The spatial distribution and temporal trends of livestock damages caused by wolves in Europe

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Summary

Wolf populations are recovering and expanding across Europe, causing conflicts with livestock owners. To mitigate these conflicts and reduce livestock damages, authorities spend considerable resources to compensate damages, support damage prevention measures, and manage wolf populations. However, the effectiveness of these measures remains largely

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unknown, especially at larger geographic scales. Here we compiled incident-based livestock damage data across 21 countries for the years 2018, 2019 and 2020, during which 39,445 wolf-caused incidents were reported from 470 NUTS3 regions. We found substantial regional variation in all aspects of the data, including the primary target species, the density of damages, their seasonal distribution, and their temporal trend. About one third of the variation in damage densities is explained by the area of heterogeneous landscapes consisting of forests and extensively cultivated habitats occupied by wolves. However, most of the variation remains unexplained, illustrating the inherently stochastic nature of wolf-caused livestock damages and regional variation in husbandry practices, including damage prevention measures. As we argue, the intensity of the wolf-human conflict may be monitored through trends in livestock damages, which are robust to variation in data collection across regions. We estimated increasing trends for the majority of regions, reflecting the current expansion of wolves across the continent. Nonetheless, many of these increases were moderate and for more than one third of all regions, trends were negative despite a growing wolf populations, thus indicating that wolf-livestock conflicts can be successfully mitigated with proper management.
Keywords: *Canis Lupus*, grey wolf, livestock predation, wolf–livestock conflicts, coexistence

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1. Introduction

The twenty-first century has seen the recovery of wolves (*Canis lupus*) across Europe, including in several regions where the species had previously been extinct for decades or even centuries (Chapron et al., 2014; Reinhardt et al., 2019). Between 2012 and 2016, an estimated 17,000 wolves roamed the European continent (excluding Russia and Belarus, Boitani et al. (2018)) and populations are continuing to expand (Chapron et al., 2014; Linnell and Cretois, 2018), with only few exceptions (e.g. López-Bao et al., 2018). This recolonization process is taking place without direct human aid and is due to three main factors: first, wolves are granted strict legal protection in many countries by the EU Habitats Directive and/or the Bern Convention (Chapron et al., 2014; Epstein et al., 2016). Second, populations of important prey species such as roe deer, red deer and wild boar were able to recover following land abandonment and reforestation in Europe (Trouwborst, 2010). Third, wolves have a remarkably high adaptive capacity, allowing them to establish in fragmented, human-dominated landscapes (Mech and Boitani, 2007; Trouwborst, 2010; Sazatornil et al.,

2016; Cimatti et al., 2021).

Wolf recovery is not exempt from social tensions and conflicts (Dressel et al., 2015; Skogen et al., 2017). While ecologists are regarding the growing wolf population in Europe as a conservation success story, many farmers in recovering areas fear increased depredation of their livestock and, as a consequence, a threat to their livelihoods (van Eeden et al., 2018; Bautista et al., 2019; Rode et al., 2021). It is imperative to address these conflicts and to facilitate the coexistence of humans and wolves to ensure positive conservation outcomes in a densely populated Europe. The absence of wolves for an extended period has often resulted in reduced adaptations for coexistence (López-Bao et al., 2017), which in turn harbors potential for conflict once the species is recolonizing its former habitat (Chapron et al., 2014; Gervasi et al., 2021).

To mitigate these conflicts, authorities aim at reducing the risk of livestock depredation by raising the standards of livestock protection (van Eeden et al., 2018; Eklund et al., 2017). In Europe, most countries provide financial support to their farmers to procure and maintain livestock damage prevention measures such as electric fences, livestock guarding dogs, or permanent herding either via the Common Agricultural Policy (CAP) (Marsden and Hovardas, 2020) or similar schemes (e.g. Agridea, 2022). Lethal interventions, both illegal and by governments to remove problem individuals (Ordiz et al., 2013), are an additional element of damage prevention. While lethal interventions are generally not regarded as effective in the long-term (Bruns et al., 2020), the varying quality and scope of implementation of non-lethal measures has given way to a debate on whether and what kind of damage prevention performs best (Eklund et al., 2017; Bonnet et al., 2019; Oliveira et al., 2021). A large-scale randomized control trial on the effectiveness of different prevention measures is still missing to date (van Eeden et al., 2018).

To contribute to our understanding of livestock damages caused by wolves in Europe in recent years, we compiled a large European-wide data set of case-based livestock damage incidents at the municipality level from 2018-2020. We then characterized their distribution in space and time, identified regional densities and trends across Europe, and examined the extent to which they can be explained by wolf presence and landscape features reflecting the density and overlap between wolves and livestock. We then evaluated if trends in livestock damage incidents are reliable indicators for coexistence of wolves and humans.

Previous work reported mixed results, with several studies at regional scales reporting that livestock in heterogeneous landscapes and in particular close to forest edges were the most vulnerable to wolf predation (Rigg et al., 2011; Kaartinen et al., 2009), yet across multiple countries no landscape features were correlated with the number of compensated sheep (Gervasi et al., 2021). In contrast, the number of wolves correlated positively with the number of compensated sheep at the scale of multiple countries (Gervasi et al., 2021), yet incidents appeared to increase with the geographic spread of wolves at regional scales, but not with an increase in their numbers (Khorozyan and Heurich, 2022). Here, we reconcile these findings by compiling data from many additional regions and by adopting a temporal perspective: while landscape features indicating extensive land-use and suitable wolf refuge areas were the best predictors of livestock damages caused by wolves, these relationships appeared modulated by local conditions and the use of mitigation measures, resulting in a de-correlation of trends in wolf numbers from trends in damage incidents.

2. Material and Methods

2.1. Case-based livestock incidents

We collected incident-based livestock damage data for 2018, 2019 and 2020 at the regional level (i.e. NUTS3 regions, see below), where incidents are cases of livestock depredation as recorded by authorities. While most reported incidents reflect a single attack of wolves on livestock, they may rarely involve multiple attacks if livestock was not checked daily. To obtain incident-based data, we consulted regional authorities' websites if available. Otherwise, we reached out to regional and national authorities of all EU member states, Norway and Switzerland in spring 2019, 2020 and 2021 to report livestock damage incidents of the previous year using a template questionnaire (Supplementary Table S.1 for a list of all sources). Our questionnaire, outlined in Supplementary Table S.2, consisted of mostly fixed-response questions to be filled per incident, with an option to comment in a separate column.

