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Initial assessment of the economic burden of major parasitic helminth infections to the ruminant livestock industry in Europe

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ABSTRACT

We report a European wide assessment of the economic burden of gastrointestinal nematodes, *Fasciola hepatica* (common liver fluke) and *Dictyocaulus viviparus* (bovine lungworm) infections to the ruminant livestock industry. The economic impact of these parasitic helminth infections was estimated by a deterministic spreadsheet model as a function of the proportion of the ruminant population exposed to grazing, the infection frequency and intensity, the effect of the infection on animal productivity and mortality and anthelmintic treatment costs. In addition, we estimated the costs of anthelmintic resistant nematode infections and collected information on public research budgets addressing helminth infections in ruminant livestock. The epidemiologic and economic input data were collected from international databases and via expert opinion of the Working Group members of the European Co-operation in Science and Technology (COST) action COMbatting Anthelmintic Resistance in ruminants (COMBAR). In order to reflect the effects of uncertainty in the input data, low and high cost estimates were obtained by varying uncertain input data arbitrarily in both directions by 20 %. The combined annual cost

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[low estimate-high estimate] of the three helminth infections in 18 participating countries was estimated at € 1.8 billion [€ 1.0–2.7 billion]. Eighty-one percent of this cost was due to lost production and 19 % was attributed to treatment costs. The cost of gastrointestinal nematode infections with resistance against macrocyclic lactones was estimated to be € 38 million [€ 11–87 million] annually. The annual estimated costs of helminth infections per sector were € 941 million [€ 488 – 1442 million] in dairy cattle, € 423 million [€ 205–663 million] in beef cattle, € 151million [€ 90–213 million] in dairy sheep, € 206 million [€ 132–248 million] in meat sheep and € 86 million [€ 67–107 million] in dairy goats. Important data gaps were present in all phases of the calculations which lead to large uncertainties around the estimates. Accessibility of more granular animal population datasets at EU level, deeper knowledge of the effects of infection on production, levels of infection and livestock grazing exposure across Europe would make the largest contribution to improved burden assessments. The known current public investment in research on helminth control was 0.15 % of the estimated annual costs for the considered parasitic diseases. Our data suggest that the costs of enzootic helminth infections which usually occur at high prevalence annually in ruminants, are similar or higher than reported costs of epizootic diseases. Our data can support decision making in research and policy to mitigate the negative impacts of helminth infections and anthelmintic resistance in Europe, and provide a baseline against which to measure future changes.

1. Introduction

Helminth infections of grazing ruminants represent a wide array of parasitic genera and species, but those of highest economic importance in Europe are the gastrointestinal nematodes (mainly *Ostertagia ostertagi*, *Cooperia oncophora*, *Teladorsagia circumcincta*, *Haemonchus contortus* and *Trichostrongylus* spp.), the common liver fluke (*Fasciola hepatica*) and the bovine lungworm (*Dictyocaulus viviparus*; Charlier et al., 2014). These infections are an important constraint on efficient ruminant livestock production in Europe and globally. All farmed ruminant populations with outdoor access are exposed to these parasites that can negatively impact on feed intake, growth, mortality rates, carcass weight & composition, wool growth, fertility, and milk yield (Fitzpatrick, 2013). The efficient management and control of helminth infections, therefore has a crucial role to play in increasing livestock production from a shrinking natural resource base, to meet the demands of a growing and nutritionally more demanding world population (Vercruysse et al., 2018).

Because livestock helminth infections are ubiquitous, and have no major regulatory or trade implications, their control has largely remained the responsibility of the farmer and his/her veterinarian. Current control, largely based on the administration of anthelmintic drugs, however is threatened by continuing development and spread of helminth populations that have become resistant to these products (Sutherland and Leathwick, 2011; Sangster et al., 2018). Today, scientific opinion supports concerted action and more policy-driven intervention. These actions could be warranted to (i) promote "best practice" parasite management programmes and reduce the indiscriminate use of anthelmintics at the expense of veterinary consultation and the use of diagnostics to inform anthelmintic treatment decisions (Charlier et al., 2018; Easton et al., 2018) and (ii) target research and innovation programmes for solutions to combat anthelmintic resistance (AR) (Morgan et al., 2019). While the first action may slow down the development and spread of AR, the second action could deliver vaccines, improved diagnostics and complementary control methods to secure the effective management of production-limiting helminth infections in the future (Jackson and Miller, 2006). However, improved policy and planning requires more insights into the economic impacts of helminth infections and AR, and monitoring mechanisms to verify the impact of concerted actions at a national and European level. Current studies towards the economic impact of helminth infections are scarce and have mostly been restricted to a limited number of helminth species, host species, production systems and a narrow geographical context (e.g. Bennett and IJpelaar, 2005; Schweizer et al., 2005; Charlier et al., 2009; Mavrot, 2016). Other models are applicable at the farm level only (see Charlier et al., 2016a for a review). Mavrot (2016) provided the first estimate of losses at the European level, but considered only gastrointestinal nematode (GIN) infections in the dairy cattle and sheep meat industries, where most data are available. Here we report the results of the Working Group that was established in the framework of the European COST Action "COMBAR – COMBatting Anthelmintic Resistance in Ruminants", to identify and collate epidemiologic and economic information from 18 COST Member or Near Neighbour Countries. The overall aim was to estimate the economic burden to the European ruminant livestock industry with a common approach that allows comparisons to be made between countries, between different helminth species, and over time. The specific objectives were to (1) identify data gaps for economic assessment of helminth infections; (2) use the available data to estimate the costs of helminth infections and AR in a representative range of European countries and (3) compare the estimated costs of the infections with public research and control budgets in these countries, insofar as they are available. We discuss how this framework could improve decision making and planning for managing the negative impacts of helminth infections and AR in ruminant livestock industries in Europe.

2. Materials and methods

2.1. Concept

A standardised spreadsheet model was previously developed to estimate the annual economic costs of GIN and *F. hepatica* infections on dairy cattle farms (Charlier et al., 2012b). This model was extended and modified to incorporate the estimation of costs imposed by GIN and *F. hepatica* infections in dairy cattle, dairy sheep, dairy goats, beef cattle and meat sheep and *D. viviparus* infections in dairy and beef cattle. The model was applied at a national level with available epidemiologic and economic data from public repositories. The economic impact of a pathogen or animal disease is a function of many factors such as disease frequency, infection intensity, the effect of the disease on mortality and productivity in animals and its effects on human health, and efforts to respond to the disease (Rushton, 2009). COMBAR working group members collected the above-mentioned data for their own country of residence. When the data were deemed to be not available from public repositories or published studies and reports, the data were either obtained through expert opinion, or not provided when the expert judged him/her-self not to be able to provide a robust estimate. The data were obtained through an online survey in two phases. First, the empty spreadsheet was completed by the experts after the consultation of their network. After compilation of all the received data, imputation of empty data values and describing the calculation methods, the spreadsheet used for calculation purposes was resent to the experts for review of the country-specific input data.

Imputation was done similarly to the approach of Mavrot (2016). Countries were grouped into four bio-climatic regions (Arctic-boreal/Atlantic/Continental/Mediterranean) as defined by Peel et al. (2007). Where countries included more than one climatic type, the dominant type by surface area was chosen. It was assumed that features such as parasite infection levels or management practices (proportion exposed to grazing, anthelmintic treatment frequency) are more similar within than between bio-climatic regions. Therefore, the imputed value on level of infection or management practice was based on the average from the same bio-climatic region if such data were available, or from all available data otherwise.

