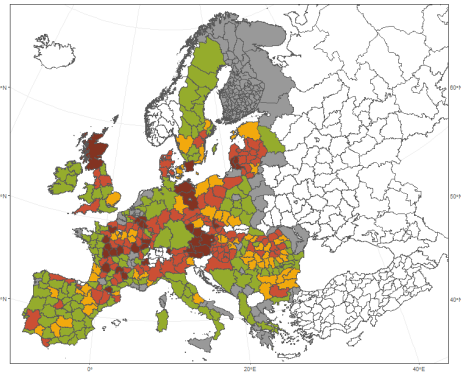
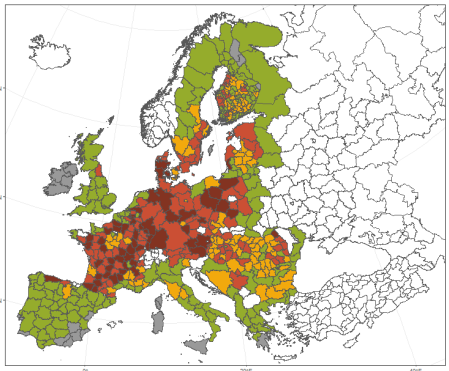


Figure 13: Distribution overlap of beef cattle and wild ungulates (Bovidae and wild boar) in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

Interface Beef cattle and Red deer



Interface Beef cattle and Roe deer



Overlapping interface categories

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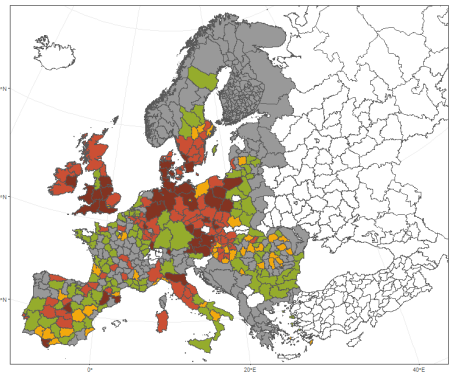
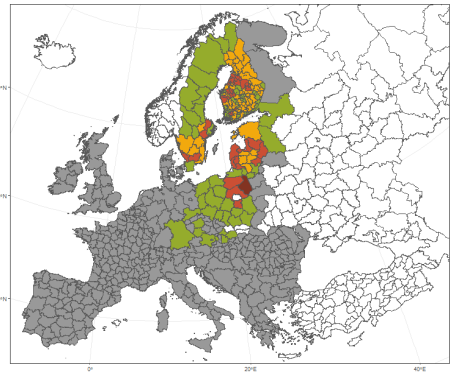
Not overlap
NA

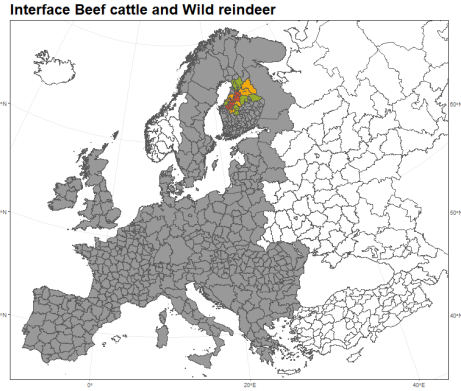
Interface Beef cattle and Fallow deer



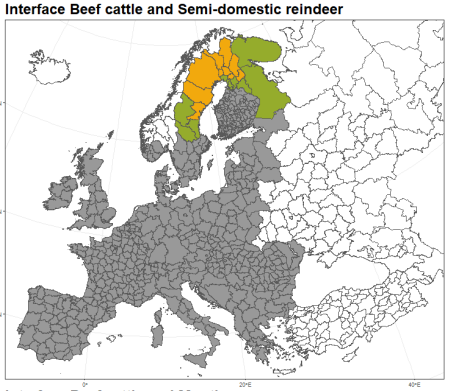
Interface Beef cattle and Moose



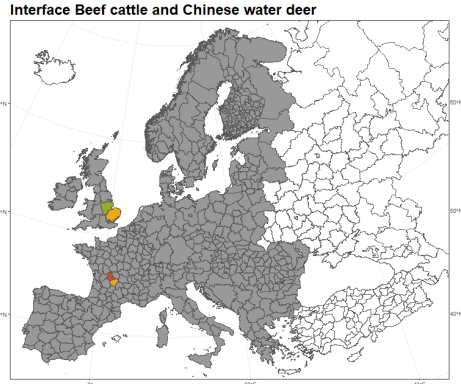
Interface Beef cattle and Wild reindeer



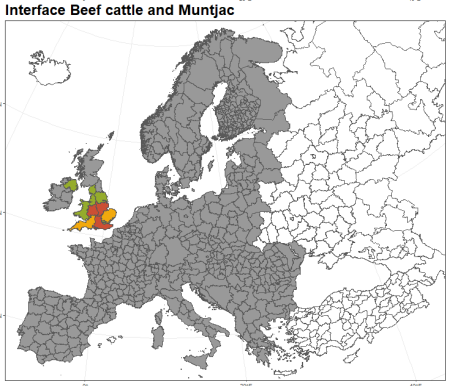
Interface Beef cattle and Semi-domestic reindeer



Interface Beef cattle and Chinese water deer



Interface Beef cattle and Muntjac



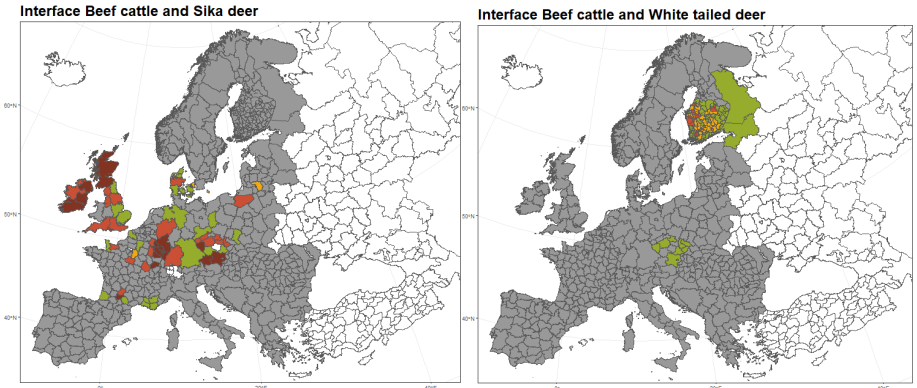


Figure 14: Distribution overlap of beef cattle and wild Cervidae in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

The beef cattle/wild ungulate overlapping maps at administrative unit level are similarly shown first for Bovidae and wild boar (Figure 13) and Cervidae species (Figure 14).

- Similarly to total cattle, and as for wild ruminant Bovidae, the detected overlapping administrative units are mainly determined by where wild species, respectively, occur, since beef cattle are widely farmed all over Europe.
- Regarding mouflon, the intense overlapping at administrative unit level in Central Europe, from West to East, from the Alps (where the presence of mountain ungulates adds diversity), towards countries with important big game tradition and presence of introduced species (Austria, Czech Republic), to finally, South Poland, is remarkable.
- Regarding wild boar and most widely distributed Cervidae, red deer and roe deer (all native species), a relevant intense overlapping occurs in Central Europe, from France, extending to Austria, Czech Republic, Hungary and Slovakia, to Poland. It also appears in certain regions of the Balkans and the UK (North UK for red deer). Specific internal differences may occur within countries compared with total cattle, since livestock typologies are not similarly distributed over administrative units in countries. Noteworthy it is the case of fallow deer, which has a similar pattern, although it is less intense in France and more intense in the UK.
- As for other Cervidae, similarly to mountain ungulates, the co-occurrence is mainly determined by the distribution of the wild species, normally restricted to certain regions of Europe for both northern native (reindeer, moose) or introduced species. Specifically, the pattern for introduced Sika deer is relevant, indicating that it occurs widely in the British Isles, and is scattered in many regions of Central Europe, mainly Germany, France and Czech Republic).

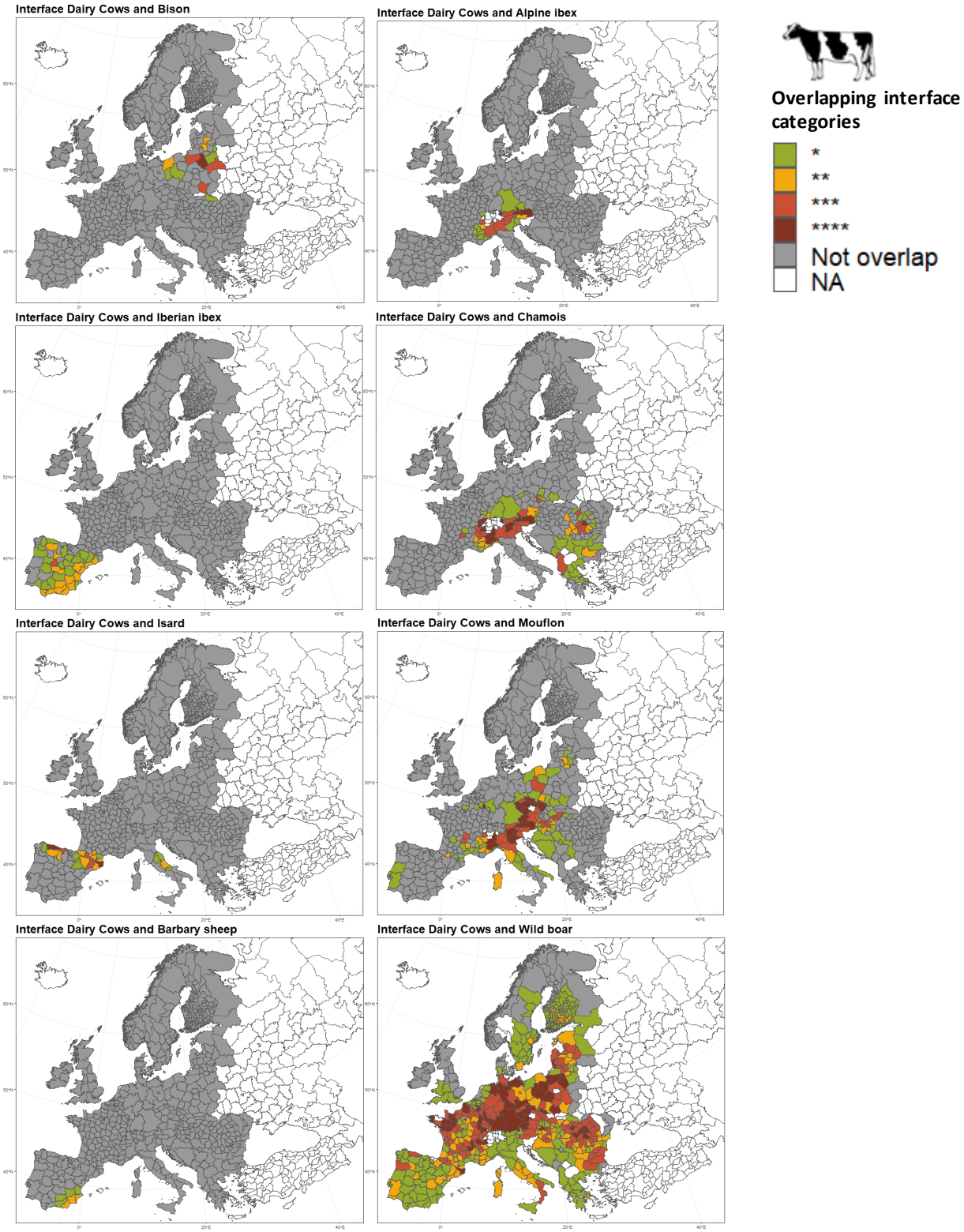
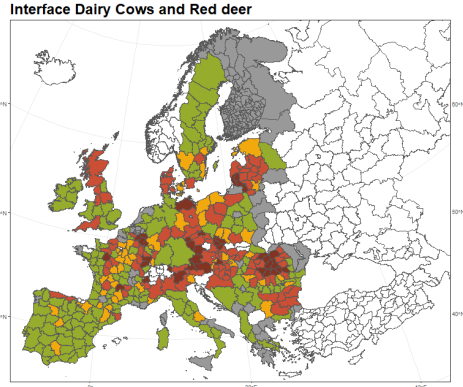
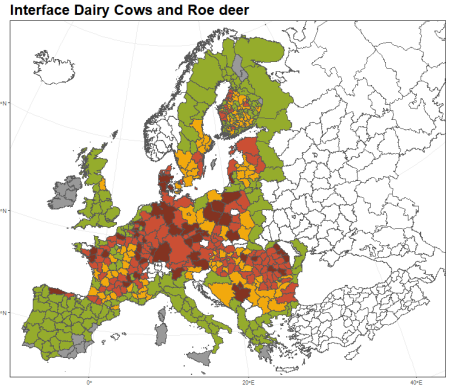