The creation of this template questionnaire was a dynamic process: we initially asked the authorities what data they had available, based on which we created a draft template that we refined iteratively. The main attributes to identify per livestock damage incident were (i) the primary asset missing, injured or killed in an incident, (ii) the assessment level or probability of the cause being identified correctly, (iii) the amount of compensation paid per

incident, and (iv) the damage prevention measure implemented at the time of the incident in the broad categories defined by (Eklund et al., 2017): *electric fence*, *wire fence*, *livestock guarding dog*, *permanent shepherd*, and *other qualified protection*.

We translated the submitted information to English. If the questionnaire was returned incomplete, we followed up and entered any additional information we received by hand. While many respondents adhered to our fixed-answer request, some replies had to be curated manually to match our standards: (i) If more than one asset species was reported for the same incident, we recorded the incident for each species separately, but kept the same incident ID and treated the event as a single incident in our analyses. (ii) If no assessment level on the certainty of wolf predation was reported, we recontacted the authorities for clarification. In case we did not receive any information, we chose the category *unspecified*. (iii) If more than one date was reported for the same incident, we took the first reported date. (iv) If no geographic coordinates were submitted indicating the location of the damage incident, we used the village name (or the smallest geographic unit available) and converted it into geographic coordinates using the Google Geocoding API (Google, 2022). If neither geographic coordinates nor geographic units were given, or if the provided name could not be converted to coordinates, we removed the incident from our analysis.

As we accumulated data annually, we sent along a report including descriptive statistics as well as the finalized national data set of the previous year for cross-checking by the authorities. In addition, we shared initial exploration of the data to demonstrate the relevance of such data. The full data set is available at Zenodo (`https://doi.org/10.5281/zenodo.6821814`), albeit without information that was considered sensitive by the authorities (compensation payments and/or exact geolocation data). This data can, however, be obtained by contacting authorities directly (see Supplementary Table S.1 for contacts).

2.2. Geographical regions

We conducted our analyses at different geographic scales: at the continental and country level, as well as for the three levels of the Nomenclature of Territorial Units for Statistics (NUTS; European Commission and Eurostat, 2020) that subdivide each country into smaller geographic units. The NUTS regions mostly follow the administrative subdivisions of the EU Member States. In addition, they are unambiguously standardized across Europe and

are strictly hierarchical. Benefiting from this hierarchical setup, we first compiled the counts n_{ik} of reported damage cases for each year $Y_k \in \{2018, 2019, 2020\}$ and all NUTS3 regions $i = 1, \ldots, I$. We next obtained counts $n_{rk} = \sum_{i \in r} n_{ik}$ for all geographic regions r in NUTS1, NUTS2, NUTS3, each country and the continent as a whole by summing across all NUTS3 regions i encompassed in r, denoted here as $i \in r$.

We restricted these counts to incidents for which wolves were sufficiently likely the cause: for administrative regions that provided an assessment level, we kept those with category *presumed correct* or *confirmed*. For administrative regions that did not provide an assessment level, we considered only cases for which a compensation was paid. If neither was provided, we considered all submitted incidents assuming that only sufficiently probable cases were shared with us.

2.3. Temporal distribution of damage incidents

To characterize the temporal distribution of damage incidents, we aggregated incidents by month, discarding all incidents for which no date was provided. To test for temporal variation, we performed χ^2-tests on monthly counts versus their expectation under a uniform distribution. To test if incidents generally occur later in the year in northern than southern Europe, we performed Mann-Whitney-U tests on the dates, grouping all incidents reported from Estonia, Finland, Latvia, Lithuania, Norway and Sweden (north) and Croatia, France, Greece, Italy and Spain (south). All tests were performed with the statistical software `R` (R Core Team, 2021), using the functions `chisq.test()` and `wilcox.test()`.

2.4. Trends in livestock damages

We estimated trends in livestock damage incidents for each region r using a Bayesian method similar to that in Aebischer et al. (2020). Let λ_{ik} denote the rate at which incidents occur in NUTS3 region i in year Y_k. We modeled the trends in these rates in region r as exponential change with rates γ_r such that $\lambda_{ik} = \lambda_{i0} \exp(Y_k \gamma_r)$ for all $i \in r$, and seek to infer the rate of change γ_r from all incident counts n_{ik} reported for all NUTS3 regions $i \in r$ and all years $k = 1, \ldots, K$. We assume these counts are Poisson distributed $n_{ik} \sim \text{Poisson}\,(\lambda_{ik} s_i)$ with means proportional to the incident rate λ_{ik} and the NUTS3 region-specific rate s_i with which incidents are reported.

To make inferences about the rate of change γ_r, we condition on the total numbers of counts $\nu_i = \sum_k n_{ik}$ across years for each NUTS3 region (see Link and Sauer, 1997). It is well-known (Johnson et al., 1997) that the conditional distribution of $\boldsymbol{n}_i = (n_{i1}, \ldots, n_{iK})$ given ν_i is multinomial:

$$\boldsymbol{n}_i | \nu_i \sim \text{Multinom}\left(p_{i1}, \ldots, p_{iK}\right),$$

in our case with probabilities

$$p_{ik} = \frac{\lambda_{i0} \exp(Y_k \gamma_r) s_i}{\sum_l \lambda_{i0} \exp(Y_l \gamma_r) s_i} = \frac{\exp(Y_k \gamma_r)}{\sum_l \exp(Y_l \gamma_r)}. \tag{1}$$

Thanks to conditioning, the nuisance parameters λ_{i0} and s_i are canceled out from the fraction, rendering trend estimates independent of any variation in reporting rates across administrative regions.

The likelihood of the full observation vector $\boldsymbol{n} = (\boldsymbol{n}_i, i \in r)$, conditional on $\boldsymbol{\nu} = (\nu_i, i \in r)$, is

$$f(\boldsymbol{n} | \gamma, \boldsymbol{\nu}) \propto \prod_{i \in r, k} p_{ik}^{n_{ik}}.$$

Following Aebischer et al. (2020), we chose the non-informative Jeffrey's prior for γ_r, which is (up to a normalizing constant) the square root of the determinant of the Fisher information

$$\mathcal{I}(\gamma_r) = -\mathbb{E}\left[\frac{\mathrm{d}^2}{\mathrm{d}\gamma_r^2} \log f(\boldsymbol{n} | \gamma_r, \boldsymbol{\nu})\right].$$

Using $\mathbb{E}[n_{ik}] = \nu_i p_{ik}$ and $\sum_k p_{ik} = 1$, we arrive at

$$\mathcal{I}(\gamma_r) = \sum_i \nu_i \sum_k \frac{\dot{p}_{ik}^2}{p_{ik}},$$

where

$$\dot{p}_{ik} = \frac{\mathrm{d}p_{ik}}{\mathrm{d}\gamma_r} = \exp(Y_k \gamma_r) \frac{\sum_l \exp(Y_l \gamma_r)(Y_k - Y_l)}{[\sum_l \exp(Y_l \gamma_r)]^2}.$$

We implemented an MCMC approach to generate posterior samples under this model in an R package available at `https://bitbucket.org/wegmannlab/birp/`. Using the function `birp_data()`, we created one data set per NUTS region for which damage incidents were reported for at least two years (setting all efforts to 1.0) and then inferred trends for this region using the function `birp()`.