In this way, it was possible to obtain data from 18 countries, including the European countries with the largest ruminant livestock economies (France, Germany, Ireland, Italy, Poland, Spain, UK). Further details on data collection, handling and processing are provided step-by-step in the sections below.

2.2. Population at risk

The population at risk of suffering production losses due to helminth infections was based on animal population data, corrected for the estimated proportion of the population that is exposed to grazing. Animal population data were obtained from FAOSTAT (FAO, 2017) and complemented with data from national data repositories for more specific numbers. Separate population data were obtained for dairy cattle (heifers and adults), beef cattle (numbers slaughtered), dairy sheep (adults), meat sheep (numbers slaughtered) and dairy goats (adults). Because no specific data are available on the number of young dairy cattle raised for future milk production, this population was estimated by applying a fixed proportion of 0.75 to the adult milk producing population. This number was chosen based on data from the Netherlands and Poland from 2015 to 2017, where the proportion of dairy young stock per adult cow varied between 0.70 – 0.82 and between 0.74 – 0.79, respectively (Statistics Netherlands, 2019; Statistics Poland, 2020). The proportion of the dairy cattle population exposed to grazing was based on a presentation from the European Grassland Federation (van den Pol - van Dasselaar, 2018), for the other production systems proportions were based on local reports or expert opinion.

2.3. Disease frequency and intensity of infection

Surveys to quantify the level of infection with helminths use various diagnostic measures, and results are seldom directly comparable. Moreover, diagnostic results (e.g. faecal egg count; FEC) may need different interpretation according to the local context (dominant parasite species, method applied, sampling season, climatic and environmental factors; Sargison, 2013). Therefore, each COMBAR participant evaluated the available information for their country and combined it into a single estimate of the animal level prevalence of “production limiting” infections per livestock category (see population at risk) and per helminth species. Because production loss is complex and related not only to the level of patent helminth infection, the thresholds were not used prescriptively, but only as a guide to national respondents in an effort to score the production limiting infections in a broadly comparable way for the different countries. For GIN infections in young dairy cattle, the use of thresholds for production limiting infections of > 3.5 units of tyrosine and > 200 eggs per gram (EPG) faeces were proposed for surveys using the serum pepsinogen assay (Charlier et al., 2010a) and FEC methods (Shaw et al., 1998), respectively. For GIN infections in adult dairy cattle, surveys using the bulk tank milk *O. ostertagi* ELISA (Forbes et al., 2008) and measuring *O. ostertagi* optical density ratios (ODR) were used. First, the average country-level bulk-tank milk *O. ostertagi* ODR was obtained. Next, the prevalence of production-limiting GIN infections at the animal level was obtained using the formula as described by Charlier et al. (2010b). For GIN infections in sheep, the use of FEC thresholds of 500 and 1000 EPG was proposed for cases where *H. contortus* was absent or present, respectively (Abbott et al., 2012). For infections with *F. hepatica*, the general prevalence of infection was used because fluke burdens as low as 1–10 parasites have been shown to negatively impact on animal productivity (Mazeri et al., 2017). For *D. viviparus*, the available coprological or serological diagnostics detect only patent infections (Ploeger et al., 2014) and thus the prevalence of patent infections was used.

Table 1
The effects on production and mortality in animals with production-limiting helminth infections used in cost calculations.

Host species and production parameter for which costs were accounted	Gastrointestinal nematodes	*Fasciola hepatica*	*Dictyocaulus viviparus*
Young dairy cattle			
Delayed puberty (days)	10[a]	25[a]	5[h]
Decreased milk production first lactation (kg)	331[a]	159[a]	166[h]
Mortality (%)	1[b]	NA	1[h]
Adult dairy cattle			
Reduced milk production (%)	3.8[a]	3[a]	1.9[g]
Intercalving interval (days)	NA	13[f]	NA
Additional inseminations	NA	0.75[f]	NA
Mortality (%)	NA	NA	1[h]
Beef cattle			
Reduced carcass weight (%)	1.9[c]	0.5[c]	NA
Intercalving interval (days)	NA	13[f]	NA
Additional inseminations	NA	0.75[f]	NA
Mortality (%)	NA	NA	1[h]
Dairy sheep			
Milk production (production ratio infected over control)	0.78[d]	0.78[h]	NA
Interlambing interval (days)	NA	6.4[h]	NA
Mortality (%)	1[h]	1[h]	NA
Meat sheep			
Carcass weight (production ratio infected over control)	0.85[d]	0.96 [i]	NA
Mortality (%)	1[h]	1[h]	NA
Dairy goats			
Milk production (production ratio infected over control)	0.57[e]	0.57[h]	NA
Interkidding interval (days)	NA	6.4[h]	NA
Mortality (%)	1[h]	1[h]	NA

NA: No impact was accounted.
References: [a] Charlier et al., 2012b; [b] Delafosse, 2013; Charlier et al., 2009; [d] Mavrot et al., 2015; [e] Veneziano et al., 2004; [f] Schweizer et al., 2005; [g] May et al., 2018; [h] Authors' judgement; [i]Dargie, 1987.

2.4. Effects of the disease on mortality and productivity

The effects of disease on production parameters and mortality are summarized per helminth group/species in Table 1. For GIN and *F. hepatica* infections in dairy cattle, the same effects were used as in the previously reported ParaCalc® model (Charlier et al., 2012b), with the following modifications. An effect of GIN-associated mortality in young dairy cattle was added as reported by (Delafosse, 2013). The effects of *F. hepatica* on fertility were slightly modified to consider animal level (Schweizer et al., 2005) instead of herd-level effects as previously used. For beef cattle, we used production effects for reduced carcass weight for GIN and *F. hepatica*, and we assumed the same effects on fertility as for dairy cattle. For *D. viviparus*, we estimated effects on parameters of young stock (Eysker et al., 1997), on milk production (May et al., 2018) and mortality (Holzhauer et al., 2011) in dairy cattle. Only mortality was assumed in beef cattle because to the authors' knowledge no production impact studies are available for beef cattle.

In sheep, the effects of GIN on milk production and carcass weight were based on the meta-analysis of Mavrot et al. (2015). The same effect was assumed for infection with *F. hepatica* on milk production, while we used the study of Dargie (1987) for the effects on carcass weight. The effect of *F. hepatica* infection on the interlambing interval for dairy sheep was proportionally deducted from the effect on intercalving interval in cattle, taking into account a shorter heat cycle in sheep than in cattle (17 versus 21 days). The effect on milk production in dairy goats was based on the study of Veneziano et al. (2004), while the effect of *F. hepatica* infection on interkidding interval was assumed to be the same as in dairy sheep. A general mortality rate of 1% was applied in small ruminants with a production limiting helminth infection.

2.5. Efforts to respond to the disease

Two different kinds of "response" costs were considered. Costs of anthelmintic treatments were estimated by using data on the percentage of animals treated, the average number of anthelmintic treatments per animal per year and an average cost of the treatment. Input data were based on local expert's opinions. Given there was more variation in prices depending on the product used and the size of the animal (e.g. sheep versus cow) than in price variations within countries, fixed treatment costs were applied across all countries. These were € 0.7, € 1.5, € 4 and € 8 per dosed lamb/goat kid, adult sheep/goat, heifer and adult cow, respectively.