Figure 15: Distribution overlap of dairy cattle and wild ungulates (Bovidae and wild boar) in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

Interface Dairy Cows and Red deer



Interface Dairy Cows and Roe deer



Overlapping interface categories

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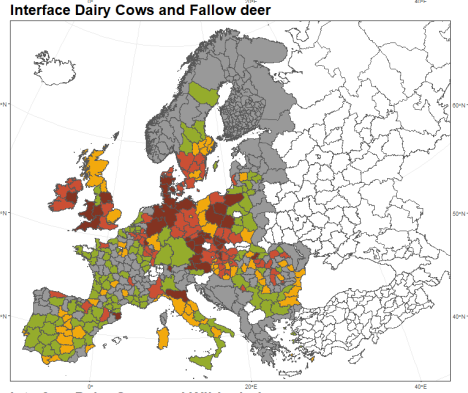
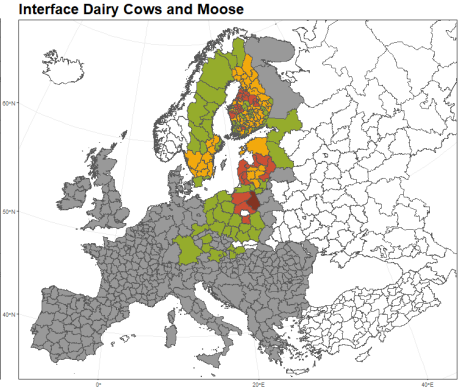
Not overlap
NA

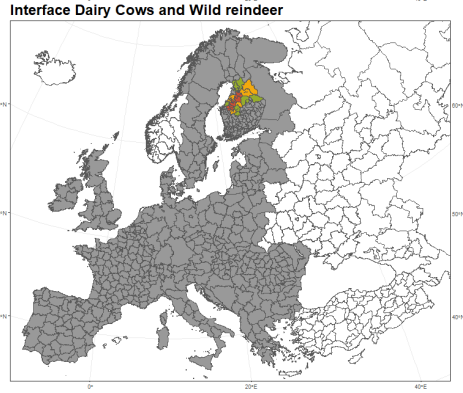
Interface Dairy Cows and Fallow deer



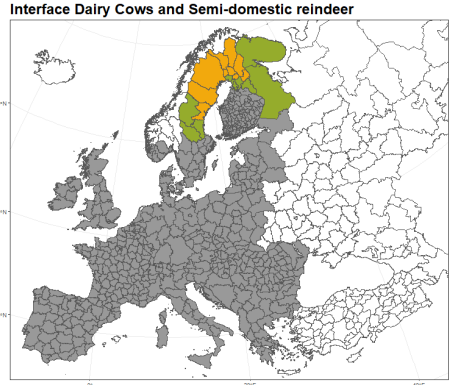
Interface Dairy Cows and Moose



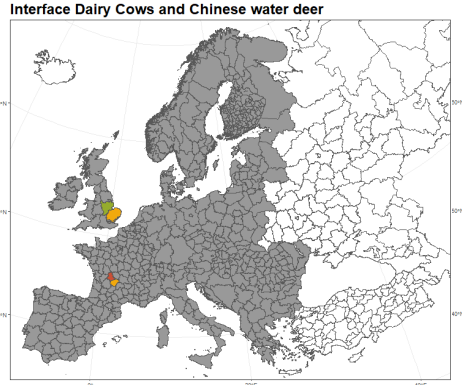
Interface Dairy Cows and Wild reindeer



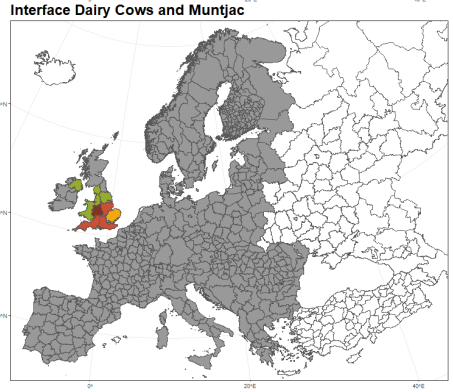
Interface Dairy Cows and Semi-domestic reindeer



Interface Dairy Cows and Chinese water deer



Interface Dairy Cows and Muntjac



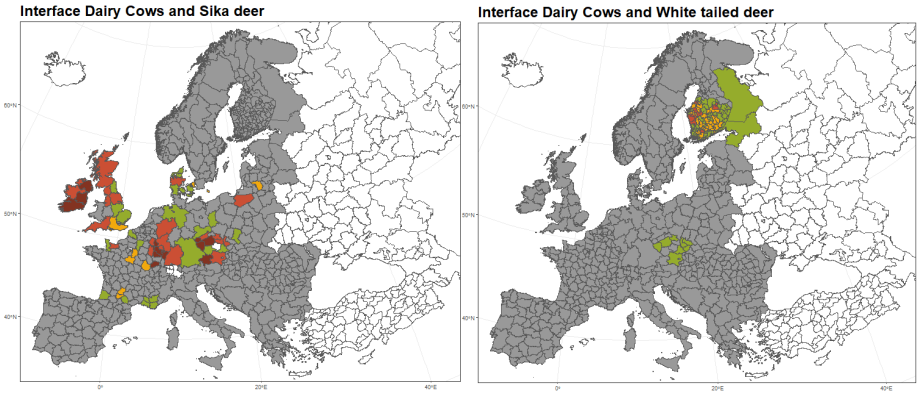


Figure 16: Distribution overlap of dairy cattle and wild Cervidae in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

The dairy cattle/wild ungulate overlapping maps at administrative unit level are similarly shown first for Bovidae and wild boar (Figure 15) and Cervidae species (Figure 16).

- Similarly to beef, and as for wild ruminant Bovidae, the detected overlapping administrative units are mainly determined by where wild species, respectively, occur, since dairy cattle are widely farmed all over Europe.
- Regarding mouflon, the intense overlapping at administrative unit level in Central Europe, from West to East, from the Alps (where the presence of mountain ungulates adds diversity), towards countries with important big game tradition and presence of introduced species (Hungary, Czech Republic, South Germany), to finally, South Poland, is remarkable.
- Regarding wild boar and most widely distributed Cervidae, red deer and roe deer (all native species), a relevant intense overlapping occurs in Central Europe, from France, extending to Austria, Czech Republic, Hungary and Slovakia, to Poland. It also appears in certain regions of the Balkans and the UK (North UK for red deer). Specific internal differences may occur within countries compared with beef cattle, since livestock typologies are not similarly distributed over administrative units in countries. Noteworthy is the case of fallow deer, with a similar but less intense pattern in France.
- As for other Cervidae, similarly to mountain ungulates, the co-occurrence is mainly determined by the distribution of the wild species, normally restricted to certain regions of Europe for both northern native (reindeer, moose) or introduced species. Specifically, the pattern for introduced Sika deer is relevant, indicating that it occurs widely in the British Isles, and is scattered in many regions of Central Europe and different countries.