We then classified each region as having an increasing or decreasing trend if the posterior mode $\gamma_r < 0$ or $\gamma_r > 0$, respectively and quantified the uncertainty associated with these point estimates as the posterior mass outside the corresponding interval.

2.5. Testing for spatial autocorrelation

We used Moran's I to test for autocorrelation in damage trends (posterior modes) and other metrics across NUTS3 region. For each pair of regions i and j, we used a weight $w_{ij} = 0, 1$ indicating whether the regions share a common border ($w_{ij} = 1$) or not ($w_{ij} = 0$), assessed using the function `st_touches()` from the package `sf` (Pebesma, 2018) in the statistical software `R` (R Core Team, 2021).

To test for variation on a north-south cline, we further determined the latitude of the centroid of each NUTS3 region using the function `st_centroid` of the `sf` package.

2.6. Explaining variation in livestock damage incidents between regions

We investigated which covariates may explain the variation in average annual livestock damage incidents between NUTS3 regions. For this we fitted linear models of the form

$$n_{rk} \sim \alpha_0 + \sum_c \alpha_c z_{rc}$$

where $z_{rc}, c = 1, \ldots, C$ are covariates obtained for each region r, α_0 is an intercept and α_c are regression coefficients. We fitted these models with the function `dredge()` from the package `muMin` in `R` (R Core Team, 2021) and used the function `anova()` to determine the fraction of the total variation explained by each model.

We considered the following covariates, which are all available through Zenodo (`https://doi.org/10.5281/zenodo.6821814`):

Wolf presence. To characterize wolf presence across Europe, we used the shapefile compiled for the most recent period available (2012 to 2016) at a 10 x 10 km resolution for the Large Carnivore Initiative of Europe IUCN Specialist Group and for the IUCN Red List Assessment (Kaczensky et al., 2021). This map encompasses the entire region considered in this study. At each grid point, the authors translated the presence and frequency of wolves into one of three categorical variables: *permanent*, *sporadic* or *no presence*. We intersected this map with the NUTS3 regions using the *st_intersection()* function from the *sf* package (Pebesma, 2018) in `R` (R Core Team, 2021) and used this intersection to determine the area (in km^2) permanently and sporadically occupied by wolves for each NUTS3 region.

Support for prevention measures. To quantify policies regarding the support of livestock damage prevention schemes, we used an ordinal variable stating whether prevention measures were financially supported between 2018-2020 in a given political region (*yes*, *partially*, or *no*) as defined in Marsden and Hovardas (2020). Our data relates to support for the purchase of fencing and livestock guarding dogs, as data on their funding is most commonly available. A partial support means that the financial support provided does not cover the full costs of the prevention measures. We used information from Marsden and Hovardas (2020) for Croatia, Finland, France, Greece, Latvia and Lithuania. For the remaining regions we used information provided by the European commission (European Union, 2022), or additional publications.

Land cover classification. We used the CORINE Land Cover (CLC, code 18) data from the year 2018 (European Environment Agency, 2018) to quantify land cover for all analyzed regions. The available data covers our area of interest at a scale of 1:100,000. The classification comprises artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands and water bodies. We used the `st_intersection()` function from the `sf` package (Pebesma, 2018) in the statistical software `R` (R Core Team, 2021) to intersect the CLC layers with the area occupied by wolves (either permanently or sporadically, see above), and further with each NUTS3 region. This way we obtained for each NUTS3 region the area of broad-leaved, coniferous and mixed forests (as a proxy for suitable wolf refuge areas) as well as the area of pastures, grasslands and agro-forestry areas (as a proxy for livestock presence and availability) occupied by wolves.

Historical continuity of wolf presence. Following Gervasi et al. (2021) and based on previous estimates (Chapron et al., 2014), we determined for each NUTS3 region, whether (1) or not (0) wolves were present during the 1950–1970s.

2.7. Explaining variation in livestock damage incident trends between regions

For Belgium, Germany and the Netherlands, information on wolf occurrences is available at a finer spatial and temporal scale from (BIJ12 et al., 2022) since 2000. We mapped these occurrences to NUTS regions with `st_intersection` as above and calculated the number of known wolf units w_{rk} per NUTS3 region r for the years $Y_k \in \{2018, 2019, 2020\}$. In contrast

to previous analyses (e.g. Reinhardt et al., 2019), we treated wolf individuals, pairs and packs each as one territorial unit since single individuals may also cause extensive damage.

We then used the function `cor.test()` in `R` to test for correlations between the number of wolf units in each region w_{rk} and the number of reported incidents n_{rk}, limiting the analyses to regions for which wolves, incidents or both were reported. We further used these data to test for correlations between trends in livestock damage incidents and trends in wolf occurrences. For this, we inferred trends in the number of known wolf units $\gamma_r^{(w)}$ for each NUTS region r using the same approach as described above for incidents. We then tested for correlations between the trends inferred for wolf units ($\gamma_r^{(w)}$) and those inferred for damage incidents (γ_r) at all NUTS levels, only considering regions for which at least one wolf was reported in any of the years 2018, 2019 or 2020. Finally, we tested if the inferred trends correlate with the number of years that wolves were present in each region, defined as the number of years between the first reported wolf and 2020.

3. Results

We collected data on livestock damage incidents caused by wolves for 2018, 2019 and 2020 from national or regional authorities for the following 16 countries: Austria, Belgium, Croatia, Czech Republic, Finland, France, Germany, Greece, Latvia, Netherlands, Norway, Poland, Slovakia, Slovenia, Sweden and Switzerland. We obtained partial data for five additional countries: For Estonia we could only obtain data for 2018 and 2019, for Lithuania only for 2019 and 2020. For Italy, Romania and Spain, we received data only for a subset of the provinces (7, 8 and 1 NUTS3 regions, respectively). Requests were declined or left unanswered by five countries: Belarus, Denmark, Hungary, Portugal and Ukraine. In total, we obtained data for 910 NUTS3 regions, of which 470 reported incidents. The total number of reported incidents is 43,703, of which 43,513 (99.6%) could be unambiguously attributed to a single NUTS3 region and were kept for our analyses. These incidents were distributed as 13,895, 15,086 and 14,532 across the three years 2018, 2019, 2020, respectively.