In addition, data were collected on publicly funded research programmes at the national and European level that worked on the topic of the considered helminth infections. To this aim, the budgets of research projects were extracted from the Research Project Database of the Collaborative Working Group (CWG) of European Animal Health & Welfare research and STAR-IDAZ International Research Consortium (IRC) (STAR-IDAZ, 2019). Because the database is incomplete, COMBAR working group members complemented these data by searching national databases and contacting their networks. Only relevant research projects that started after 1 January 2008 and ended before 31 December 2017 were considered.

2.6. The effects of anthelmintic resistance

The costs of AR were modelled as a function of the farm-level prevalence of AR, the production penalty of using a partially versus a fully effective anthelmintic and the cost of the ineffective anthelmintic as described below. Costs of AR were not added to total production loss and treatment costs. Rather, the estimated cost of AR was disaggregated from the total cost of helminth infections.

Although the presence of AR in ruminants has now been confirmed in most European countries (Rose et al., 2015), available data on its prevalence and production impacts are few and patchy. Therefore, each scientist was asked to provide a value for the most likely prevalence of resistance against macrocyclic lactones (ML) in their country, for cattle, sheep and goats. If no data were provided, the value was imputed based on the overall average by animal species. ML were chosen because they are by far the most commonly used anthelmintic class in lactating animals, and in cattle of all ages, across Europe. Moreover, in sheep and goats, resistance to other classes, especially benzimidazoles, is now very common (Rose et al., 2015) and farms experiencing high levels of resistance to one class of drug are likely to progressively switch to other drug classes, favouring the more effective ML. It was therefore considered that the farm-level prevalence of resistance to ML provides the fairest indication of the likelihood of treatment failure, given options available to farmers in a given country.

Expert opinion on prevalence of ML resistance was supplemented by estimates of sample size weighted prevalence from published studies and abstracts, listed in Rose et al. (2015) complemented with recent studies. For countries with no available data, average prevalence across other countries in the same climatic zone was used. Reported prevalence is likely to be strongly influenced by farm selection and publication bias (Rose et al., 2015), while expert opinion can be influenced by various pre-conceptions, so neither measure should be considered as a gold standard. The arithmetic mean of the prevalence estimated by experts and that from publications was therefore used in the present analysis.

For production penalties, in their cost-benefit analysis of AR delaying strategies, Geurden et al. (2014) reported a penalty on live weight gain in lambs of 10 % following the use of a partial versus fully effective wormer. However, Learmount et al. (2018) argued this may be an underestimation of the true production cost of AR. Study groups cograzed the same pasture with a negative effect on live weight gain of the treated animals because the pasture became more heavily contaminated by the lambs treated with the ineffective wormers and by untreated sheep. In calves, Fazzio et al. (2019) found a 18 % decrease in weight gain comparing the use of partial versus a fully effective wormer. Based on these studies, and as an initial estimate of the production costs of AR, we attributed 15 % of the different helminth induced effects on production and mortality of GIN infections to occur due to the presence of AR. In addition, we attributed 15 % of the anthelmintic treatment costs to the overall costs of AR, because this part of the treatment could be considered as ineffective. As almost no data are available on the prevalence and production effects of AR in *F. hepatica* and *D. viviparus*, no cost estimate was provided for these parasites. The cost of AR was thus defined according to the formula:

$$COST_{AR} = \sum_{i,j} [A_i * G_i * T_i * 0.15]*[P_i * L_{ij} + N_i * R_i * C_i]$$

Where i (i = 1–6) is the animal category (e.g. dairy young stock, beef cattle, …); j (j = 1–3) is the category of production impact within animal category; A is the size of the animal population; G is the proportion of animals exposed to grazing; T is the proportion of animals receiving anthelmintic treatment; 0.15 is the loss coefficient attributed to anthelmintic resistance; P is the prevalence of production limiting infections; L is the effect of production-limiting infections on production and mortality; N is the average number of anthelmintic treatments per animal; R is the prevalence of anthelmintic resistance and C is the cost spent on anthelmintic treatments.

2.7. Monetary value of production in- and outputs

Producer prices for live weight meat, and milk in 2017 were obtained from (EUROSTAT, 2017). For countries, where data were missing, imputed values were used based on the overall average. Live weight prices were converted to carcass weight prices using a generic dressing percentage (carcass weight/live weight) of 0.50 in cattle and 0.45 in sheep. According to van Soest et al. (2019) price differences between countries of feed, labour, animal replacement value and destruction costs are relatively small, at least between Germany, France, Spain and Sweden. Therefore, we used fixed costs across countries, derived from the scientific literature for the following parameters, and accounted for an inflation until 2017 since the original report. Additional rearing costs due to delayed puberty were derived from variable rearing costs in dairy heifers (Mohd Nor et al., 2015) and set at € 2.1 per day. Cattle insemination costs were set at € 30 per insemination (Charlier et al., 2012b). Costs for a prolonged inter-calving interval (€ 0.79 per day) were derived from Inchaisri et al. (2010). Costs for a prolonged inter-lambing or inter-kidding interval were set at € 0.41 per day, based on an annual rearing cost of € 150 per ewe (Schoenian, 2019). Animal mortality led to disposal costs, which were set at € 134 and € 20 per dead cow (van Soest et al., 2019) and sheep/goat, respectively. Feeding costs were set at € 0.12 per kg milk (van Soest et al., 2019).

2.8. Cost calculations

The cost (C) of helminth infections was defined as the value of the loss (L) in expected output together with the treatment (T) costs in trying to mitigate the effects of disease on production (C = L + T) (Bennett et al., 1999). In addition, reseassrch budgets were considered as an additional investment cost to preserve the future control of parasitic helminth infections. In order to obtain an idea of the effects of uncertainty in the input data, the input data that did not come from public and regularly updated repositories were increased and decreased by 20 % to obtain a low and high estimate of the cost, in addition to the best estimate. A sensitivity analysis was conducted to understand which changes in input data have the greatest effect on the estimated total cost. This was done by modifying the values of a single input class (e.g. levels of infections, impact of infection on production) by – or + 20 % and monitor at each change the effect on the total cost of helminth infections.

For calculating the production losses, saved feeding costs (See section 2.6) were deducted from the value of the lost milk production because animals that produce less milk due to helminth infections can be considered to also eat less (Forbes et al., 2004). Production losses in carcass weight in sheep were calculated according to the formula of Mavrot (2016). This formula considers a baseline carcass weight that corresponds to the amount of carcass weight reached by the age of two months, before GIN infection is established. In this way, production losses do not apply to the part of the total carcass weight that is not influenced by GIN infection. The used production losses in milk production or carcass weight in cattle were estimates based on annual milk production or whole carcass weight data.

The annual cost of helminth infections in the EU-28 was estimated by calculating the average cost of infection per animal by production type and multiplying this average cost by the total number of animals in the EU-28 in 2017 (FAO, 2017).

Research budgets from collaborative European research projects were divided by the number of countries in our assessment (N = 18) and an equal amount was allocated to each country.

3. Results

3.1. Data gaps

Data gaps were present in every phase of the data collection. They are listed in Table 2 and are further explained in the discussion.