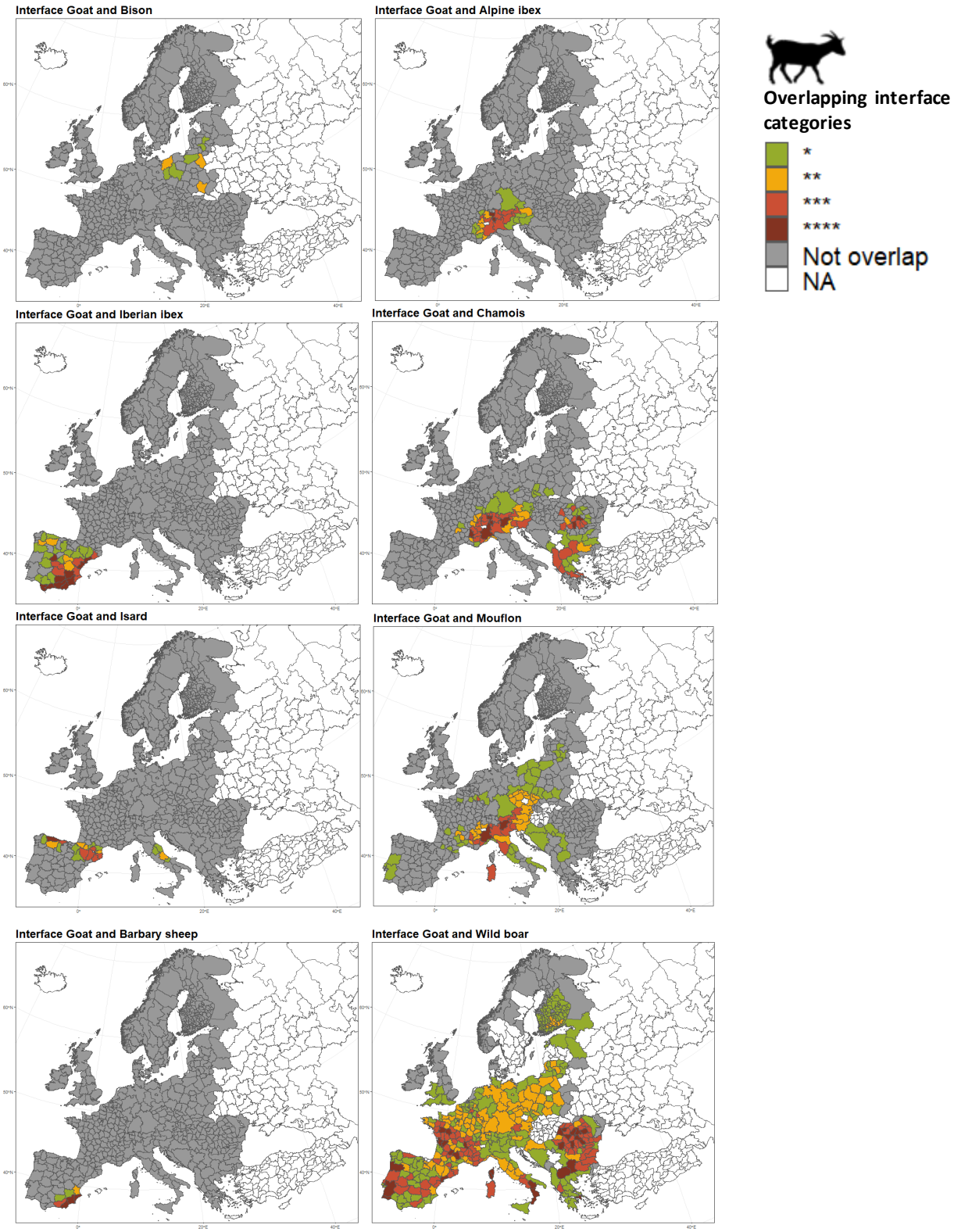
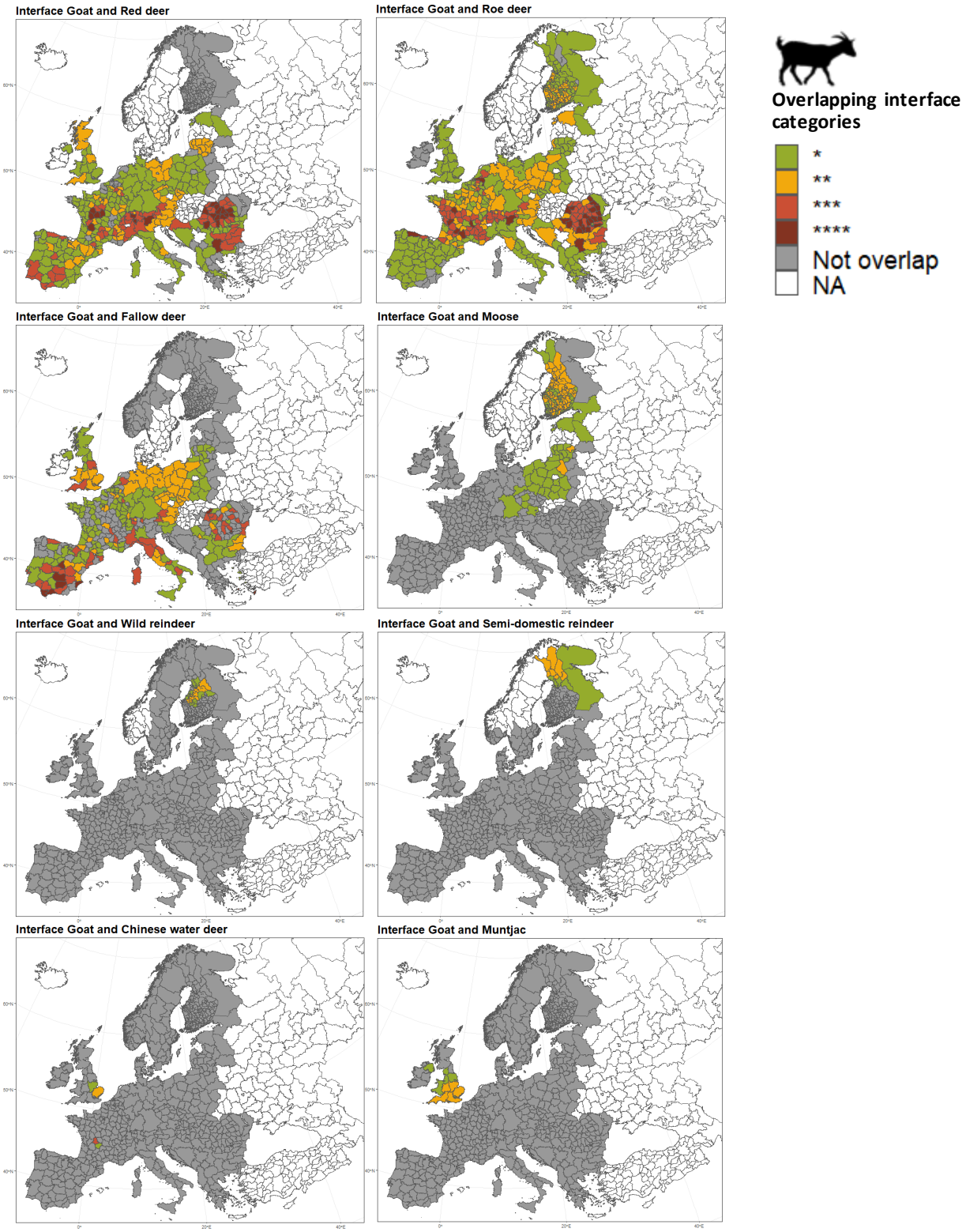


Figure 17: Distribution overlap of goats and wild ungulates (Bovidae and wild boar) in Europe. Legend. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.



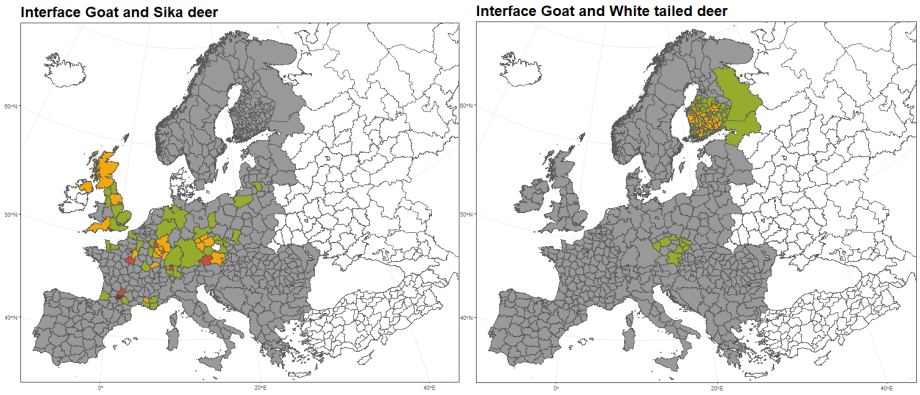


Figure 18: Distribution overlap of goats and wild Cervidae in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

The goat/wild ungulate overlapping maps at administrative unit level are similarly shown first for Bovidae and wild boar (Figure 17) and Cervidae species (Figure 18).

- Like cattle, and in relation to ruminant Bovidae, the detected overlapping administrative units are mainly determined by where wild species, respectively, occur, since goats are widely farmed all over Europe.
- Regarding wild boar, and most widely distributed Cervidae, red deer, roe deer and fallow deer, contrary to cattle, a relevant intense overlapping occurs in Southern Europe, from Spain, passing by France to Italy and the Balkans region (the pattern is less marked for roe deer, mainly absent in southernmost regions of Europe).
- As for other Cervidae, similarly to mountain ungulates, the co-occurrence is mainly determined by the distribution of the wild species, normally restricted to certain regions of Europe for both northern native (reindeer, moose) or introduced species. Specifically, the pattern for introduced Sika deer is relevant again, indicating that it occurs widely in the British Isles, and is scattered in many regions of Central Europe and different countries.

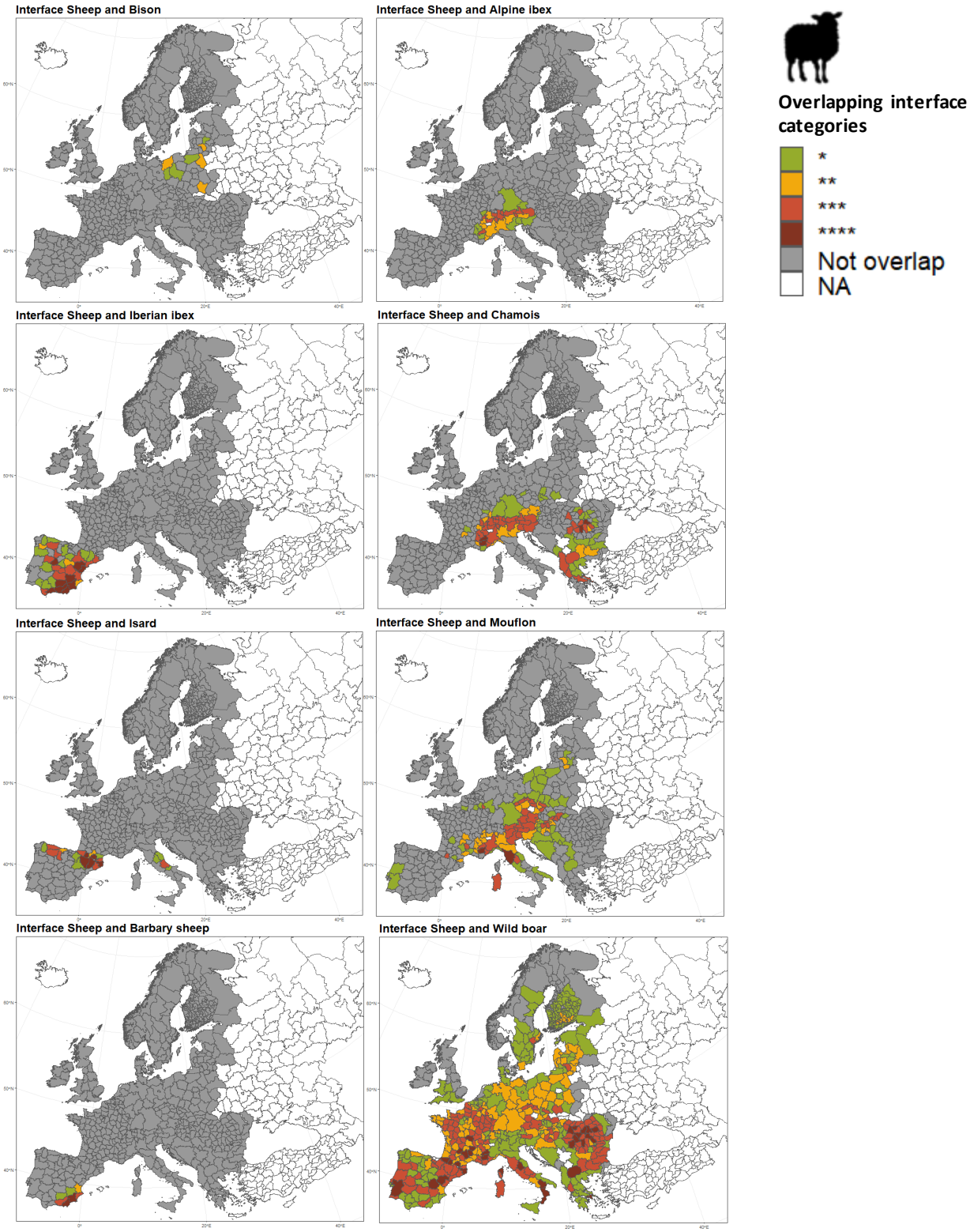
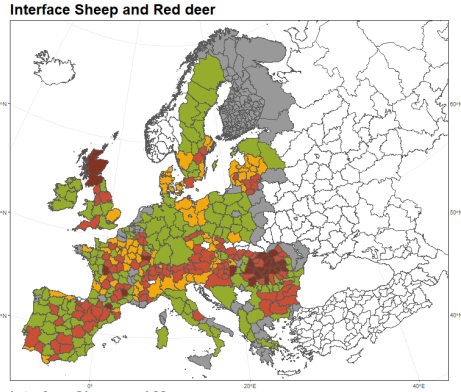
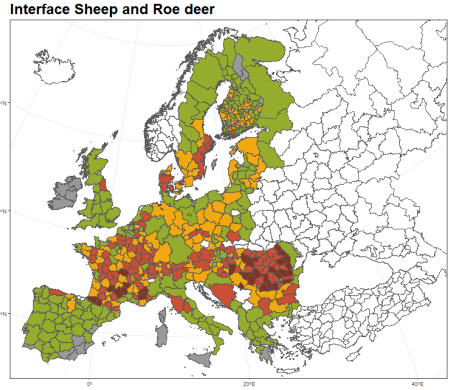