We further restricted our analyses to incidents for which wolves were sufficiently likely the cause. A subset of countries (Austria, Belgium, Switzerland, Germany, Estonia, Greece, Croatia, Latvia, Netherlands, Norway, Poland, Sweden, Slovenia) provided an assessment level. Of the 22,112 incidents from these countries, we kept 17,904 (80.97%) that were

reported as *confirmed* (4,803, 21.7%) or *presumed correct* (13,101, 59.2%), excluding incidents that were *negative* (2,017, 9.1%), *uncertain* (706, 3.2%), *no assessment possible* (1,200, 5.4%), *assessment pending* (269, 1.2%) or *unspecified* (16, 0.1%). For Finland, Romania and Spain that did not provide an assessment level, we kept the 9,181 (99.5%) incidents for which compensation was paid. For the remaining countries (Czech Republic, France, Italy, Lithuania, Slovakia) that provided neither information, we kept all 12,177 incidents, assuming that only sufficiently probable cases were shared with us. In total, we thus kept 39,262 (89.8%) incidents and will refer to these as *wolf-caused incidents* below. They are summarized in Table 1.

The countries with the highest number of wolf-caused incidents across the three years were France (9,840), Greece (6,870) and Spain (6,856). The countries with the lowest number of wolf-caused incidents were Belgium (79), Latvia (91) and Austria (115). As shown in Figure 1, regions varied greatly in their densities of wolf-caused incidents, with south-eastern France, coastal Croatia, northern Greece and the Spanish province of Asturias being regional hot-spots of livestock damage incidents in our data set.

In terms of wolf-caused incidents, sheep were most frequently affected (21,301, 54.2%), followed by cattle (7,672, 19.5%) and goats (4,328, 11%). Other animals less frequently affected included horses (3,125 wolf-caused incidents, 8%), reindeer (1,976, 5%), dogs (529, 1.4%), deer (201, 0.5%), donkeys (166, 0.4%), pigs (10, <0.1%) and lamas or alpaca (8, <0.1%). For 343 (0.9%) additional incidents, the affected animals were not indicated to the species level. For most countries, the most frequently affected species was sheep, with three exceptions: For Finland, the most affected species was reindeer (85.8%), for Greece cattle (46.5%) and for Spain (i.e. Asturias) horses (42.3%).

To gain insights into temporal patterns of livestock damage incidences, we aggregated records by month, discarding 359 (0.9%) incidents which did not provide a date. As shown in Figure 2, incidents show strong temporal variation ($p < 10^{-15}$ for all species, χ^2-test). Across all species, incidents peak between July and October with 48.7% of the total incidents falling within these months. This pattern is particularly visible for sheep (55.2%), as well as for cattle (43.4%) and goats (40.9%), albeit less pronounced. In contrast, incidents involving horses peak between April and July (51.8%) and those involving reindeer between September and December (67.5%). The differences between target species are explained by the geographic

distribution of livestock and the observation that incidents in northern Europe (Estonia, Finland, Latvia, Lithuania, Norway and Sweden) generally occur later in the year than in southern Europe (Croatia, France, Greece, Italy and Spain, Mann-Whitney-U test, p $< 2.210^{-16}$): In southern Europe, 23.3% of all incidents occur before May, but in northern Europe only 5.1%. This pattern was also found for each species with enough data to perform the Mann-Whitney-U test, namely sheep ($p < 0.042$), cattle ($p < 10^{-8}$), goats ($p < 10^{-3}$), horses ($p < 10^{-3}$) and dogs ($p < 10^{-4}$).

Among the 39,262 wolf-caused incidents of all 21 countries, 99,056 animals were killed, injured or went missing, with 58.9% of all incidents involving a single animal, 82.1% involving three or less and only 3.5% involving ten or more individuals. Only two incidents involved more than 100 animals, the largest being the only reported case from the Romanian province of Timis affecting 402 animals. Sheep had the most individual causalities (71,023, 71.7%), but goats had more casualties (11,338, 11.4%) than cattle (8,415, 8.5%), in line with goat incidents usually involving more animals (2.6 on average) than cattle incidents (1.1 on average). Incidents involving sheep involved 3.3 animals on average.

Most data collected was not associated with information on the implementation of damage prevention measures (84.3%), with only eight countries (Belgium, Croatia, Germany, Latvia, Netherlands, Poland, Slovenia, Sweden) reporting whether or not a prevention measure was implemented at the time of the incident. Among those incidents (6,158, 15.7%), the most common measure was *electric fence* (767, 12%), followed by *wire fence* (311, 5%), *guarding dog* (31, 0.5%) and *permanent shepherd* (8, 0.13%). For an additional 3,826 (62%) of incidents the prevention measure was indicated as *other qualified protection*, while 1,430 (23%) affected unprotected animals.

3.1. Covariates explaining number of wolf-caused incidents

Across NUTS3 regions, only 2.1% of the total variation in the number of wolf-caused incidents is within regions across years, while 97.9% is across regions ($p < 10^{-15}$). To explain that latter part, we conducted regression analyses on the average number of wolf-caused incidents across years within each NUTS3 region. As explanatory covariates, we used 1) the total area occupied by wolves, either sporadically or permanently, 2) the area within regions occupied by wolves for the CORINE land cover classes *Pastures* (2.3.1), *Agro-Forestry*

areas (2.4.4), *Broad-leaved forests* (3.1.1), *Coniferous forest* (3.1.2), *Mixed forests* (3.1.3) and *Natural grasslands* (3.2.1), 3) the degree of governmental support for prevention measures and 4) whether or not wolves were present at their lowest extent during the 1950-1970s. The best fitting model according to the Akaike Information Criterion (AIC) included the total area within regions occupied by wolves of *Agro-Forestry areas*, *Broad-leaved forests*, *Grasslands* and *Pastures* as the only explanatory variables (Table 4). This model, which is highly significant ($p < 10^{-15}$), explained 32.8% of the total variance. The nine next best models that were not significantly worse (ΔAIC < 2.0), all included the same explanatory variables, always augmented by a single additional variable.

Among the covariates tested, several correlated positively with $\rho > 0.5$, namely the area permanently occupied by wolves with the occupied area for the three forest land cover classes Mixed forests (0.50), Broad-leaved forests (0.58) and Coniferous forests (0.62), the area sporadically occupied by wolves with Mixed forests (0.67) and Coniferous forests (0.87), and Mixed forests with Coniferous forests (0.65). However, we unlikely missed effects due to collinearity since a model only including the area occupied of Broad-leaved forests explained 24.1% of the total variance, or 97.0% of the variance explained by a model including all of the highly correlated variables (i.e. the total area permanently or sporadically occupied by wolves and the area occupied for the three forest classes). A model only including the area permanently or sporadically occupied by wolves only explained 7.9% of the total variation and had a much poorer fit (ΔAIC $= 104.6$).