3.2. Costs of infection and AR

The estimated combined costs of GIN, *F. hepatica* and *D. viviparus* infection per country and per livestock sector are detailed in Table 3, and the total estimated cost per country in Fig. 1. The data are also represented as a map in Annex 1. The combined annual cost [low estimate - high estimate] of the three helminth infections in 18 participating COMBAR countries was estimated at € 1.8 billion [€ 1.0–2.7 billion]. Eighty-one percent of this cost (€ 1.46 billion [€ 0.84–2.10 billion]) was composed of costs due to lost production and 19 % (€ 0.35 billion [€ 0.14 – 0.57 billion]) was attributed to treatment costs. The annual costs per sector were € 941 million [€ 488 – 1442 million] in dairy cattle, € 423 million [€ 205–663 million] in beef cattle, € 151 million [€ 90–213 million] in dairy sheep, € 206 million [€ 132–248 million] in meat sheep and € 86 million [€ 67–107 million] in dairy goats. The average annual cost [low estimate - high estimate] per adult dairy/slaughtered animal in the population (including non – exposed animals) was estimated at € 41 [€ 21–63] in dairy cattle, € 13 [€ 6–21] in beef cattle, € 14 [€ 9–17] in dairy sheep, € 4 [€ 3–5] in meat sheep and € 24 [€ 20–26] in dairy goats. Extrapolating this average cost per animal to the whole EU-27 and EU-28 ruminant livestock population yields a total cost of € 1.9 billion and 2.1 billion per year, respectively. The helminth parasite taxon representing the highest burden was variable between countries, and climate zones (Fig. 2). Relative impacts across livestock sectors also differed regionally (Fig. 3). Overall the annual production costs were estimated to be € 686 million [€ 411–997 million] for GIN, € 635 million [€ 342–970 million] for *F. hepatica* and € 139 million [€ 86–225 million] for *D. viviparus*.

The estimated costs of AR in GIN are given in Table 4, per country and livestock sector. Overall annual costs were estimated at € 38 million [€ 11–87 million] annually (6 % of the production cost of GIN). These costs were largest in dairy cattle (€ 17.2 million [€ 5.6–39.3 million]), followed by beef cattle (€ 9.3 million [€ 3.1–19.4 million]), meat sheep (€ 8.0 million [€ 1.4–20.4 million]), dairy sheep (€ 2.5 million [€ 0.6–5.5 million]) and dairy goats (€ 1.1 million [€ 0.4–2.5 million]).

3.3. Public research budgets

The estimated annual public budgets for research on the considered helminth infections, together with the total cost of helminth infections is given per country in Table 5. Overall, the total annual public research budgets of collected projects was € 2.7 million (0.15 % of the total cost); 56 % (€ 1.5 million) was spent at the national level while 44 % (€ 1.2 million) was spent at the European level.

Table 2
Data gaps hampering the economic assessment of gastrointestinal nematode, liver fluke and lungworm infections of farmed ruminants in Europe.

Data layer	Data gaps	Recommendations for national and European decision makers
Population	Poor differentiation of population size by age and production system. Limited data availability on goat and sheep numbers in countries where these represent minor species. Poor data availability of proportion of population exposed to grazing.	Develop more granular and harmonized data collection and reporting methods on livestock numbers. Support European Grassland Federation in developing deeper understanding of exposure to grazing in various livestock categories.
Disease frequency	Limited prevalence data at national level. Limited number of surveys in eastern European countries.	Encourage studies to estimate disease prevalence at national level. Support epidemiologic studies in Eastern Europe.
Production effects	Lack of information on production impact of lungworm in beef cattle or *Nematodirus battus* infections in sheep. Limited information on impacts in beef cattle, dairy sheep and on impacts in general in east European countries.	Support studies to fill data gaps in production impacts. Support impact studies in Eastern Europe.
Anthelmintic drug consumption	No public repository of anthelmintic drug consumption at national or European levels.	Develop standardized method to monitor anthelmintic drug consumption. Develop public repository with veterinary drug use information.
Anthelmintic resistance (AR)	Poor quantitative knowledge on prevalence of AR. Poor knowledge on production impacts of anthelmintic treatments with incomplete efficacy.	Support research in cost-effective diagnostic tests to detect and monitor AR. Support AR impact studies
Research projects	Database with publicly funded research projects is incomplete.	Support the European Collaborative Working Group on Animal Health and Welfare research and STAR-IDAZ research project database to develop better reporting mechanisms and become more comprehensive

Table 3
The estimated annual costs (€) of helminth infections to ruminant livestock industries in 18 COMBAR countries, split up into costs of lost productivity and costs spent on anthelmintic treatment.

Country	Variable	Dairy cattle	Beef cattle	Dairy sheep	Meat sheep	Dairy goats	TOTAL
Austria	Production	12,869,317	11,753,725	859,466	1,102,066	2,250,616	28,835,190
	Treatment	1,736,961	356,180	76,791	123,317	67,760	2,361,009
	Total	14,606,278	12,109,905	936,257	1,225,383	2,318,377	31,196,200
Belgium	Production	20,421,574	15,616,397	16,156	394,082	286,752	36,734,961
	Treatment	1,826,983	3,533,778	16,641	194,641	35,508	5,607,550
	Total	22,248,556	19,150,175	32,797	588,723	322,260	42,342,512
France	Production	238,746,058	65,878,270	27,227,296	72,187,226	1,830,700	405,869,551
	Treatment	7,817,493	10,167,768	8,372,464	7,645,602	142,594	34,145,921
	Total	246,563,551	76,046,038	35,599,760	79,832,828	1,973,294	440,015,471
Germany	Production	80,119,748	38,671,874	149,850	9,813,860	3,363,655	132,118,988
	Treatment	7,013,929	5,574,744	28,907	934,988	113,046	13,665,614
	Total	87,133,677	44,246,618	178,758	10,748,848	3,476,702	145,784,602
Ireland	Production	132,654,910	38,154,165	0	10,095,763	0	180,904,838
	Treatment	24,444,456	24,016,231	0	7,486,886	0	55,947,574
	Total	157,099,366	62,170,396	0	17,582,650	0	236,852,412
Israel	Production	0	0	0	162,971	36,033	199,004
	Treatment	0	26,170	0	0	0	26,170
	Total	0	26,170	0	162,971	36,033	225,174
Italy	Production	7,639,570	20,337,358	12,299,457	1,954,814	967,067	43,198,265
	Treatment	3,926,528	4,420,452	10,122,423	3,195,004	1,598,447	23,262,853
	Total	11,566,098	24,757,809	22,421,880	5,149,817	2,565,514	66,461,119
Lithuania	Production	12,119,985	1,427,277	9,140	35,568	310,126	13,902,097
	Treatment	148,720	116,144	3,311	50,762	16,034	334,971
	Total	12,268,705	1,543,421	12,451	86,331	326,160	14,237,068
Netherlands	Production	62,515,980	29,043,315	81,105	1,895,470	3,175,464	96,711,334
	Treatment	7,091,557	412,489	39,394	693,277	239,149	8,475,867
	Total	69,607,537	29,455,804	120,499	2,588,747	3,414,613	105,187,201
North Macedonia	Production	3,101,495	198,536	2,264,120	810,589	614,055	6,988,795
	Treatment	492,666	150,400	1,489,516	180,600	378,280	2,691,463
	Total	3,594,162	348,936	3,753,637	991,189	992,336	9,680,258
Norway	Production	18,085,418	1,330,002	1,828	1,164,846	1,116,166	21,698,260
	Treatment	124,377	425,440	1,214	2,360,625	68,699	2,980,355
	Total	18,209,795	1,755,441	3,042	3,525,471	1,184,865	24,678,614
Poland	Production	43,781,796	20,126,676	51,313	302,085	1,315,281	65,577,152
	Treatment	7,210,968	886,722	470,044	35,785	234,839	8,838,359
	Total	50,992,764	21,013,399	521,357	337,870	1,550,121	74,415,510
Portugal	Production	5,521,002	359,757	1,835,072	1,752,277	8,826,680	18,294,786
	Treatment	1,049,569	3,480,608	670,928	887,795	743,040	6,831,939
	Total	6,570,570	3,840,365	2,505,999	2,640,071	9,569,720	25,126,726
Romania	Production	26,249,054	4,200,486	36,739,404	6,604,380	759,548	74,552,872
	Treatment	5,063,566	1,231,210	35,536,071	11,937,678	5,274,738	59,043,262
	Total	31,312,620	5,431,695	72,275,475	18,542,058	6,034,286	133,596,134
Spain	Production	6,553,441	4,347,867	2,172,220	0	45,807,203	58,880,731
	Treatment	309,592	24,891,491	7,904,241	0	4,832,010	37,937,335
	Total	6,863,033	29,239,358	10,076,461	0	50,639,214	96,818,066
Sweden	Production	29,376,486	2,760,642	0	237,507	5,750	32,380,385
	Treatment	666,540	608,683	0	314,966	24,926	1,615,116
	Total	30,043,026	3,369,325	0	552,473	30,676	33,995,501
Tunisia	Production	6,663,090	390,489	1,611,199	10,196,076	570,256	19,431,110
	Treatment	232,109	1,082,990	754,245	3,219,587	963,139	6,252,070
	Total	6,895,199	1,473,479	2,365,445	13,415,663	1,533,394	25,683,180
United Kingdom	Production	147,420,482	58,653,446	0	16,949,846	0	223,023,774
	Treatment	17,505,417	27,967,310	0	30,754,647	0	76,227,374
	Total	164,925,899	86,620,756	0	47,704,493	0	299,251,148