Figure 19: Distribution overlap of sheep and wild ungulates (Bovidae and wild boar) in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

Interface Sheep and Red deer



Interface Sheep and Roe deer



Overlapping interface categories

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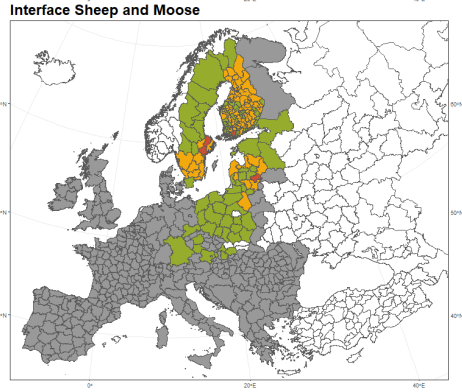
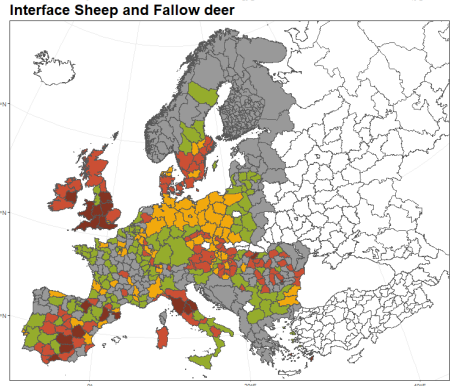
Not overlap
NA

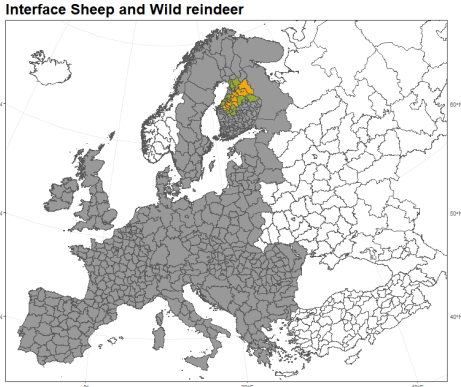
Interface Sheep and Moose



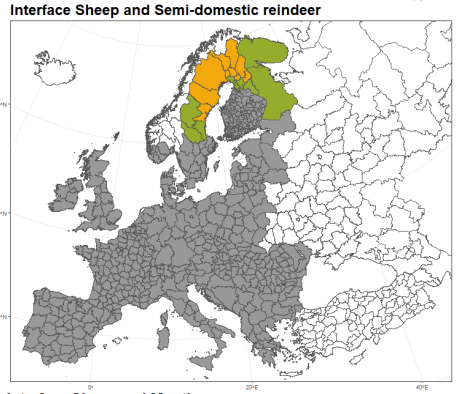
Interface Sheep and Fallow deer



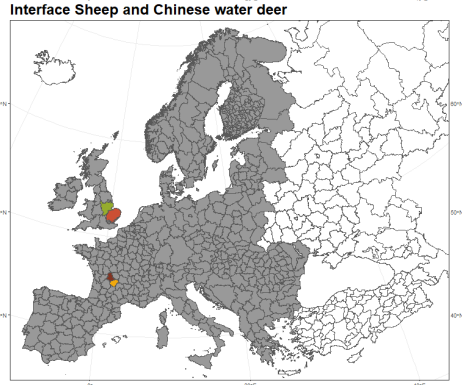
Interface Sheep and Wild reindeer



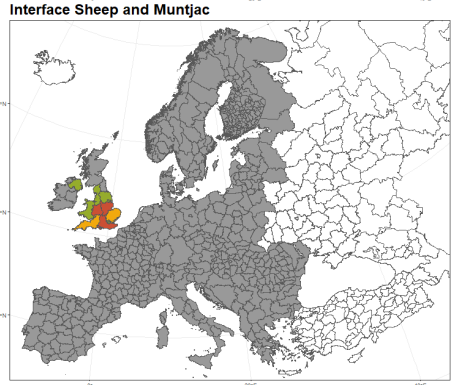
Interface Sheep and Semi-domestic reindeer



Interface Sheep and Chinese water deer



Interface Sheep and Muntjac



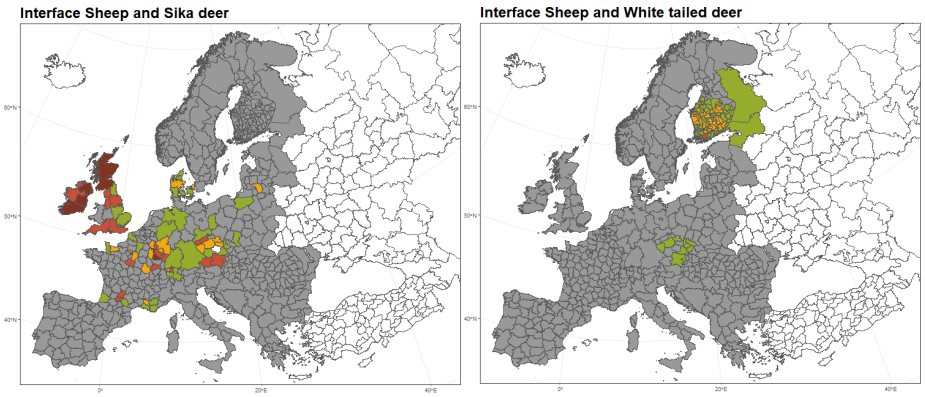


Figure 20: Distribution overlap of sheep and wild Cervidae in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

The sheep/wild ungulate overlapping maps at administrative unit level are similarly shown first for Bovidae and wild boar (Figure 19) and Cervidae species (Figure 20).

- Similarly to cattle and goats, and as for ruminant Bovidae, the detected overlapping administrative units are mainly determined by where wild species, respectively, occur, since sheep are widely farmed all over Europe.
- As for mouflon, its domestic counterpart, the intense overlapping at administrative unit level in Central Europe, from West to East, from the Alps (where the presence of mountain ungulates adds diversity), to countries with important big game tradition and presence of introduced species (Hungary, Czech Republic, South Germany) is remarkable. Relevant spots are in central Italy and Sardinia.
- Regarding wild boar, the intense overlapping at administrative unit level is remarkable in three regions: (i) France and Spain, (ii) Central and South Italy plus Corsica and Sardinia, and (iii) Central-eastern Europe: Czech Republic, Hungary, and the Balkans.
- Regarding red deer, a relevant intense overlapping strip occurs from Spain, France, the region north to Alps towards the Balkans region. It is also relevant for northern UK and Southern Sweden.
- The pattern is similar for roe deer, but less marked in the British Isles and Spain (where some relevant spots are in the north).
- As for other Cervidae, similarly to mountain ungulates, the co-occurrence is mainly determined by the distribution of the wild species, normally restricted to certain regions of Europe for both northern native (reindeer, moose) or introduced species (e.g., Muntjac in England). Specifically, the pattern for introduced Sika deer is relevant, indicating that it occurs widely in the British Isles, and is scattered in many Central Europe regions and different countries.