Residuals of the best model were significantly spatially autocorrelated ($p = 0.003$) and also correlated significantly with latitude ($\rho = -0.21$, $p < 10^{-}4$), which explained 4.6% of the remaining variation. Thus, additional variance may be explained with landscape features or other spatial factors not included in our model.

For Belgium, Germany and the Netherlands, detailed information is available on the number of wolf units in each NUTS region for each of the three years studied here. Focusing on the NUTS3 regions for which livestock damage incidents, wolves or both were reported, the number of wolf units is significantly correlated with the number of reported incidents for each year ($p < 0.001$, $p < 0.001$ and $p = 0.028$, respectively) as well as for all years combined ($p < 0.001$). The magnitude of the correlation diminishes over time, from $\rho = 0.60$ in 2018, to $\rho = 0.48$ and $\rho = 0.28$ in 2019 and 2020, respectively.

3.2. Trend analysis

We estimated trends of wolf-caused incidents across the three years 2018, 2019 and 2020 for all geographic regions with at least one incident reported damage data from at least two years, accounting for survey gaps and stochastic variation. At the continental scale, our analysis indicates certainty that incidents were increasing ($\mathbb{P}(\gamma > 0|\boldsymbol{n}) = 1.0$)) with an estimated rate of $\gamma = 0.021$ per year (posterior mode), translating into an 4.2% increase from 2018 to 2020. At smaller geographic scales (Figure 3), the pattern is rather heterogeneous: Of the 320 NUTS3 regions with sufficient data (two years with damage incidents), we estimated a positive ($\gamma_r > 0$) for 195 (61%) and a negative trend ($\gamma_r < 0$) for 125 (39%), with posterior modes for NUTS3 regions spanning from $\gamma_r = -2.91$ for NO074 (Troms og Finnmark, Norway) to $\gamma_r = 3.41$ for FRC13 (Saône-et-Loire, France). Despite this heterogeneity, γ_r estimates, and thus the directionality of the trends, were spatially autocorrelated ($p < 0.003$).

We next estimated trends individually for the most commonly affected species (sheep, goats, cattle and horses, Supplementary Figures S.1, S.2, S.3 and S.4). Trends did not appear to be correlated between any pair of species at neither NUTS1, NUTS2 or NUTS3 level (p$>$ 0.06 in all cases), likely because trends could be estimated for a only partially overlapping subset of regions for each species due to lower number of incidents and a restricted geographic distribution of some species.

For Belgium, Germany and the Netherlands, we also estimated trends in the number of wolf units for each NUTS region with at least one wolf unit reported across the three years 2018, 2019 and 2020. The joint trend across all such regions revealed a rapidly growing population ($\mathbb{P}(\gamma_r^{(w)} > 0|\boldsymbol{w}) = 0.97$)) with $\gamma_r^{(w)} = 0.12$ (posterior mode), corresponding to a growth rate of 14% per year. Previous estimates for the period 2000-2015 were even higher at 36% per year (Reinhardt et al., 2019). To confirm that rates decrease with time, we estimate them for all three-year intervals from 2005 to 2020, during which at least two NUTS3 regions had wolves in all years. Estimated annual growth rates (posterior modes) decreased from 66% for 2005-2008 to 34%, 32%, 31% and finally 14% for 2018-2020.

There was considerable regional variation, with 49 NUTS3 regions showing positive ($\gamma_r^{(w)} > 0$) and 29 negative ($\gamma_r^{(w)} > 0$) trends of wolf units for 2018-2020. We tested whether these trends predict trends in wolf-caused incidents, but did not find such a correlation at any NUTS level ($p > 0.4$ for Spearman correlations and $p > 0.06$ for Pearson correlations in all

cases). The trends in wolf-caused incidents did neither correlate with the time since wolves were first reported in a region ($p > 0.17$ at any NUTS level). Across all three countries, however, wolf units ($\gamma_r^{(w)} = 0.12$) and damage incidents ($\gamma_r = 0.11$) grew at comparable rates ($\mathbb{P}(\gamma_r < \gamma_r^{(w)}) = 0.58$).

4. Discussion

We here consolidate a large, incident-based data set on livestock damages caused by wolves across Europe in recent years. A total of 16 countries reported complete data for the years 2018, 2019 and 2020, and an additional five countries reported partial data. Remarkably, the majority of reported incidents involved a single livestock head and only very few involved more than ten individuals. In line with previous reports (Kaczensky, 1999; Bautista et al., 2019; Gervasi et al., 2021) sheep were the most affected species, both in terms of incidents and affected individuals, but there was variation reflecting the regional importance of different livestock species such as reindeer in Finland or horses in Spain.

We found considerable seasonal variation with incidents peaking in August and September. There was a clear north-south cline with a much smaller fraction of incidents reported during winter in northern compared to southern Europe, likely because in the north, livestock is kept indoors more often during these months.

The data also revealed substantial spatial variation in the number of incidents caused by wolves across Europe. This variation is not driven by the area occupied by wolves in each region, but about one third of it can be explained by a linear combination of areas of agro-forestry, grasslands, pastures and broad-leaved forests that are occupied by wolves. Thus, areas with high numbers of incidents are not only qualified by the presence of wolves, but also through extensively cultivated habitats where wolves may be numerous (Jedrzejewski et al., 2004) and livestock more accessible or more difficult to protect (Rigg et al., 2011).

Correlations for similar landscape features were recently reported from damages in Poland (Fedyń et al., 2022), but not from a recent, multi-national analysis on sheep incidents for which compensation was paid (Gervasi et al., 2021). Based on that data, they reported an effect of historical continuity of wolf presence, but unlike our study found no correlation with any of the environmental variables tested. While our data set is much larger (470 vs. 140 NUTS3 regions with damage data) and hence has more statistical power to detect such

correlations, the major differences likely lies in that we considered landscape features only within the areas predicted to be occupied by wolves, rather than on NUTS3 regions as a whole. Indeed, most NUTS3 regions are only partially occupied by wolves, potentially due to historical or political reasons not connected to the landscape features of the entire region. On top of such land cover metrics, the historical continuity of wolf presence then appeared to have no extra explanatory power.