3.4. Sensitivity analysis

The estimated costs of helminth infections were most sensitive to variations in the assumed effects of infection on production, followed by variations in producer prices of livestock products, the used levels of infection (disease intensity) and grazing exposure (Fig. 4). Variation in anthelmintic treatment parameters (frequency and cost of treatments) had a much lower impact on the final cost estimate.

4. Discussion

This study represents a comprehensive attempt to assess the economic burden of GIN, *F. hepatica* and *D. viviparus* infections to the European ruminant livestock industry. Although the resulting figures are surrounded by considerable levels of uncertainty due to knowledge gaps in the input data (reflected by the large variation between the "low" and "high" cost estimates), our work provides a framework which can be further built upon as more precise data becomes available in the future. We discuss subsequently (1) data gaps and uncertainty, (2) methodological limitations, (3) the study outcomes including comparison with previous studies and (4) how these results can represent a starting point to inform decision making in control programmes and research investments.

4.1. Data gaps and uncertainty

Lack of data is known to be a common obstacle to the assessment of economic cost of animal diseases (Rushton, 2017). Therefore, our first objective was to identify the data gaps that hamper an economic assessment at the country, and subsequently the European level, in order

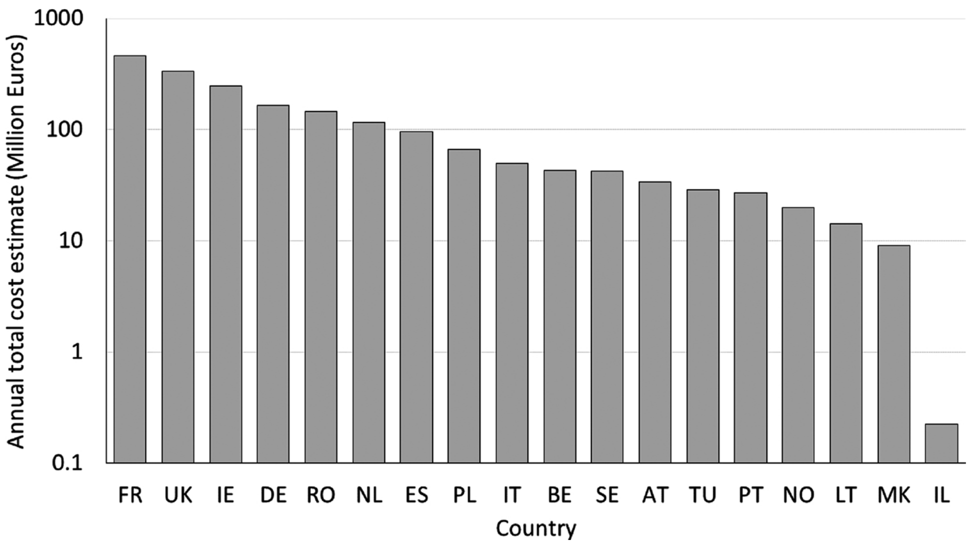

Fig. 1. Estimated total annual cost of helminth infections on ruminant livestock production in 18 European and neighbour countries, ranked and excluding disaggregated costs of drug resistance. FR = France, UK = United Kingdom of Great Britain and Northern Ireland, IE = Republic of Ireland, DE = Germany, NL = Netherlands, RO = Romania, ES = Spain, PL = Poland, IT = Italy, SE = Sweden, BE = Belgium, NO = Norway, AT = Austria, TU = Tunisia, PT = Portugal, LT = Lithuania, MK = North Macedonia, IL = Israel.

to help direct future effort and resources in better collection of epidemiological information. Data gaps were identified in every phase of the data collection. Although general livestock population data are easily available from FAO and EUROSTAT databases, these data lack the granularity needed to support detailed economic assessments. In particular, they do not differentiate the production category (dairy, meat) of growing animals. This is a drawback because the economic impacts of helminth and other infections will be different according to production system and animal age (Charlier et al., 2014; Waret-Szkuta et al., 2017). In addition, in countries where goats and sheep are considered minor species, data on the number of these animals are often lacking. Further, despite its importance for production cost, landscape conservation and the public's image of the ruminant production sector, there is no standardized data collection on grazing exposure in farmed ruminants (van den Pol-van Dasselaar, personal communication). Therefore, we relied on data from a relatively small survey from the European Grassland Federation and the opinion of the local experts. Given this factor had a significant impact on our estimates, it would be important to invest in a more reliable data collection on the status of grazing in Europe (e.g. timings, seasonality, strategies employed). Grazing season length in Europe is strongly associated with bioclimatic variables, and climate change and husbandry changes are altering grazing practices with implications for production, directly and through parasitism (Phelan et al., 2016).