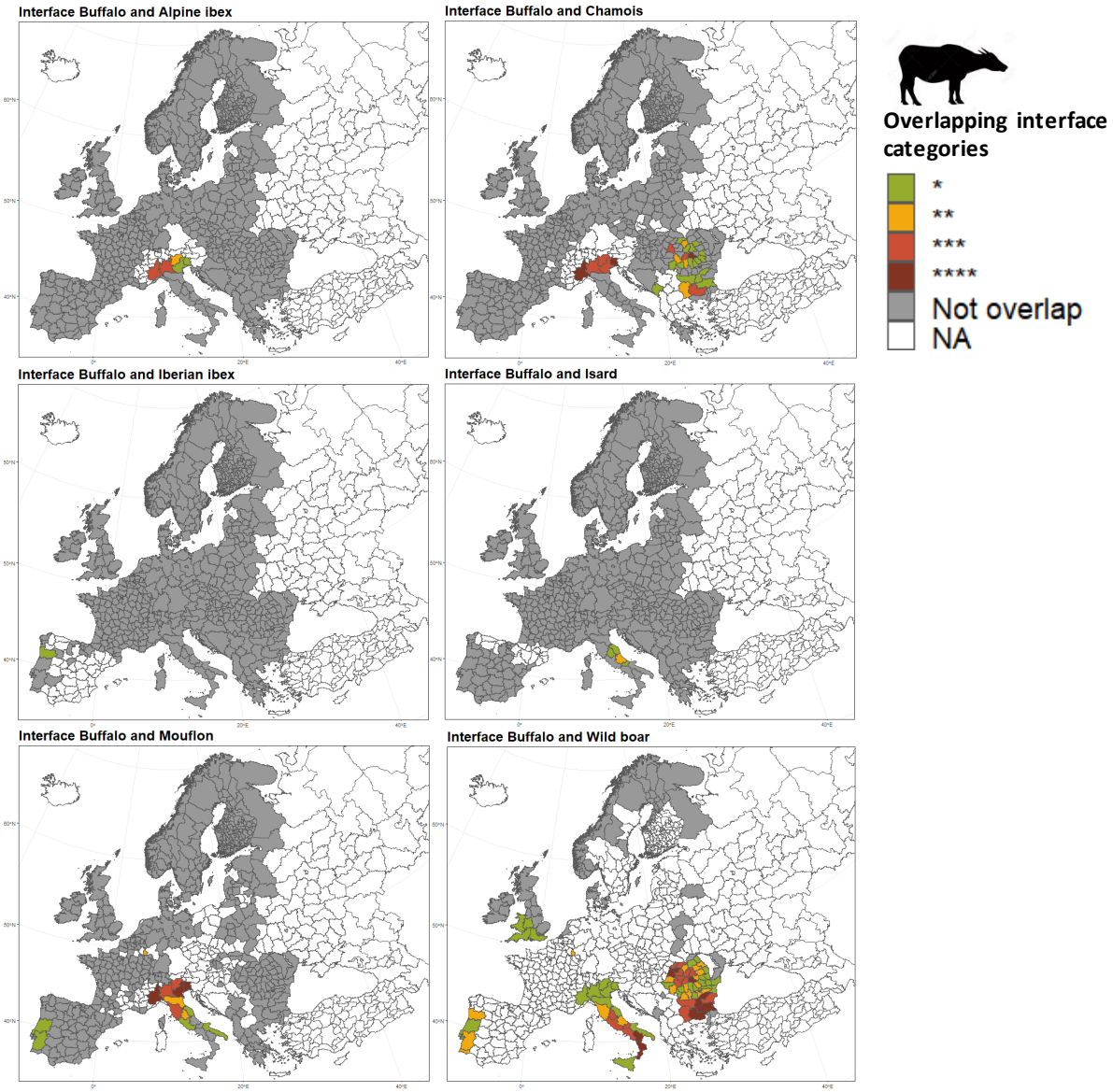


Figure 21: Distribution overlap of buffalo and wild ungulates (Bovidae and wild boar) in Europe. Only the wild species for which overlapping at NUTS2 level was found are displayed. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

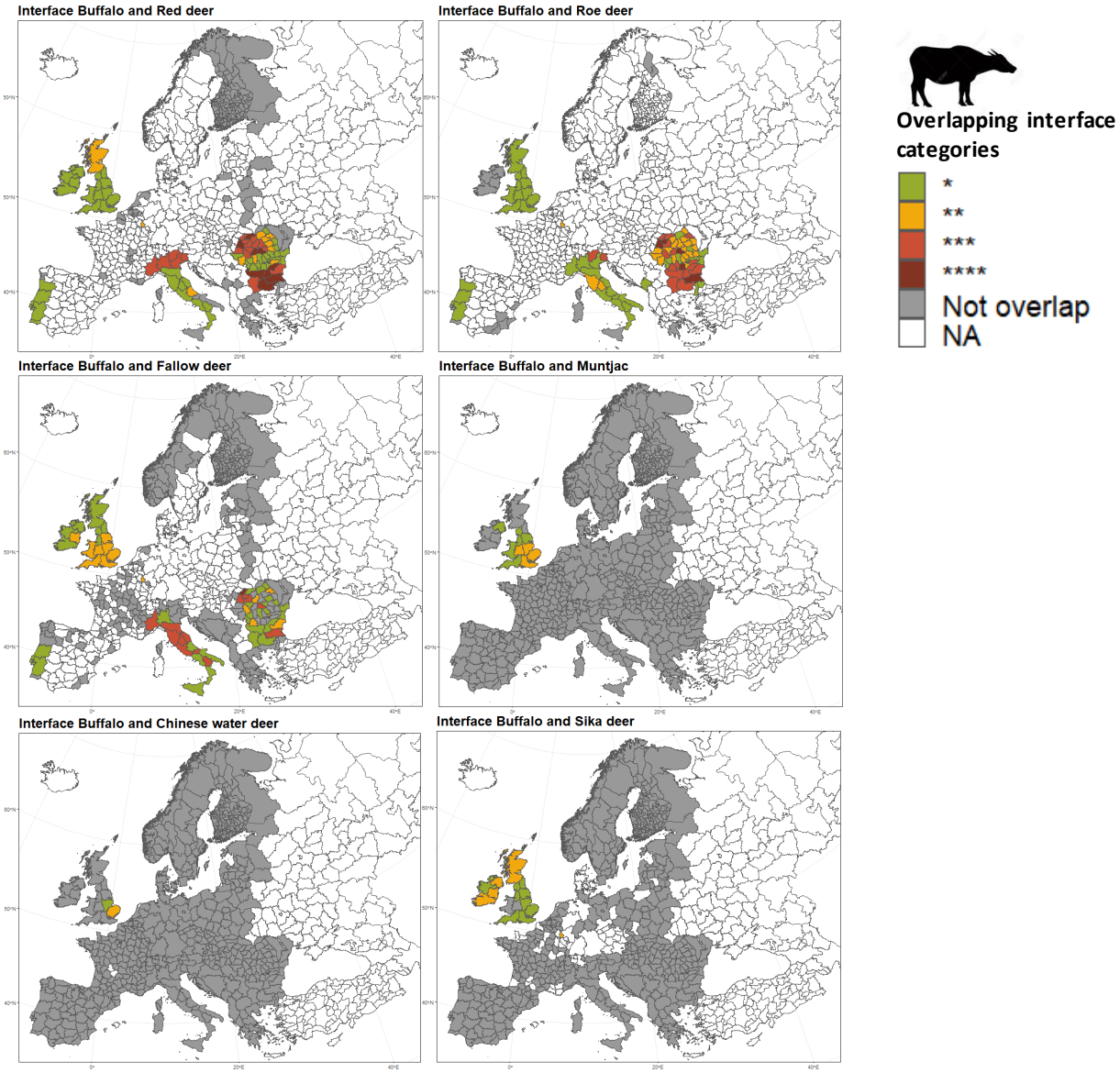


Figure 22: Distribution overlap of buffalo and wild Cervidae in Europe. Only the wild species for which overlapping at NUTS2 level was found are displayed. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

The domestic buffalo/wild ungulate overlapping maps at administrative unit level are similarly shown first for Bovidae and wild boar (Figure 21) and Cervidae species (Figure 22). The other bovine species, buffalo, is mainly distributed East to the Balkans (Bulgaria, Romania, Turkey), in Italy, and to a lesser extent in other countries, which determine the restricted regions of Europe where the spatial overlapping with wild ungulate distribution may occur. Wild boar and the more generalist deer species (red deer, roe deer, and fallow deer) are present all over the distribution area of buffalo, highlighting as more intense spatial overlapping the regions east to Balkans and Italy.

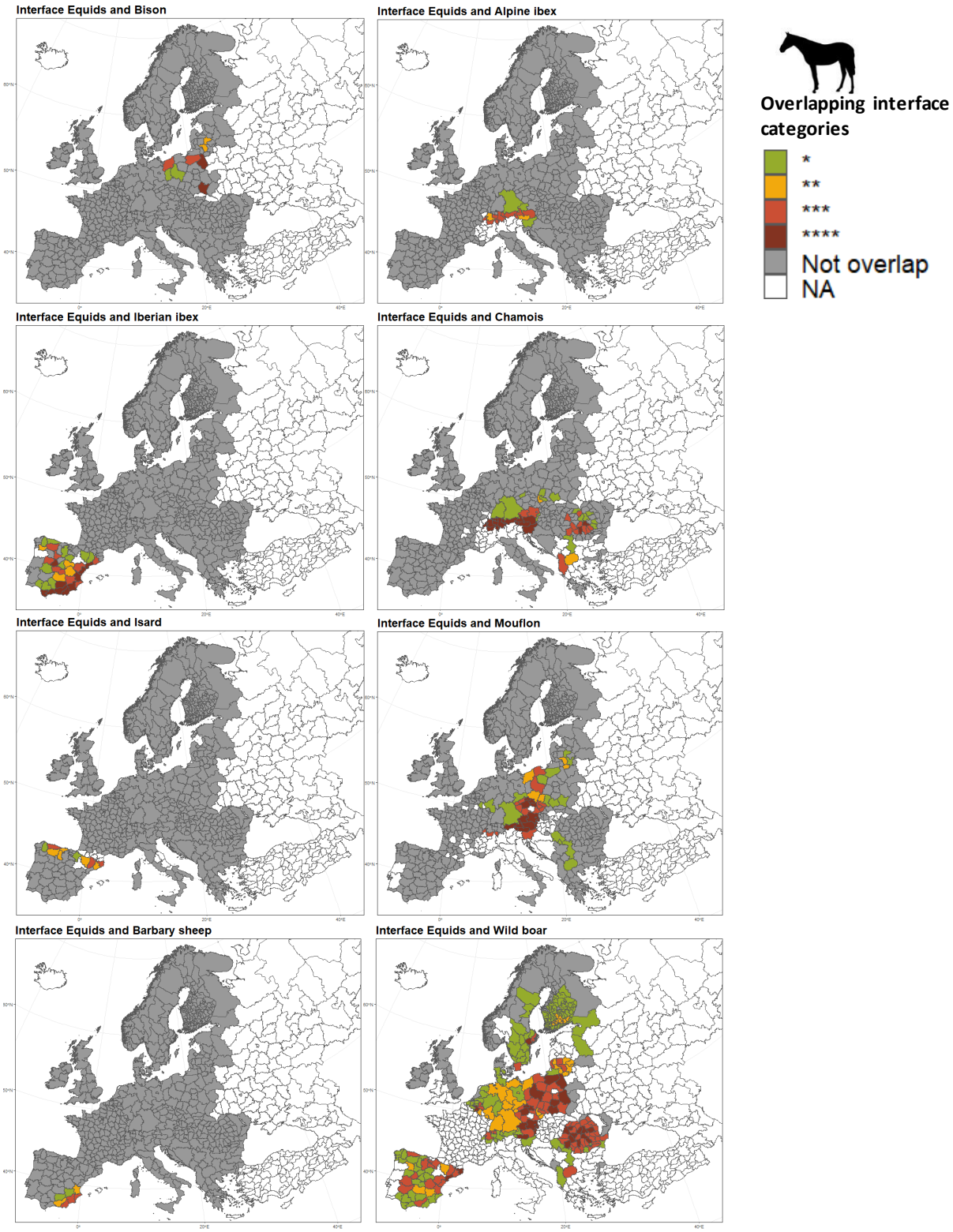


Figure 23: Distribution overlap of equids and wild ungulates (Bovidae and wild boar) in Europe. Only the wild species for which overlapping at NUTS2 level was found are displayed. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