Importantly, however, almost 70% of the total variation between NUTS3 regions remained unexplained even with our best fitting model. Incident numbers may be inherently stochastic, especially if wolf numbers are low such that a single problem individual can cause a spike in incidents for a short time. In the NUTS2 region AT12 (Niederösterreich, Austria), for instance, most of the 19 incidents in 2018 could be attributed to a single female wolf. This individual was no longer active in 2019 and 2020, when incidents dropped to two and only one, respectively. But since residuals appeared to be geographically clustered such that too many (or too few) incidents were often predicted for multiple neighboring regions, there likely exist additional covariates predictive of incident numbers. These likely include more accurate estimates of prey availability and the number of wolves within each region, rather than the environmental proxies used here. Further, residuals strongly correlated with latitude, which explained an additional almost 5% of the remaining variation, and indicated that our best model predicted too many incidents in the north and too few in the south. This may reflect differences in husbandry practices across latitude, which also lead to variation in both the seasonal distribution of incidents as well as the target species most affected.

There is likely also a temporal component with incidents thought to often spike in areas recently colonized by wolves (Trouwborst, 2018; Marucco and Boitani, 2012; Dalmasso et al., 2011; van Eeden et al., 2018; Gervasi et al., 2021), as measures preventing livestock damages may have been abandoned in the absence of large carnivores (Kaczensky et al., 2021; Linnell et al., 1996). While the historical continuity of wolf presence since the 1950-1970s is unlikely to capture this effect in full, only limited data is available to test for more recent effects. At the continental scale, for instance, the most recent estimate of wolf presence dates to the period of 2012-2016 Kaczensky et al. (2021), but with no reference point except the estimate for the 1950-1970s we used here to assess historical continuity.

More detailed data on the presence of wolves is available, however, for Belgium, Germany

and the Netherlands. Wolves were not present in most regions within these countries about ten years ago, but have since made an astonishing comeback (BIJ12 et al., 2022): While Reinhardt et al. (2019) reported an annual growth rate of 36% for the period 2000-2015, it appears that the growth has been slowing down steadily to a still astonishing 14% for the three years considered here. Along with wolves, livestock damage incidents have increased at comparable rates at the larger scale, but the connection between the number of wolves and the number of reported incidents appears complex at local scales: First, we did not find any correlation between trends in the number of wolf units and trends in the number of damage incidents on the NUTS3 level. Thus, a growing wolf population does not seem to imply a growing number of incidents, a finding previously reported for sheep lost to wolves in Germany (Khorozyan and Heurich, 2022). Second, and while the number of wolves in a region seems to correlate well with the number of damage incidents, this correlation appears to diminish over time, in line with a lack of correlation between these trends. Thus, with wolves establishing themselves in more regions at higher numbers, the relationship between wolves and damage incidents becomes more complex.

It may seem tempting to interpret these findings as evidence that a renewed presence of wolves leads to a more wide-spread adoption of protective measures, or at least that the relationship between damage incidents and wolf presence is modulated by variation in the adoption of such measures. However, the dataset gathered here is not ideal to directly test such hypotheses, nor hypotheses about the effectiveness of different prevention measures, as we lack information on their use. To assess damage prevention effectiveness, the frequency of damage incidents should be contrasted between sites differently protected. Authorities, however, tend to only record the prevention measure in place at the time of an incident, if at all, which does not allow conclusions on the effectiveness. In our dataset, for instance, the most frequently reported prevention measure was *electric fence*, most likely not because it was ineffective, but because it was very commonly used.

Despite the large amount of public money spent on supporting prevention measures, a large-scale randomized control trial on the effectiveness of different prevention measures is still crucially missing. As an alternative, the data reported here could be intersected with geo-referenced data on the use of prevention measures and accurate data on the presence of wolves, provided that the spatial auto-correlation in the use of prevention measures can

be accounted for. To the best of our knowledge, such data is currently not available at a larger geographic scale. We thus strongly encourage authorities to collect and share such information in the future, ideally using specific categories that distinguish among the diverse set of measures treated under the same broad categories here. We note, however, that collecting such information without bias is delicate since livestock owners may not report honestly should they fear consequences if their measures were not implemented correctly.

By estimating trends in damage incidents, however, the data collected here provides useful indicators on the intensity of the conflict between wolves and livestock owners, which are, in contrast to analyses on incidents directly, comparable at any geographic level and robust to variation in sampling effort and data collection across regions. With wolf populations in Europe generally growing and expanding their range, decreasing trends indicate a reduction in conflicts, for instance through the adoption of additional prevention measures, other changes in husbandry practices, or the successful management of problematic individual wolves. Increasing damage incident trends, in contrast, identify regions where current damage prevention and mitigation seem insufficient and thus require additional attention. Nearly stable numbers of incidents, finally, indicate conflicts at equilibrium, either because damage prevention practices have been put in place successfully, because wolf numbers plateaued, or both.

Across the years 2018-2020 studied here, the majority of regions showed an increasing trend, reflecting the growth of the European wolf population and the need for conflict mitigation. In Belgium, Germany and the Netherlands, for which we have detailed information on the distribution of wolves, for instance, the number of wolf units and damage incidents grew at comparable rates. While we lack information on the growth of wolf populations at the continental scale, regional trends in damage incidents perfectly illustrate the small-scale nature of livestock damage incidents and their mitigation: First, we estimated negative trends for 39% of all NUTS3 regions, although wolf populations unlikely shrank in any of these. Second, and while the inferred trends were spatially auto-correlated with incidents either increasing, decreasing or showing no trend in multiple neighboring regions, trends did not point uniformly in one direction for any country, neither at NUTS3 or NUTS2 level. Rather, there are regions in each country that are currently affected by an increasing number of damage incidents. Third, trends inferred individually for each of the most commonly affected

species were not correlated. While species-specific trends may serve as useful indicators for the conflict between wolves and owners of a particular livestock species, the observed variation in trends may also reflect the limited number of incidents per species and limited geographic overlap in their use. Of the 272 NUTS3 regions for which we could infer trends for the most commonly affected species (sheep), only for 119 NUTS3 regions (43.8%) trends could also be inferred for the second most commonly affected species (cattle). This overlap is further reduced to 5 NUTS3 regions (1.8%) when comparing sheep and reindeer.

More importantly, however, trends were inferred here over just three years, and may hence be subjected to random fluctuations not entirely captured by the Poisson assumption, particularly if wolf numbers are low. We therefore invite regional and national authorities to continue integrating their damage data into accessible data bases, and use trends over longer time periods, at larger geographic scales, or both, to effectively monitor and help mitigate human-carnivore conflicts across Europe.

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Tables

Table 1: Number of wolf-caused livestock damage incidents per year and per country. Countries marked with a * reported data only for a subset of the provinces for which the presence of wolves is documented. Countries marked with a $^{+}$ did not report an assessment level and we therefore analyzed all submitted records.