Disease frequency data at least for the economically most relevant ruminant species and production systems are available, but mostly only for specific regions within a country, and it is difficult to deduct nationwide estimates. Moreover, prevalence studies may become rapidly outdated and there is no structured mechanism in place to monitor livestock helminth prevalence over time or to gather the data that is available from sources like veterinary practices, diagnostic laboratories or abattoirs (Charlier et al., 2016b). Another difficulty is to deduct from prevalence data the relevant production impacts at a national scale. Production effects of helminth infections have been reasonably well described for GIN and *F. hepatica* but generally in controlled studies with mono-infections and rarely as part of co-infections as generally seen in the field. Yet, in such a high level (European) assessment, and because of lack of granularity in population structure data and missing knowledge, it remains impossible to account for every production impact such as fertility or mortality effects in young sheep. Therefore, only the major and best described production impacts were used in our study. The production effects may also depend on factors such as the local management system, level of nutrition, breed, the dominant helminth species, and the sampling season (Charlier et al., 2014). Because the impact of helminth infections on productivity had the largest influence on the outcome in the sensitivity analysis, further local

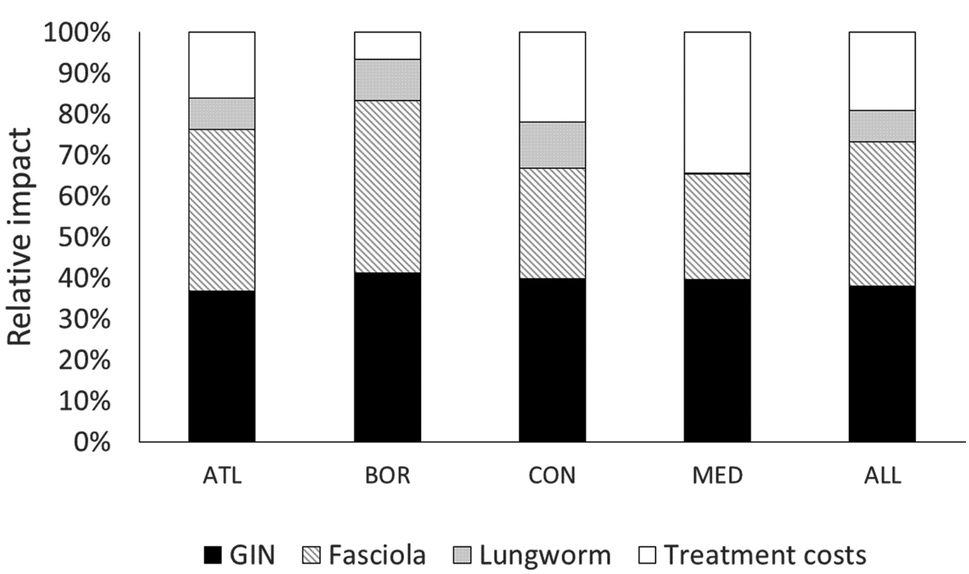

Fig. 2. Estimated relative impact of different helminth taxa on ruminant livestock by climatic zone in Europe and near neighbour countries, calculated as proportion of total production loss and treatment costs. GIN = gastrointestinal nematodes; Lungworm = *Dictyocaulus viviparus*. Climate zones based on aggregated Köppen-Geiger categories (country abbreviations in brackets, see legend to Fig. 1): ATL = Atlantic (BE, FR, UK, IE, NL), BOR = Boreal (NO, SE), CON = Continental (AT, DE, LT, MK, PL, RO), MED = Mediterranean (ES, IL, IT, PT, TU), ALL = all combined.

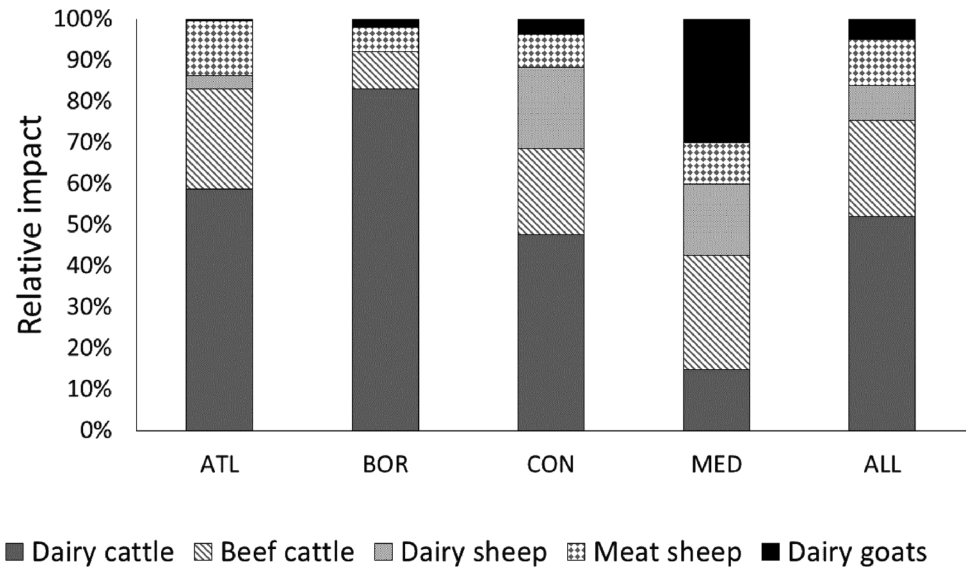

Fig. 3. Estimated relative impact of helminths on ruminant livestock sectors in different climatic zones in Europe and near neighbour countries, calculated as proportion of total production loss and treatment costs. GIN = gastrointestinal nematodes; Lungworm = *Dictyocaulus viviparus*. Climate zones based on aggregated Köppen-Geiger categories (country abbreviations in brackets, see legend to Fig. 1): ATL = Atlantic (BE, FR, UK, IE, NL), BOR = Boreal (NO, SE), CON = Continental (AT, DE, LT, MK, PL, RO), MED = Mediterranean (ES, IL, IT, PT, TU), ALL = all combined.

assessments of helminth induced production impacts would greatly enhance a more accurate economic assessment; especially in Eastern Europe, where such studies generally are lacking today. Estimation of treatment costs for parasite infections face two particular difficulties. First, in contrast to the situation of antibiotics where the sales data are monitored on the European level through the European Medicines Agency, consumption data on anthelmintic drugs are not in the public domain. These data however, will become available once the new regulation (EU) 2019/6 on veterinary medicinal products comes into force (2022). Second, there is a wide range of different products available (different anthelmintic classes, long versus short action, topical/oral/injectable administration and different concentrations). For example, in the UK, there are at least 45 single active products, marketed by twelve different companies for sheep alone (SCOPS 'Know your anthelmintics' guide; https://www.scops.org.uk). In addition, differences also exist due to local price settings and breeds with different weight expectations (inherent and due to different management) and requirements for anthelmintic administration. This leads to a wide range of potential costs for an anthelmintic treatment administration (estimated between € 0.16 to € 24 in cattle and € 0.015 to € 10 in sheep) and there is a need to develop a standardized measure to quantify anthelmintic usage and treatment costs. Our data on public

Table 5
Overall annual cost (€) of helminth infections in 18 COMBAR countries and estimated annual national public research budgets (excl. research at European level) towards improved control of these infections.

Country	Cost of infection	Research budget	%
Austria	31,196,200	0	0.00
Belgium	42,342,512	107,028	0.25
France	440,015,471	50,000	0.01
Germany	145,784,602	56,896	0.04
Ireland	236,852,412	0	0.00
Israel	225,174	120,000	53.29
Italy	66,461,119	64,000	0.10
Lithuania	14,237,068	NA	NA
Netherlands	105,187,201	0	0.00
North Macedonia	9,680,258	0	0.00
Norway	24,678,614	0	0.00
Poland	74,415,510	210,548	0.28
Portugal	25,126,726	NA	NA
Romania	133,596,134	0	0.00
Spain	96,818,066	238,478	0.25
Sweden	33,995,501	127,262	0.37
Tunisia	25,683,180	0	0.00
United Kingdom	299,251,148	538,285	0.18

NA: Not available.