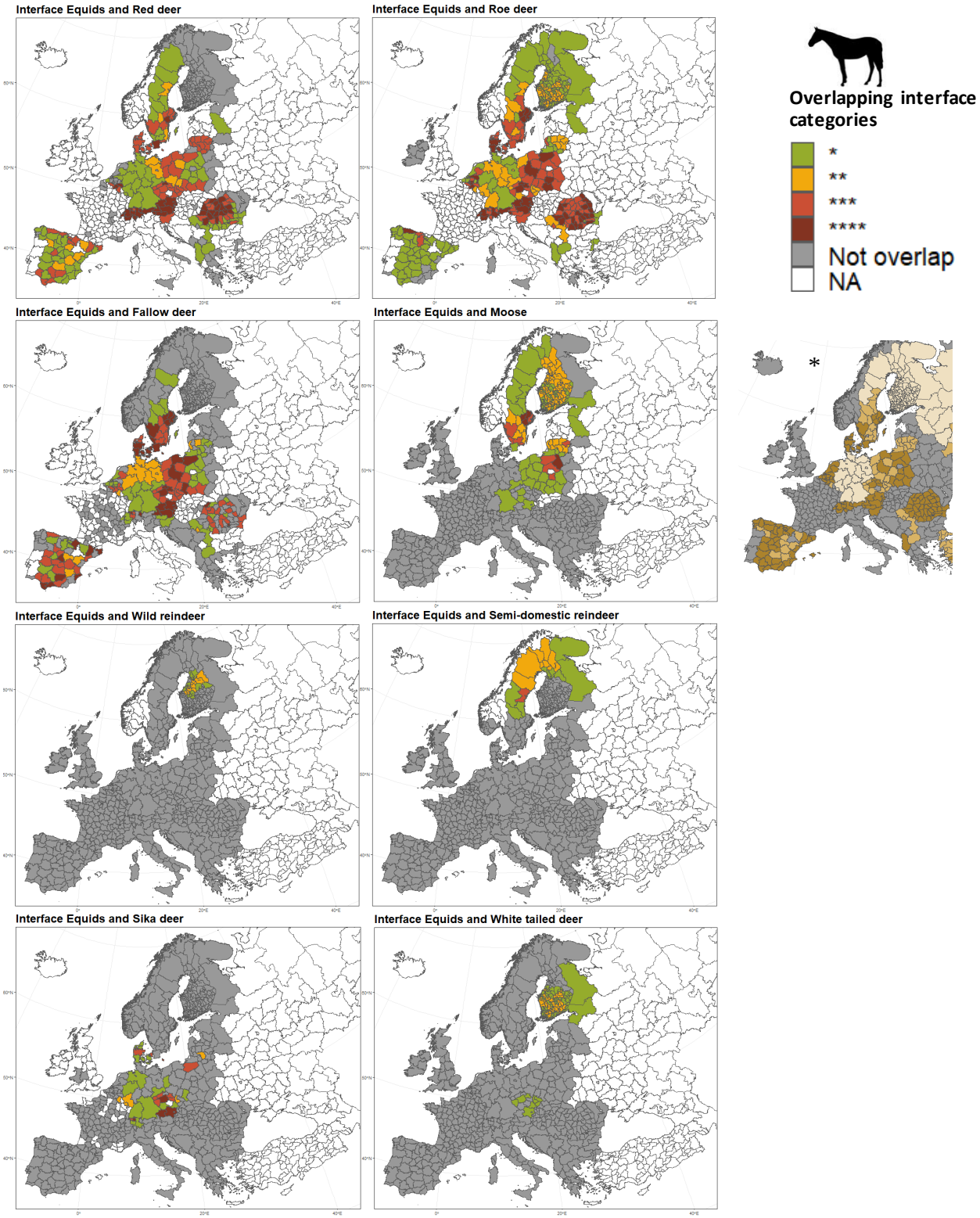


Figure 24: Distribution overlap of equids and wild Cervidae in Europe. Only the wild species for which overlapping at NUTS2 level was found are displayed. Categories of interaction are indicated in color as detailed in section 3.1. The arena for the overlapping spatial analysis for equids is show on top (*). NA category means that there is not information about ungulates.

The domestic equids (horses, donkeys, and mules)/wild ungulate overlapping maps at administrative unit level are similarly shown first for Bovidae and wild boar (Figure 23) and Cervidae species (Figure 24). The arena for the overlapping spatial analysis for equids is shown on top (*), which evidences important data lacks (France, Italy, Eastern regions of Europe). Therefore, we can only partially display the spatial overlapping at European level. Equids, mainly horses, are widely distributed over Europe. This partial picture indicates the more intense overlaps in Spain, Poland, Romania, Austria, Switzerland, and regions of Germany with wild boar, red deer, roe deer, and more specifically for other species in other countries (for instance red deer and fallow deer in Denmark, Ibex in Spain). Equids are the least phylogenetically related species to ruminant wild ungulates, and therefore, overall, they present less risk for disease sharing. However, interaction may be close, which may play relevant ecological and conservation roles (e.g. semi-domestic or extensive horses). Therefore, more detailed information on equid census distribution over Europe is needed to depict the spatial overlap with wild ungulates.

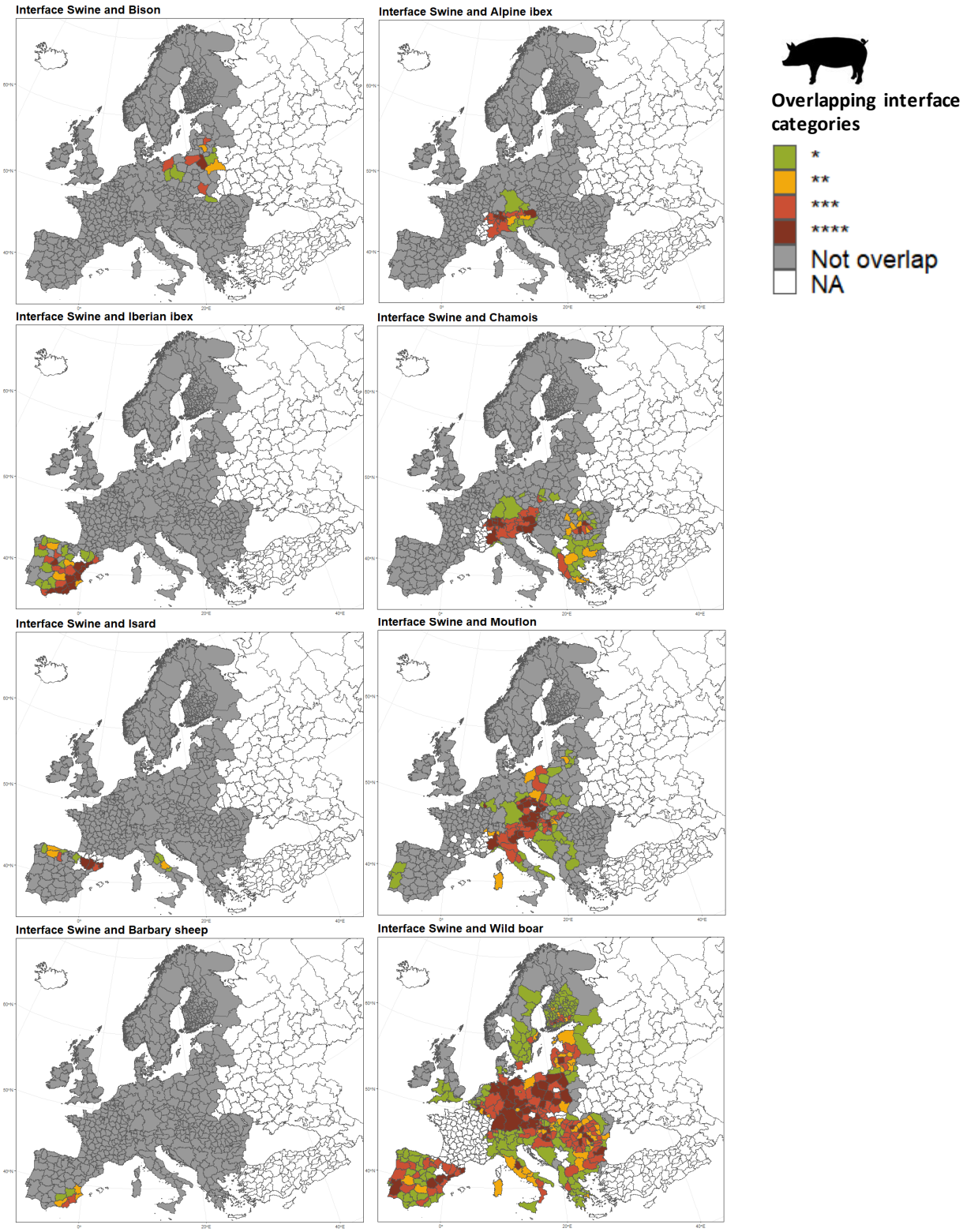
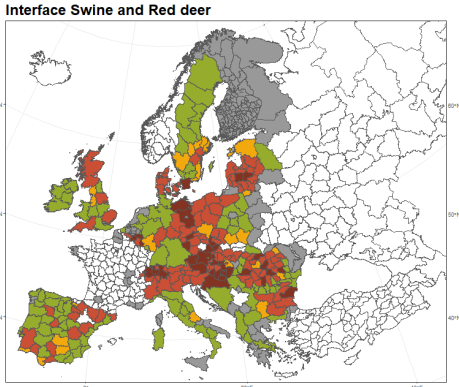
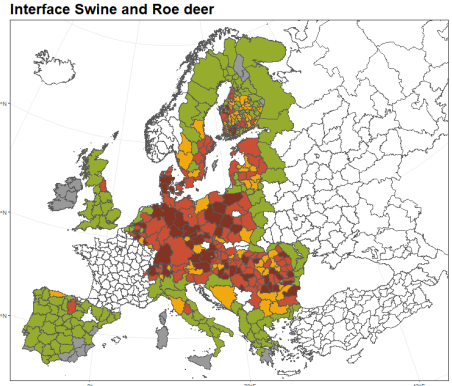


Figure 25: Distribution overlap of pigs and wild ungulates (Bovidae and wild boar) in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