Country	**2018**	**2019**	**2020**
Austria	34	20	61
Belgium	11	22	46
Croatia	1,111	1,229	1,541
Czech Republic^{+}	88	198	265
Estonia	121	178	N/A
Finland	553	756	832
France^{+}	3,359	3,389	3,092
Germany	550	684	696
Greece	2,283	2,405	2,182
Italy*$^{+}$	171	186	148
Latvia	30	39	22
Lithuania^{+}	N/A	408	492
Netherlands	44	25	95
Norway	703	239	205
Poland	680	727	121
Romania*	82	33	69
Slovakia	95	111	175
Slovenia	201	357	253
Spain*	2,145	2,474	2,237
Sweden	31	86	135
Switzerland	238	188	311
Total	12,530	13,754	12,978

Table 2: Linear models fitted to wolf-caused incidents. The table shows the models with the best fit (delta AIC < 2.0) as well as the model including wolf presence only. The full column names from left to right are as follows: Intercept, Permanent wolf presence, Sporadic wolf presence, Agro-Forestry Area, Pasture, Grassland, Broadleaved forest, Coniferous forest, Mixed forest, Support for prevention measures.

	Wolf presence		Agricultural		Forest & seminatural						
Inter.	Perm.	Spor.	Agro-F.	Pasture	Grassl.	Broad.	Conif.	Mixed	Prev.	df	ΔAIC
-7.68	-	-	420.33	-0.06	0.27	0.17	-	-	-	6	0
-11.63	-	-	443.38	-	0.26	0.16	-	-	-	5	0.22
-4.5	-	< 0.01	416.23	-0.07	0.26	0.18	-	-	-	7	0.53
-5.77	-	-	421.2	-0.07	0.26	0.18	< 0.01	-	-	7	1.34
-9.99	-	< 0.01	443.6	-	0.26	0.17	-	-	-	6	1.55
-7.95	-	-	-	-0.07	0.29	0.18	-	-	-	5	1.7
-4.88	-	< 0.01	408.37	-0.08	0.26	0.19	-	0.01	-	8	1.86
-4.5	-	< 0.01	401.24	-0.07	0.25	0.18	-	-	+	9	1.92
-10.57	-	-	445.49	-	0.26	0.16	< 0.01	-	-	6	1.93
-7.89	-	-	426.26	-0.06	0.27	0.17	-	-	-	7	1.98
16.21	0.02	< 0.01	-	-	-	-	-	-	-	4	104.62

Figures

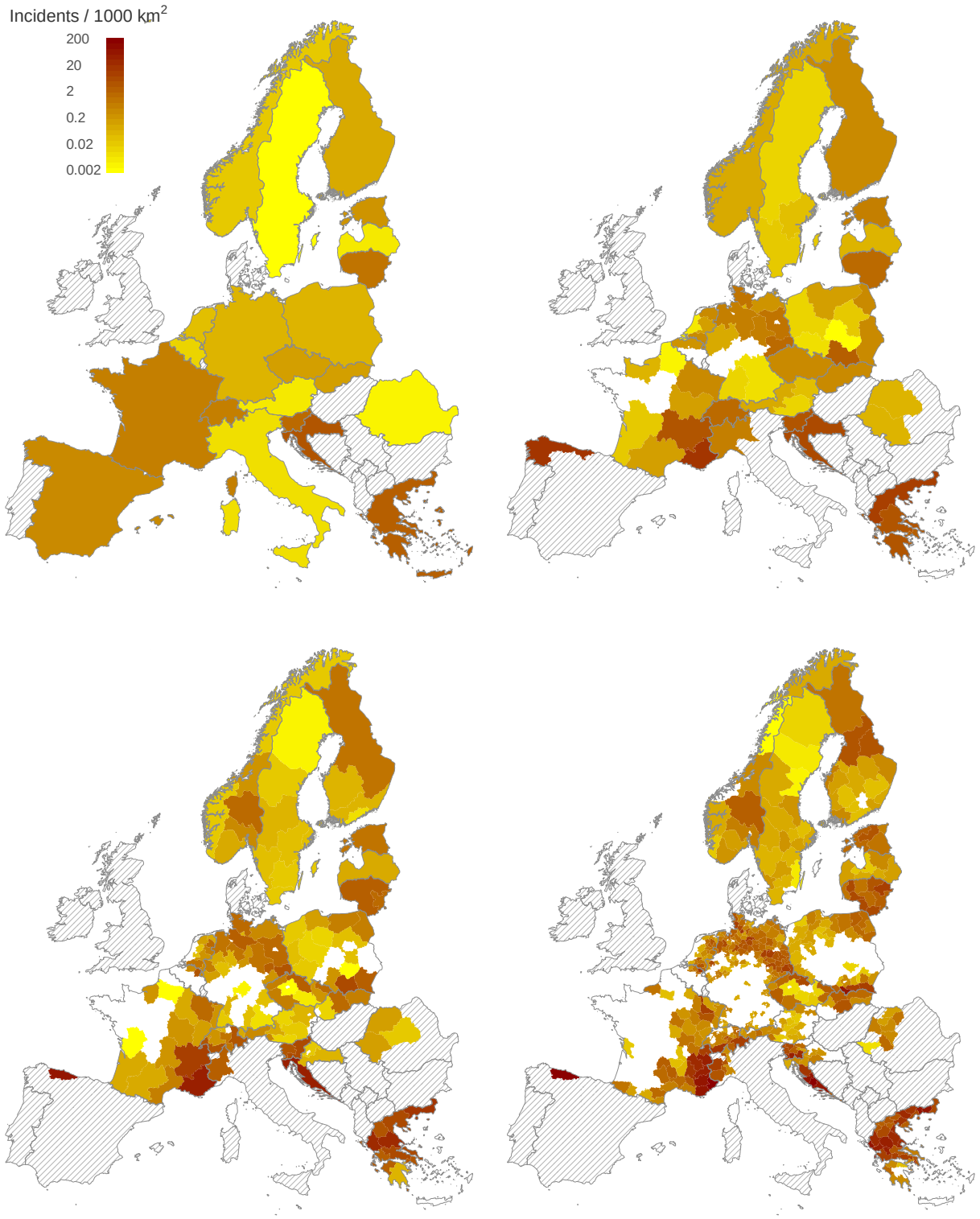

Figure 1: Average wolf-caused livestock incident density plotted on the country level, NUTS1 level, NUTS2 level and NUTS3 level (top left to bottom right) across the years 2018, 2019 and 2020. Gray shaded regions indicate regions from which we did not obtain data. Regions shown in white indicate regions from which no damages were reported.