Table 4
Estimated costs (€) of anthelmintic resistant gastrointestinal nematodes, resulting from lost productivity and the cost of partially ineffective anthelmintic drugs.

Country	Dairy cattle	Beef cattle	Dairy sheep	Meat sheep	Dairy goats	Total
Austria	391,809	54,913	10,163	21,576	155,826	634,288
Belgium	200,126	233,931	1,065	25,304	20,021	480,447
France	4,373,931	844,473	786,719	2,150,462	21,966	8,177,552
Germany	657,732	364,678	2,699	318,601	158,209	1,501,918
Ireland	4,911,750	2,731,982	0	804,002	0	8,447,734
Israel	0	1,164	0	142	5	1,311
Italy	381,714	653,922	29,486	17,373	7,633	1,090,128
Lithuania	31,286	10,984	381	3,790	6,376	52,817
Netherlands	741,876	109,517	8,297	209,963	235,000	1,304,653
Norway	60,772	57,365	48	80,740	22,603	221,528
Poland	1,228,492	185,286	17,996	10,154	20,138	1,462,066
Portugal	151,540	154,763	35,286	45,892	25,421	412,903
Republic of Macedonia	86,080	9,552	54,046	32,708	30,144	212,530
Romania	914,636	111,778	1,240,305	425,410	0	2,692,129
Spain	377,539	2,100,836	235,942	0	404,151	3,118,468
Sweden	145,007	83,246	0	12,110	0	240,364
Tunisia	177,951	57,371	38,310	254,177	30,226	558,035
United Kingdom	2,323,478	1,540,352	0	3,584,824	0	7,448,654
TOTAL	17,155,720	9,306,113	2,460,742	7,997,228	1,137,720	38,057,523

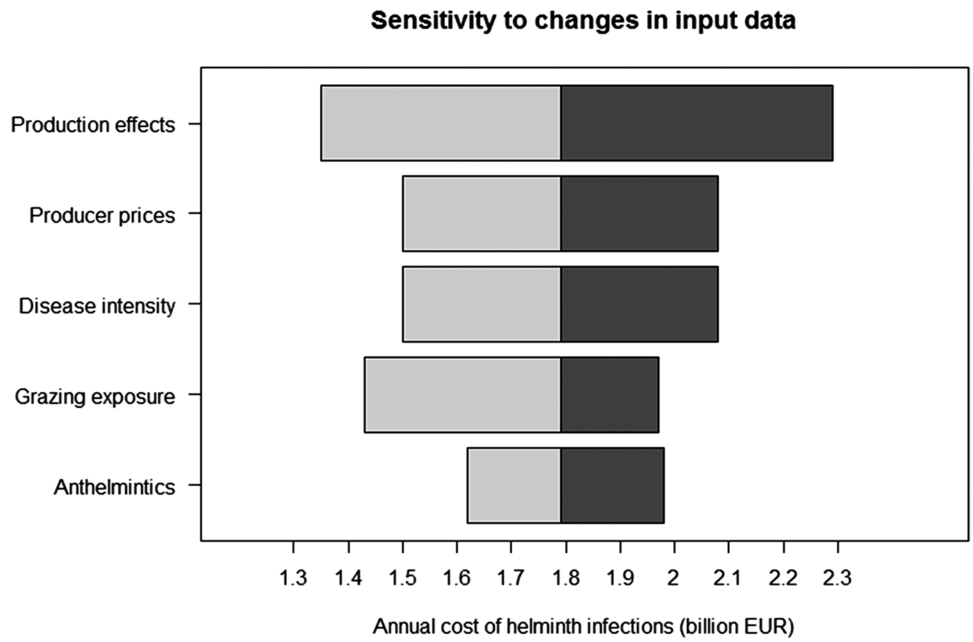

Fig. 4. Sensitivity of the total estimated cost of helminth infections in 18 COMBAR countries to changes in the input parameters. Light gray: Input parameters decreased with 20 %. Dark gray: input parameters increased with 20 %.

research budgets are certainly not complete. Despite the research project database of the European Animal Health & Welfare CWG and the STAR-IDAZ IRC (STAR-IDAZ, 2019), a comprehensive database where all publicly funded animal health research projects are listed, remains elusive. Nevertheless, given the wide range of contributors providing input to this data collection and their insight into their respective national ruminant parasite research field, it provides a first indication of the research investments in this field. Finally, although there are numerous surveys to demonstrate the presence of AR, very few studies provide a useful quantitative estimate on the prevalence of AR (Rose et al., 2015). Even fewer studies are available to assess the effect of using drugs with incomplete efficacy on production parameters (Candy et al., 2018).

4.2. Methodological limitations

Besides data gaps and uncertainty, our study also has methodological limitations. The use of expert opinion took advantage of the COST Action COMBAR network and was necessary to (i) cover data gaps and to interpret locally available data which are often only obtained in specific regions within a country, and (ii) to use local data to inform national level estimates. Inevitably, this will have introduced bias into the estimations. Other limitations include the use of fixed parameters across countries where country-specific data were difficult to obtain (e.g. some price indices and a fixed method to estimate the number of replacement heifers from the adult number of dairy cows). However, country-specific prices were used for the main factors driving helminth economic cost models (i.e. milk price and carcass value) and using a fixed approximation of number of dairy young stock is justified given similar replacement rates in differing dairy production systems from West- and Eastern-Europe. Our approach to evaluate data variability and uncertainty (i.e. de- and increasing the input data by a fixed proportion) is arbitrary and may be replaced by a Monte Carlo simulation approach (e.g. Li et al., 2019). For comparison, a previous cost assessment using Monte Carlo simulation in Switzerland resulted in a relative wider uncertainty interval (upper limit being 1.8 times the median value vs. 1.5 times in our study; Schweizer et al., 2005). However, we argue that variations of 20 % on the data provided by expert opinion are realistic and sufficient to demonstrate the considerable impact of data uncertainty. Finally, it is not always possible to avoid with certainty double counting of costs. For instance, costs of a prolonged calving interval include costs of a resulting lower milk production and these could be already included in the direct association between infection and milk production. On the other hand, direct milk yield responses in the order of magnitude modelled here have been frequently observed following anthelmintic treatment, independent of effects on fertility (Charlier et al., 2014). All of the above issues should be considered in future improvements of the model.

4.3. Study outcomes and comparison to previous studies

Comparing our study results between countries yields a number of remarkable findings. For instance, compared to Ireland, Germany has approximately half of the predicted losses in dairy cattle while the size of the dairy population is nearly three times as large. However, these differences are explained by the much lower exposure to grazing in Germany than in Ireland (0.30 vs. 0.95) and the lower infection levels (e.g. 0.34 vs. 0.49 for the proportion of production limiting GIN infections in Germany and Ireland, respectively). The large cost of AR in Ireland compared to countries with a larger livestock population may also be surprising. A first explanatory factor is our modelling approach. We estimated the cost of AR by disaggregating its cost from the overall cost of GIN infection. Consequently, the cost of AR will be related to the size of the overall cost. A second factor is the estimates of AR prevalence used. These are based on the average between prevalence estimates from a systematic review (Rose Vineer et al., in prep.) and expert elicitation. The estimated prevalence of AR used for Ireland were 0.33 in sheep and 0.64 in cattle, among the highest prevalences of AR compared with other countries. Although these estimates take into account published studies (e.g. O'Shaugnessy et al., 2019), it should be born in mind that AR prevalence estimates in most countries are based on small scale, non-randomized surveys, which produce highly variable results. Therefore, we recommend consultation of the underlying data for interpretation of country-level data (provided in the Supplementary file). Moreover, this limitation emphasises the need for more representative surveys of AR in livestock at national level.