Interface Swine and Red deer



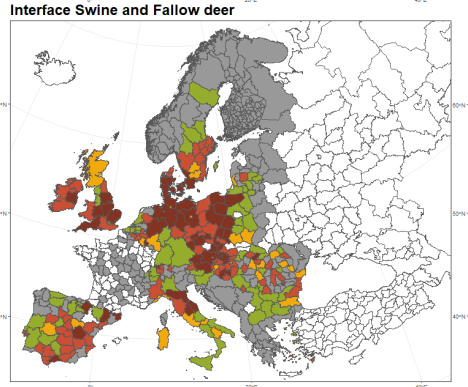
Interface Swine and Roe deer



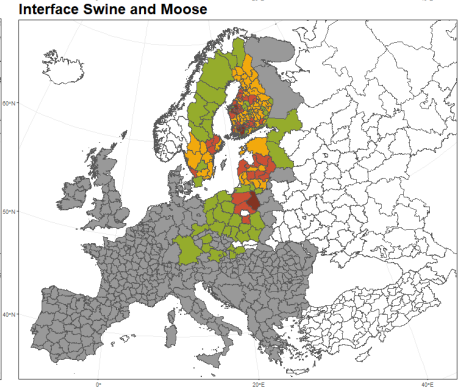
Overlapping interface categories

*
**
***
****
Not overlap
NA

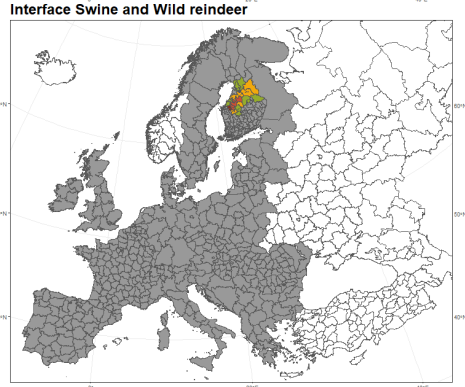
Interface Swine and Fallow deer



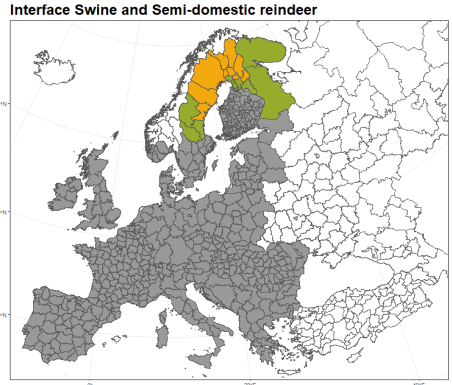
Interface Swine and Moose



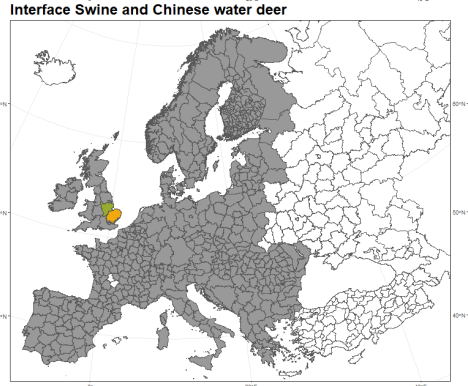
Interface Swine and Wild reindeer



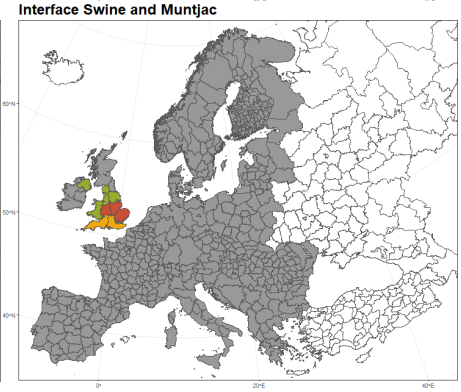
Interface Swine and Semi-domestic reindeer



Interface Swine and Chinese water deer



Interface Swine and Muntjac



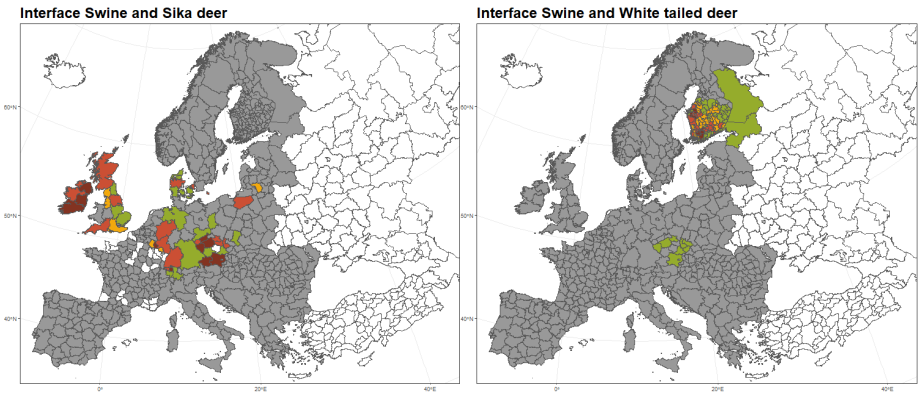


Figure 26: Distribution overlap of pigs and wild Cervidae in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about ungulates.

The pig/wild ungulate overlapping maps at administrative unit level are shown first for Bovidae (Figure 25) and for Cervidae (Figure 26). No pig data was available at required spatial resolution from France.

- As for ruminant Bovidae, the detecting overlapping administrative units are mainly determined by where wild species, respectively, occur, since pigs are widely farmed all over Europe.
- Regarding mouflon, like other widely distributed livestock (cattle, sheep), the intense overlapping at administrative unit level in Central Europe, from West to East, from the Alps (where the presence of mountain ungulates adds diversity) and North Italy, to countries with important big game tradition and presence of introduced species (Hungary, Czech Republic, South Germany), to Poland, is remarkable.
- Regarding wild boar (its domestic counterpart) and most widely distributed Cervidae, red deer, roe deer and fallow deer, a relevant overlapping occurs from Spain to Central Europe and the Balkans regions, and in Denmark (for above-mentioned deer species), Southern Sweden and the Baltic republics. Remarkable is red deer and fallow deer in the UK.
- As for other Cervidae, similar to mountain ungulates, co-occurrence is mainly determined by the distribution of the wild species, normally restricted to certain regions of Europe for both northern native (reindeer, moose) or introduced species. Specifically, the pattern for Sika deer (an introduced species) is relevant, indicating that it occurs widely in the British Isles, and is scattered in many Central Europe regions and different countries.

4.2.2. Richness overlapping areas

The wild ungulate/livestock richness overlapping maps (determined between wild ungulates richness categories and livestock density) at administrative unit level are shown in Figure 27. Two different patterns, depending on livestock type, can be seen:

- Bovidae livestock (except buffaloes) tend to have an intense overlapping in Central Europe, from France to Austria, Czech Republic, Hungary, Slovakia to Poland and Romania.
- Buffaloes show the higher overlap for Italy, Romania and Bulgaria, and present low values of overlapping in Turkey where, however, their abundance values rank from moderate to high.
- Similar tendency as Bovidae is observed for domestic pigs, except for Spain, where it a more intense overlapping is noted.
- Ovine and caprine livestock show a similar pattern, which is mostly influenced by its abundance along Europe, where higher overlapping areas are found in the Mediterranean and Balkans regions.
- Equids (horses, donkeys, and mules) pattern show an intense overlap in Eastern-Central Europe, from Austria and Slovenia to Poland. Other countries such as Spain, Albania or Romania, also show a relevant overlap. It is remarkable for this domestic animal that the lack of information of its distribution and abundance impedes to obtain the complete picture.
- On the contrary, there is information available for domestic old-world camels in Eastern Europe (i.*e.* Turkey, Russia, and Azerbaijan), but the lack of information on wild ungulates impede to obtain an overlapping area. It is remarkable that south American camelids statistics (the two domesticated species, llamas and alpacas) are not available in Eurostat in spite their numbers in many European countries are on the rise. In the year 2005, over 19,000 animals from more than 10 European countries are stored in LAREU's database by spring 2017, with a yearly growth of about 10 percent (https://www.lareu.org/).

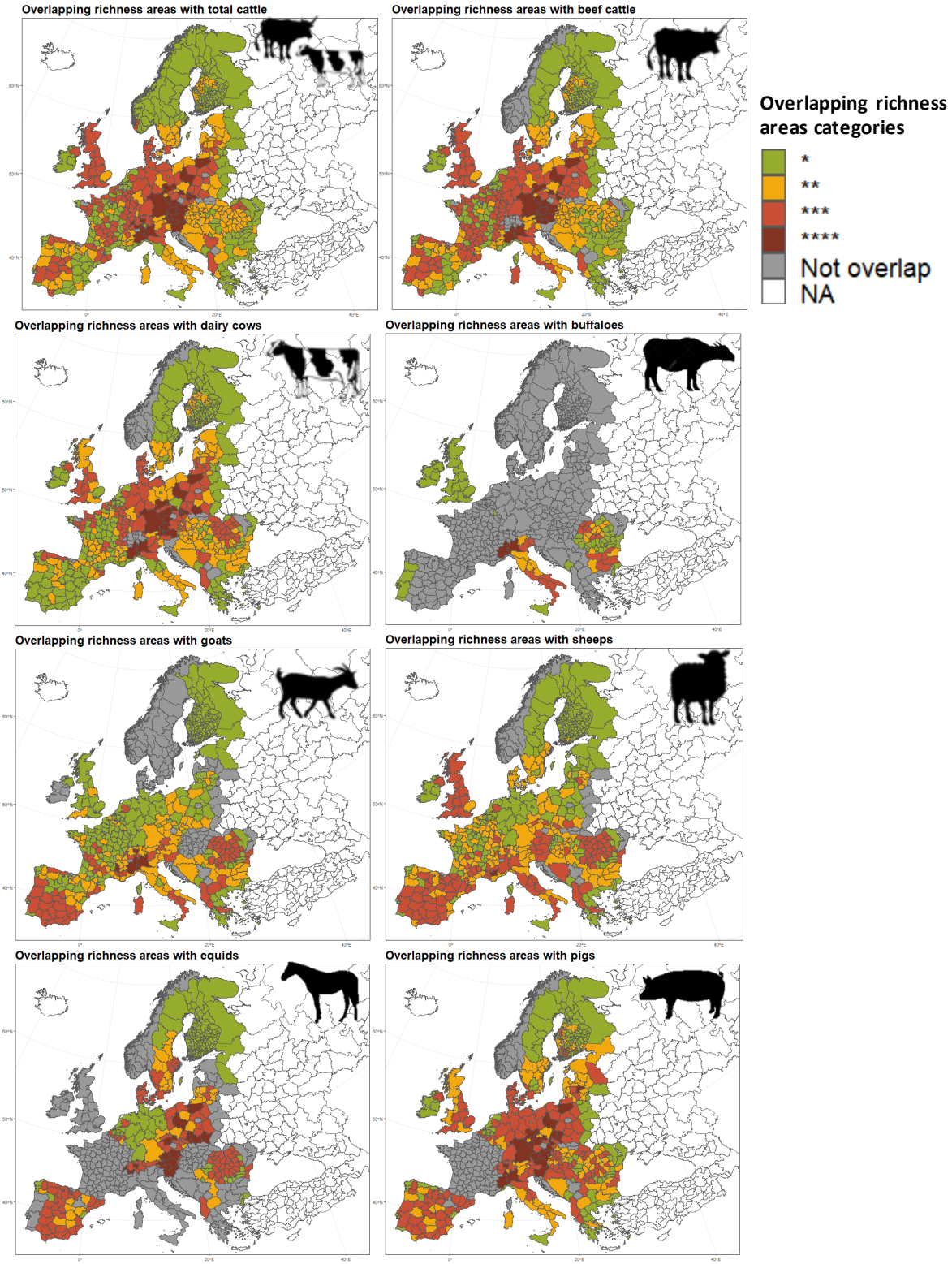


Figure 27. Distribution overlap of richness and wild ungulates in Europe. Categories of interaction are indicated in color as detailed in section 3.1. NA category means that there is not information about wild ungulates.