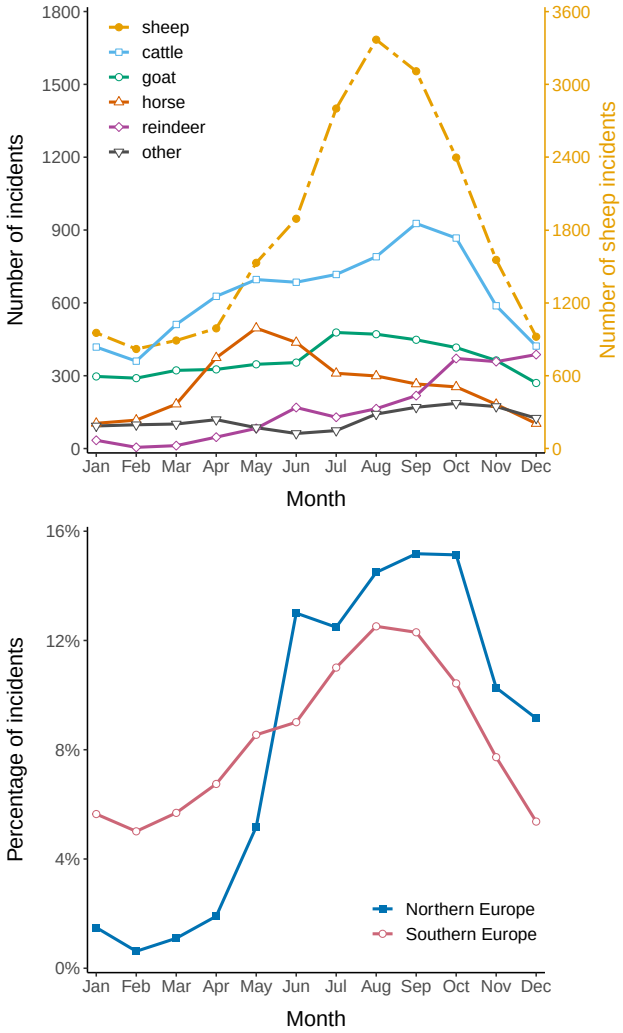

Figure 2: Top: Annual distribution of wolf-caused livestock damage incidents. Bottom: Percentage of monthly wolf-caused livestock damage incidents for northern Europe (Estonia, Finland, Latvia, Lithuania, Norway, Sweden) and southern Europe (Croatia, France, Greece, Italy, Spain).

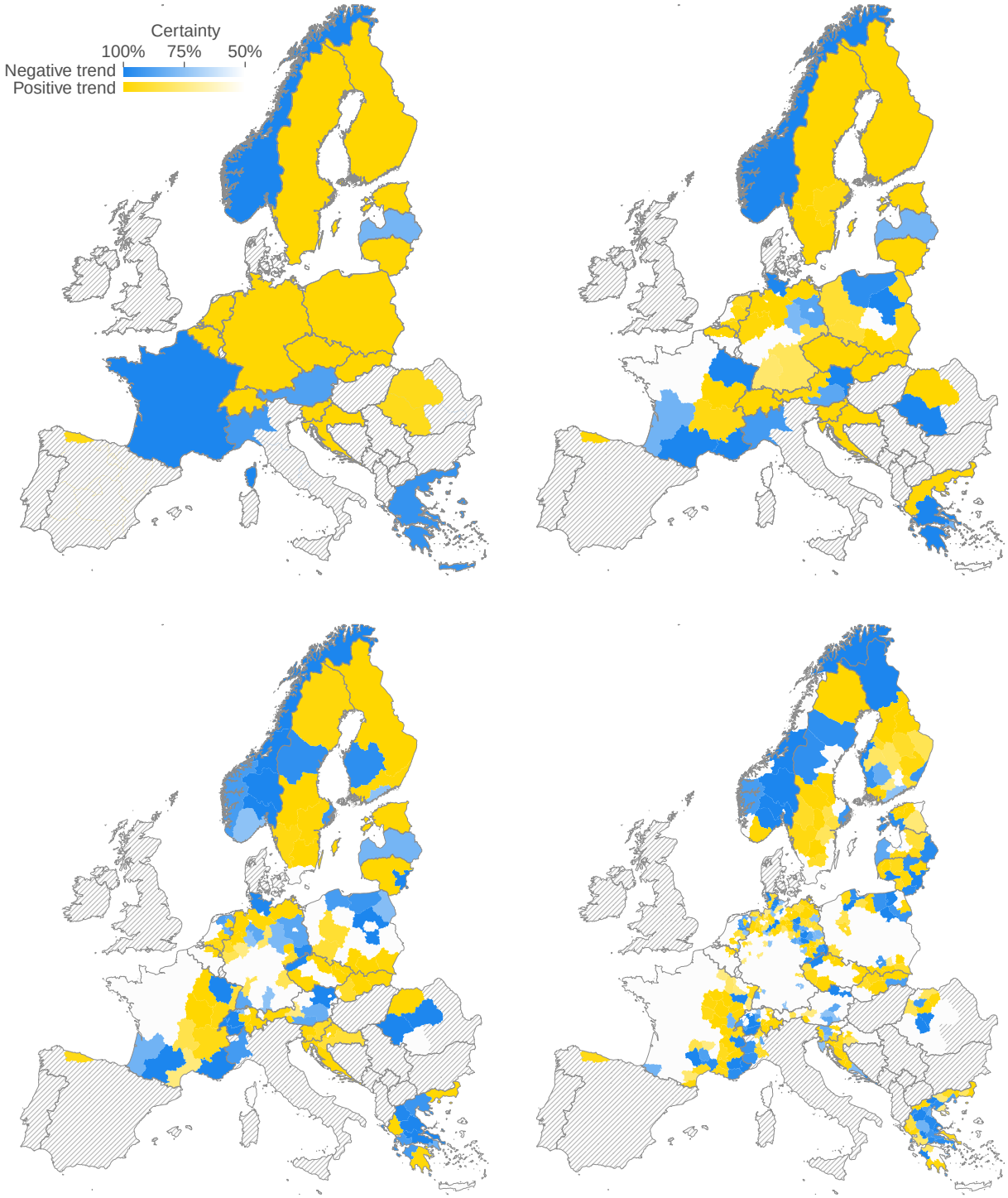

Figure 3: Wolf-caused livestock damage trends at the country, NUTS1, NUTS2 and NUTS3 level (top left to bottom right). Each region was classified as having an increasing (yellow) or decreasing (blue) incident trend, depending on the posterior mode $\gamma_r < 0$ for decreasing trends and $\gamma_r > 0$ for increasing trends. Color saturation indicates uncertainty quantified as the posterior mass within the classified interval, ranging from solid (1.0) to white (≤ 0.5). Regions without reported incidents are shown as white, regions with no data reported are shaded in gray.