Mavrot (2016) previously estimated the annual cost of GIN infection in 30 European countries between at € 0.8–1.2 billion in dairy cattle and € 157–477 million in meat sheep, considerably higher than our estimates (€ 404 million and € 120 million, respectively). This is due to the higher number of countries included by Mavrot (2016), and also by the use of lower “production thresholds”. In dairy cattle, Mavrot (2016) applied herd level estimates of GIN infection levels and production impacts at the animal level, which will result in higher burden impacts (Charlier et al., 2010b). Also, our use of a higher production threshold (500 − 1,000 EPG) in sheep, may result in lower production impact estimates than in the study of Mavrot (2016), where a continuous relationship with weight gain for lambs with FEC > 40 EPG was modelled (Mavrot et al., 2015). Our estimates of the costs of GIN and *F. hepatica* infection in the Belgian dairy population (€ 19 million) are of the same order of magnitude as previous estimates for the Flemish dairy population only (Charlier et al., 2009). The Flemish dairy population represents 63 % of the Belgian dairy population and the lower estimates in the current study are largely due to the continuing trend towards lower exposure to grazing and thus helminth infection of dairy cattle, especially in Flanders. Our central estimates for the costs of GIN and *F. hepatica* in the German dairy population (€ 51 million) are also lower than those (€ 96 million) in a previous report by Fanke et al. (2017). However, Fanke et al. extrapolated the farm-level cost estimates from a convenience sample of 334 farms to the whole of Germany, and did not take into account pasture exposure. Moreover, their estimate falls within our “high estimate” boundary. Another point of comparison is the study of Bennett and IJpelaar (2005), where the costs of fasciolosis and dictyocaulosis in cattle in Great Britain were estimated at € 23 million and € 10 million, respectively. This is considerably lower than our estimates for the UK (€ 111 million for liver fluke and € 16 million for lungworm infection). Although the full calculation method in the study of Bennett and IJpelaar (2005) is no longer accessible, we hypothesize the differences are due to (i) a stronger simplification in their model because it was applied across highly different diseases and animal species as well as (ii) the improved availability since then of epidemiological data (McCann et al., 2010; McCarthy, 2018) and production impact studies (e.g. Mazeri et al., 2017; May et al., 2018). In contrast, for sheep, our cost estimate for the UK is around half that of Nieuwhof and Bishop (2005) for Great Britain. Fuller comparison of methodologies is warranted, and in the meantime the current model provides a conservative overall estimate and a basis for further refinement. We note that previous published estimates often report their methods with insufficient detail to allow full replication, a limitation we aim to overcome in the current study.

Given that anthelmintic resistance is considered a greater problem in small ruminants than in cattle, it may be surprising that the costs of AR were considerably bigger in the latter species. However, this is mainly driven by the larger economic output value of the cattle sector. Moreover, there is overlap in the uncertainty intervals of the estimates. It should also be considered that we only modelled ML resistance, while levels of BZ resistance in sheep are often much higher (Claerebout et al., 2020). On the other hand, recent AR surveys make clear that levels of resistance in cattle have escalated over the last decade (Kaplan, 2020).

4.4. Towards informed decision making

Our data can start to inform decision making on control programmes and research investments at national and European level. It can support the identification of sectors (dairy cattle, vs. beef vs. sheep vs. goats) as well as helminth species (GIN vs. liver fluke vs. lungworm) where the largest (economic) returns may be achieved. Next, we propose to integrate our approach into larger initiatives such as the Global Burden of Animal Diseases Programme (Rushton et al., 2018) in order to increase the geographical coverage of the estimates as well as to compare the costs of helminth infections with other enzootic, zoonotic and epizootic animal diseases. Below, we report selected studies on the costs of some of these diseases in European member states. The costs of mastitis in dairy cows in the Netherlands is estimated at € 410 million per year, half of which are composed of production losses and treatment costs and the other half of prevention costs (Hogeveen and van der Voort, 2017). Also in the Netherlands, the costs of bluetongue virus (BTV) (Velthuis et al., 2010) and Q-fever (van Asseldonk et al., 2013) outbreaks were estimated at € 101 million and € 61 million per year, respectively. In Germany, the costs of BTV and Bovine Spongiform Encephalopathy during multi-year disease episodes were estimated at € 33 and 182 million per year, respectively (Gethmann et al., 2015). In France, the costs of Schmallenberg virus were estimated at approximately € 33 per cow or ewe per year (Waret-Szkuta et al., 2017). In the UK, the losses to agriculture and the food chain of the Foot and Mouth Disease outbreak in 2001 were estimated at £ 3.1 billion (Thompson et al., 2002), while approximately £ 100 million is spent each year on control measures against bovine tuberculosis with arguably very limited public health benefits (Torgerson and Torgerson, 2010). We estimated the annual costs of helminth infections at € 105 million in the Netherlands, € 146 million in Germany and € 299 million in the UK. In France, we estimated the annual cost at € 66 per adult dairy cow, € 17 per slaughtered beef cow, € 23 per adult dairy sheep and € 14 per slaughtered lamb. These data suggest that the costs of enzootic infections such as mastitis or helminth infections which occur annually, are similar or higher than (i) epizootic diseases (i.e. BTV, Schmallenberg, FMD), the costs of which should be spread over multiple years because they only occur sporadically and (ii) zoonotic diseases, where the impact on public health of the implemented control measures at animal level may be relatively low. Traditionally, enzootic production diseases were seen as a farmer’s problem and there was little involvement of governments or processing industries. However, with increased attention on food security, animal welfare, prudent use of antimicrobials and environmental impact of livestock production, enzootic diseases are coming into renewed focus (Hogeveen and van der Voort, 2017). This regained interest does not yet seem to have reached the topic of helminth infections with currently only 0.016 % of the annual costs invested in visible research and innovation on the topic. Our data suggest that there is still ample room for improvement to reduce the cost of enzootic helminth infections to the ruminant livestock industry, while also delivering on broader societal goals.

5. Conclusion

We report a comprehensive attempt to assess the burden of common helminth infections to the European ruminant livestock industry. This provides a framework on which to build further as more data becomes available in the future. The combined annual cost of the three major helminth infections in 18 participating countries was estimated at € 1.8 billion. Extrapolating our assessment to the EU-28 ruminant livestock population yields an annual cost of € 2.1 billion or 2% of the ruminant livestock output value (EUROSTAT, 2018). Eighty-one percent of this cost was composed of costs due to lost production and 19 % was attributed to treatment costs. The cost of anthelmintic resistant GIN infections was estimated at € 38 million annually, while there were not enough data to estimate the costs of AR in *F. hepatica* or *D. viviparus*. We identified important data gaps in all phases of the calculations, leading to large uncertainties around the estimates. The declared current public investment in research on improved helminth control was 0.16 % of the annual costs. Comparing the burden of helminth infections with that of other epizootic and zoonotic animal diseases supports a higher level of public investment in research and control to both reduce the burden to the ruminant livestock industry while delivering on societal goals of food security, efficient animal production, animal welfare and prudent use of antimicrobials.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.prevetmed.2020.105103.

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