Veterinary Parasitology 315 (2023) 109864

Contents lists available at ScienceDirect

Veterinary Parasitology

journal homepage: www.elsevier.com/locate/vetpar

Reducing anthelmintic inputs in organic farming: Are small ruminant farmers integrating alternative strategies to control gastrointestinal nematodes?

Caroline Chylinski[a], Spiridoula Athanasiadou[a], Susann Thüer[b], Christian Grovermann[b], Simon Moakes[b], Hervé Hoste[c], Saulius Petkevicius[d], Cynthia Verwer[e], Jan Verkaik[f], Steffen Werne[b,*]

[a] Scotland's Rural College (SRUC), Roslin Institute Building, Easter Bush, EH25 9RG, United Kingdom
[b] Research Institute of Organic Agriculture FiBL, Ackerstrasse 113, 5070 Frick, Switzerland
[c] Université de Toulouse, UMR 1225 IHAP INRAE/ENVT, 31076 Toulouse, France
[d] Veterinary Academy, Lithuanian University of Health Sciences, Kaunas LT-47181, Lithuania
[e] Louis Bolk Institute, 3981 AJ Bunnik, the Netherlands
[f] Wageningen University & Research, AH 6700 Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Organic farming
Small ruminants
Gastrointestinal nematodes
Anthelmintic
Alternative control

ABSTRACT

To counter the global spread of anthelmintic resistance (AR), considerable efforts have been invested in the development and dissemination of sustainable alternatives to control gastrointestinal nematode (GIN) infections in small ruminants. The degree to which these have been accepted and integrated by farmers, particularly in organic systems, where the drive to reduce chemical inputs is arguably even more pressing, has been little studied. To identify whether more comprehensive actions are needed to support the uptake of alternative GIN controls amongst organic farmers, this study conducted a survey in five European countries on organic dairy goat and meat sheep farmers to gain insight into current GIN control strategies and farmer attitudes towards AR and alternative measures in these countries. The structured survey was disseminated in the five European countries Switzerland, France, Netherlands, Lithuania and United Kingdom, receiving a total of 425 responses, 106 from organic dairy goat farmers and 319 from organic meat sheep farmers. Regression analyses were carried out to identify factors impacting anthelmintic drenching on meat sheep production systems, whereas all data were analysed descriptively. Four key findings emerged: i) The frequency of anthelmintic treatments averaged less than two per animal a year in all production systems; ii) Overall, organic farmers seemed well informed on the availability of alternative GIN control methods, but fewer stated to put them into practice; iii) Targeted selective treatment (TST) strategies of anthelmintics appears to be not commonly incorporated by organic farmers; iv) Despite operating under national and EU organic regulations, each of the organic dairy goat (Switzerland, France and Netherlands) and meat sheep (Switzerland, Lithuania and United Kingdom) production systems developed distinct approaches for GIN control. To increase uptake of alternatives to GIN control and optimise anthelmintic use, initiatives that promote research dissemination, farmer participatory and knowledge transfer activities at national level would be desirable.

1. Introduction

Organic agriculture utilises a holistic and proactive management approach to enhance the health of a biosystem, encompassing soil, plant, animal and human health alike. One of the greatest challenges to the health of organic livestock is disease from gastrointestinal nematodes (GIN), particularly in the production of small ruminants (Escribano, 2016). Traditionally, conventional practices have relied on the use of anthelmintic drugs to treat GIN infections, yet the global spread of anthelmintic resistance (AR) has led to a precarious control situation across all productions systems. While organic principles aim to maintain high herd health with low usage of synthetic medicines, the use of

* Correspondence to: Department of Livestock Sciences, Research Institute of Organic Agriculture FiBL, Ackerstrasse 113, 5070 Frick, Switzerland.
E-mail address: steffen.werne@fibl.org (S. Werne).

https://doi.org/10.1016/j.vetpar.2022.109864
Received 17 May 2022; Received in revised form 15 December 2022; Accepted 17 December 2022
Available online 22 December 2022

synthetic medicines is authorised to prevent suffering in the animal (Council Regulation No 834/2007, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007R0834&from=EN). However, studies have noted that organically reared small ruminants continue to incur a greater prevalence and range of GIN infections compared to those in conventionally reared systems that are drenched at shorter intervals (Lindqvist et al., 2001; Keatinge, 2004; Silva et al., 2014).

To reduce the input of anthelmintics and slow the spread of AR, the scientific community has invested considerable efforts in the development and dissemination of sustainable GIN control alternatives. Although there are a number of reports on the GIN control practices used in conventional farming systems (Morgan and Coles, 2010, Morgan et al., 2012; McMahon et al., 2013; McArthur and Reinemeyer, 2014; Moore et al., 2016), the degree to which alternative GIN control practices have been accepted and integrated by European organic farmers of small ruminants has been little studied. A recent study into the parasite control strategies of EU organic cattle farmers in both dairy and beef production noted country specific variations in their approaches despite operating under the same organic principles (Takeuchi-Storm et al., 2019). Such findings carry important implications for identifying strengths and weaknesses in the dissemination of these alternatives and in optimising future knowledge transfer.