4.3. Predictive accuracy validation of Gridded Livestock of the World (GLW v3, by FAO[3])

The results obtained from this comparison show a linear relation between the GWL v3and the data obtained for this report (Figure 28). However, we notice that there is relevant overprediction for all domestic animals.

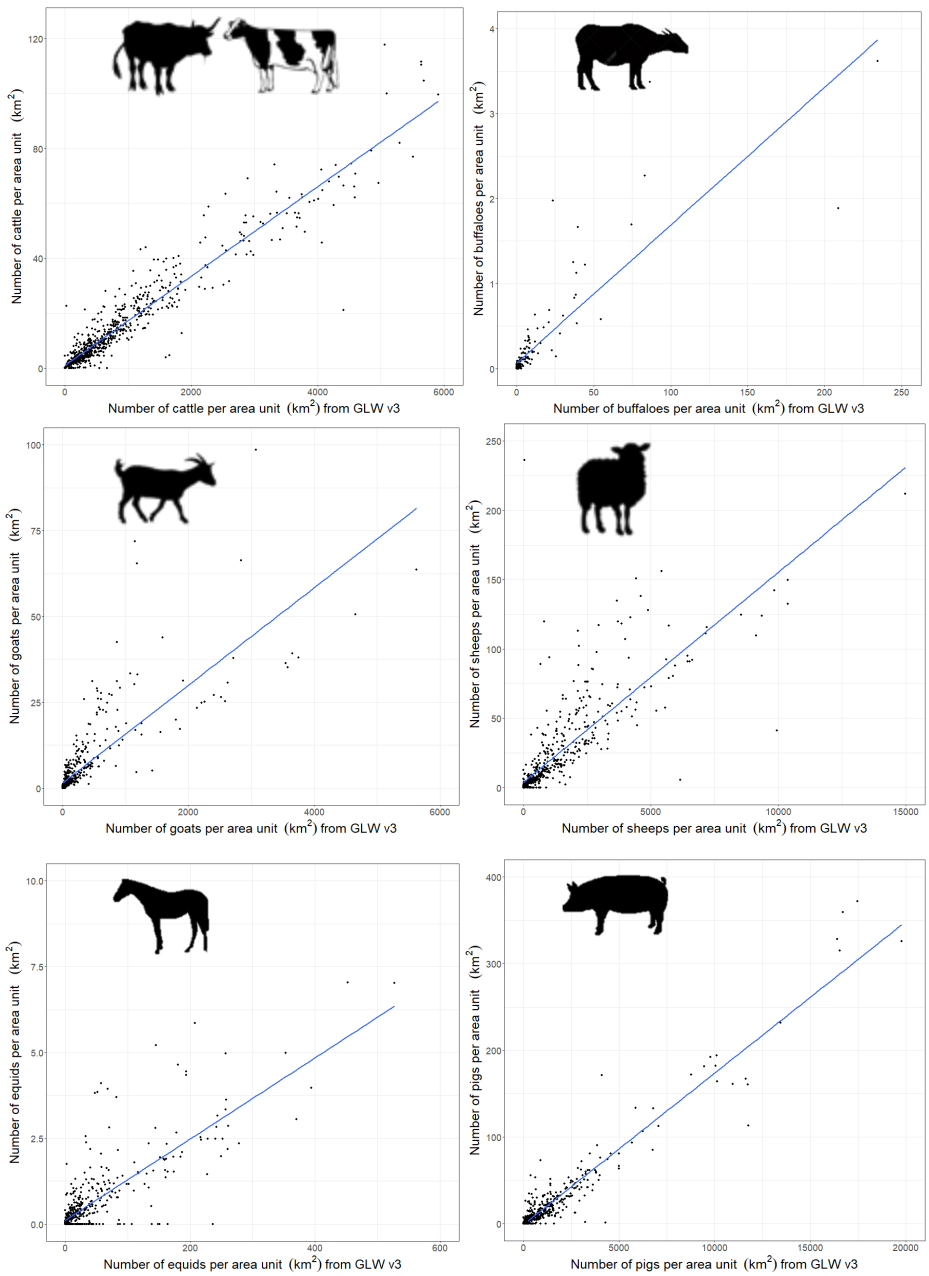


Figure 28. Scatter plots of number of domestic livestock obtained for this report and number of domestic livestock from the Gridded Livestock of the World (GLW v3).

[3] https://www.fao.org/livestock-systems/global-distributions/en/

5. Conclusions and further steps

5.1.1. Data

- As for ungulates livestock, overall, data is usually publicly available aggregated at low administrative level, but we found exceptions (important data gaps) for some species in certain areas, which impeded full assessment over Europe. For this purpose, EFSA has launched a project called SIGMA (EFSA 2019), which specifically aims to provide the Member States with tools to produce automatically their own draft national reports and quality data on animal stocks, health and surveillance in a protected environment to ensure data protection. The present Eurostat UE-wide livestock census distribution information is generally restricted to a spatial resolution of NUTS 2 (province level), although downscaling modelling frameworks developed to disaggregate livestock data up to 1 km grid level (Gridded Livestock of the Word by FAO, GLW) need to be validated for ruminants at higher resolution (see study cases in ENETWILD consortium 2020b for pigs at higher resolution). Overall, land-related, and climatic factors can only, to a certain extent, explain the current spatial domestic livestock distribution in Europe and therefore determining the real distribution (having reliable complete data on distribution and abundance, and metadata, at high resolution) rather than modelling it, is needed.

- Accessible information on the distribution and abundance of livestock in Europe at higher spatial resolution is needed for analyses of the risk at livestock/wild ungulate interface (EFSA 2019). However, abundance and distribution data at sufficient resolution is even less accessible than for wild ungulates in certain regions, for given species or farming typologies.

- When attending to national sources of data in Europe for domestic ungulates, there is a mosaic of data from different spatial resolutions, time periods, and classification of farming production systems. Livestock are produced throughout the EU in several types of farming systems with considerable variations between Member States to another. Extensive farming regions can be risky areas for interaction with wildlife. To date, the exact and complete data about distribution at European level of housing types (outdoor *vs* indoor, extensive *vs* intensive) of the livestock are unobtainable. It is not possible to differentiate between backyard and outdoor production systems (backyard herds do not have a complete fence, and the livestock are not enclosed). To interpret livestock farming patterns (see EFSA 2019 for a glossary), there and numbers of animals raised in an area, being optimal detailed geographical coordinates.

- Therefore, the ENETWILD initiative is essential to create central databases of parameters in this endeavour, but there is need to centralize and unify the collection of livestock data.

5.1.2. Assessment of the interface between wild and domestic ungulates at European scale

- The analysis of the spatial overlapping between the distribution of livestock and wild ungulates at highest possible spatial resolution to date to provide a general picture of Europe (using relatively similar sized regions.
- Since 90% of Europe's land area hosts from one to five species of wild native ungulate, the interface between livestock and wildlife, can be considered potentially wide spread over the European continent. However, there is need to characterize its diverse forms and community composition at local level.
- Overall, the wild ungulate/livestock overlapping maps (determined between wild ungulates and livestock density at administrative unit level) evidenced two main different patterns,

depending on livestock type. First, cattle and pigs tend to have an intense overlapping in Central Europe, with other local concentrations of the potential interface, such as pigs in Spain, where a more intense overlapping is noted. Contrary, ovine and caprine livestock present higher overlapping areas in the Mediterranean and Balkans regions.

- While this analysis is purely spatial and at administrative level, the interface between wild and domestic ungulates is influenced by livestock husbandry (e.g., enclosed, herded or free-ranging, level of biosecurity), landscape and land uses, and wildlife management practices, among other factors, operating locally.
- The results obtained from this comparison show a linear relation between the GWL v3 (FAO[4]) and the livestock data obtained for this report. However, we notice that there is relevant overprediction for all domestic animals.

Other patterns worth to remark for wild ungulates, which contribute to the prevalent local interface with livestock, are:

- Native wild boar, roe deer and reed deer are widely distributed species, present in most possible assemblages of wild/domestic communities over Europe. Mountain ungulates, mostly native, add diversity locally in mountainous areas. The introduced species tended to have more limited distributions, although a few areas have up to four sympatric species and some are relatively widespread (namely, fallow deer and mouflon).
- For several wild ungulate species, the distribution was linked to protected areas, which are crucial points for the study of the interface, shared diseases and control options.
- A wide diversity of potential interfaces is possible since species had highly variable distribution areas. The richness of ungulate species is high in Central Europe, from West to East, from the Alps (where the presence of maintain ungulates add biodiversity), passing through countries with important big game tradition and presence of introduced species (Hungary, Czech Republic, Germany), to Poland (where also typically northern species such as moose and bison appear). However, presence of medium to high richness also occurs sparsely in certain administrative regions all over Europe due the effect of different causes at local scale (presence of mountain ungulates, introduced species, or more locally/regionally distributed species, such as reindeer).
- The distribution and abundance of wild ungulates in Europe is dynamic and, in general, increasing. Therefore, mapping their distribution and interfaces with domestic ungulates should be a continuous activity. For certain introduced species there exist special concern about their expansion and for different reasons (e.g., conservation issues), for instance Asian deer species introduced in central Europe and UK. This will help to restructure and adapt technical and political directions of livestock and wildlife management institutions.
- Ungulate species present clear distribution patterns within administrative units, for instance, certain ungulate species tend to be present only in mountainous areas within each administrative region. Therefore, there is a need for a more detailed picture of the interfaces at European scale.

5.1.3. Next steps

- Concerning **data on livestock distribution and census** at European level, the next steps are:

[4] https://www.fao.org/livestock-systems/global-distributions/cattle/en/

- To collect data at the highest possible spatial resolution across European countries (SIGMA platform, see EFSA, 2019).
- To collect data that allow to differentiate intensive from extensive types of production.

- As for the **wild ungulates**, and namely wild ruminants, efforts to develop reliable **abundance models** focused on hunting yield and occurrence data will be addressed (deliverable by Dec 2021 and continued later). This will allow the wild ungulate "side" of the interface to be more reliably represented as a quantitative variable by species over the continent at fine spatial resolution. This will allow better describing the multiples and interfaces and scenarios established by livestock and wildlife.

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