The aim of this research was to gain insight into the current GIN control strategies used by organic goat and sheep farmers in European countries, as well as farmer attitudes towards AR and alternative measures, with the intent of identifying whether more comprehensive actions are needed to support the uptake of alternative GIN controls amongst organic farmers.

2. Materials and methods

2.1. Structured questionnaires

As part of the CORE Organic Plus project "PrOPara" (CORE Organic is the acronym for "Coordination of European Transnational Research in Organic Food and Farming Systems https://projects.au.dk/coreorganicplus/research-projects/propara), a structured questionnaire was developed to collect cross-sectional data on organic dairy goat farming in CH: Switzerland, FR: France and NL: Netherlands and organic meat sheep farming in CH: Switzerland, LT: Lithuania and UK: United Kingdom. The questionnaire included farm characteristics, the use of information sources to stay updated on the parasite challenge, indicators to monitor GIN infection on farm, anthelmintic treatment strategies and the presence of AR, grazing and pasture management routines, the use of alternative GIN control measures, farmer attitudes to six statements on the future of GIN control (measured on a 5-point Likert response scale, from strongly agree to strongly disagree) (Supplementary material 1). The questionnaire was first developed in English, then translated into the local language by the respective partners. No backtranslation to English took place to check for possible translation bias. Farmers completed the questionnaire either as a remote survey or via phone interview.

2.2. Selection of the farms and survey/interview forms

The surveys and interviews were conducted in 2015–2016. Each country developed their own selection criteria to survey the most representative study populations according to local differences in the average flock size and total number of organic farms among the participating countries. Each partner in this project had their own network, experience, and funds for conducting the surveys, and the most appropriate dissemination strategy was agreed for each country (Table 1). Differences in the country specific sampling approaches and sample size were managed statistically using sampling weights and clustered standard errors.

Table 1
Questionnaire dissemination strategy for the six small ruminant production systems.

Country	Questionnaire format	ID of target farms
Swiss dairy goat farmers	Phone	A list of organic dairy goat farmers with a minimum of 20 producing animals was obtained from Bio Suisse (the Swiss organic farming association). Farms were categorised based on size (small, medium, large) and randomly selected for questionnaire. Approx. 50% of total organic dairy goat farms were covered.
French dairy goat farmers	Phone	11 farms mainly located in the Departement Drôme were contacted by phone. The farms belonged to a research network of FiBL France.
Dutch dairy goat farmers	Hard copy	Registered organic dairy goat farmers were invited to complete the survey at the yearly organic meeting and at farm visits. The farms were of varying sizes. Approximately 30% of organic dairy goat farms were covered.
Swiss meat sheep farmers	Phone	A list of organic meat sheep farmers with a minimum of 20 productive animals was obtained from Bio Suisse. Farms were categorised based on size (small, medium, large) and randomly selected for questionnaire. Approx. 10% of total farms were covered.
Lithuanian meat sheep farmers	Phone	A list of organic meat sheep farmers with a minimum of 20 productive animals was obtained from EkoAgros Lithuania (Certification of agricultural and food products). Farms were categorised based on size and randomly selected for questionnaire. Approx. 10% of total farms were covered.
United Kindom meat sheep farmers	Hard copy	A comprehensive list of organic small ruminant farmers was obtained from DEFRA (Department for Environment Food & Rural Affairs). All farmers (1304) were contacted by post. Approx. 17% responded.

2.3. Statistical analyses

As only 106 responses from goat farmers were received, the regression analysis was only performed on the sheep and lamb dataset. The results of the questionnaires are presented as untransformed descriptive summaries in the first part of the results; additional analyses are described below.

2.3.1. Determinants of anthelmintic drench frequency in sheep systems

To analyse the effects of farm characteristics and management on the use of anthelmintics, explanatory variables were included in a Poisson regression model (see below for justification). Collinearity was tested based on the variance inflation factor, which was found to be below two for all variables. Based on previous evidence and our expert knowledge on possible risk factors, the following variables grouped into five categories, were hypothesised to have a relationship with drenching frequency in sheep and lamb data:

(1) ***General farm characteristics***: Years under organic farming, farm size, permanent pasture size, farmer attitude index (based on 5-point Likert response to six statements).
(2) ***Risk management***: grazing duration (12 or 24 h), transhumance (seasonal movement of animals from summer to winter pastures or higher and lower altitudes), reduced stocking rate, alternate grazing, use of low-risk areas (e.g. pastures with low numbers of infectious larvae), minimal grazing (ingestion of dry matter primarily takes place indoors and grazing is reduced to low levels

compliant with regulations to avoid exposure to larval transmission stages on pasture).

(3) ***Information sources for parasite control***: Print media, veterinary services, other advisory services, own experience.
(4) ***Monitoring methods***: Faecal samples, diarrhoea, wool/hair quality, weight loss, anaemia
(5) ***Alternative control methods***: Feeding bioactive plants, protein supplements, resistant breeds, culling vulnerable animals, partial/individual drenching, homoeopathy, phytotherapy.

Homeopathy is defined as 'a popular, although highly debated, medicinal practice based on the administration of remedies in which active substances are so diluted that no detectable trace of them remains in the final product' (Donelli and Antonelli, 2021). Phototherapy is defined as the therapeutic use of plants or plant extracts (Teuscher et al., 2012).

Cross country-data were gathered on the determinants of nematode control in small ruminants in this list and regression models were estimated for meat sheep and lamb drenching. With the number of drenches as dependent variable, a count data model was chosen. As the obtained data had only few observations with no application of drenching, standard Poisson regression was considered the most suitable for the analysis.

Although data heterogeneity was quite well covered in UK, questionnaire responses resulted in oversampling in CH and LT (more observations compared to true population of farms compared to the UK) and a relatively small sample number for France. Since the responses per country received were not directly indicative of the total number of sheep or goat farmers per country, sampling weights were applied to the data used in the regression analysis, to minimise any disproportionate bias of the smaller and compared to UK rather oversampled countries. The inverse probability of a farmer response in a given country was used to address these shortcomings inherent in the sampling approach and more adequately reflect the importance of individual sampling units (Scheaffer et al., 2012). The weights were calculated by dividing the number of responses per country with the number of sheep farms in that country and then inverting the value. In addition to weights, clustered standard errors were used to obtain less biased results. It was assumed that observations were independent across clusters (countries), but not necessarily within clusters. Organic farmers within countries should follow similar regulations and share similar values.

2.3.2. Farmer's attitudes on the future of GIN control

As listed above, an index of farmers' personal attitudes on parasite control and resistance was used as an explanatory variable in the regression analysis. This was important to capture personality traits. Principal component analysis (PCA) is commonly applied as a technique for data reduction, decreasing the number of variables in an analysis by identifying one or more uncorrelated linear combinations of the variables that contain most of the variance. The attitude index was created through polychoric PCA due to its capacity to handle discrete variables on an ordinal scale (Kolenikov and Angeles, 2004). It included six attitude statements that were collected through the questionnaire. The statements included: a) AR will worsen in the future; b) to prevent further AR, farmers may have to accept reduced production due to less anthelmintic treatments; c) industry will develop improved treatments/vaccines before AR becomes a problem; d) I would accept alternative control methods that may incur greater costs e.g. monitoring, products or new equipment; e) I would accept alternative control methods that may incur greater on farm labour input e.g. sample collection, animal monitoring; f) If AR becomes a serious problem, exemption from the organic regulation is needed to keep the animals permanently indoors.

3. Results

3.1. Questionnaire responses

A total of 425 responses were obtained for the questionnaire (Table 2). Of these, 106 responses were from organic dairy goat farmers and 319 from organic meat sheep farmers. The number of farms involved in the study varied between countries, from 21 (FR) to 226 (UK). Responses from the UK accounted for more than half of the total responses in the study (53%). Of the 11 questions, one had many missing values and was therefore not analysed.

The dairy goat and meat sheep production systems with the fewest mean number of stock were both in CH (Table 2). The largest herd of dairy goats on average was in the NL, which had 7- and 11-fold more stock than FR and CH respectively. Amongst meat sheep farmers, the UK had the highest mean number of livestock per farm, 2-fold and 5-fold more than LT and CH respectively. The "average time since organic conversion" ranged from 11 to 16 years across the production systems.

3.2. Information sources and monitoring GIN on farm

To stay updated on the challenge of parasites, each of the six production systems used the information sources available to varying degrees (Fig. 1). For example, CH dairy goat and meat sheep farmers preferred to use print media, FR dairy goat farmers relied mostly on veterinarians and health advisors to obtain information on the current parasite threat, NL dairy goat farmers and LT meat sheep farmers relied on their own experience and print media, and UK meat sheep farmers used veterinarians as their main source of information. Other information sources mentioned by farmers were SCOPS (Sustainable Control of Parasites in Sheep, https://www.scops.org.uk/), further education (conferences/courses), Internet, other farmers and institutions such as University of Toulouse, Moredun Research Institute or Research Institute of Organic Agriculture (FiBL).

The use of indicators to monitor GIN infection on farm was variable in each of the six production systems (Fig. 2). Overall, FEC and loss of yield were used the most, diarrhoea was more commonly used as an indicator by meat sheep farmers and wool/hair quality was used more commonly by dairy goat farmers; anaemia was rarely included as a preferred indicator. CH dairy goat farmers showed a preference for using faecal egg count (FEC) and wool/hair quality, FR dairy goat farmers preferred wool/hair quality, NL dairy goats preferred FEC as an indicator, CH and LT meat sheep farmers primarily used loss of yield and diarrhoea, UK meat sheep farmers used FEC, loss of yield and diarrhoea as the main indicators for GIN infection. Other indicators mentioned by farmers were bottle jaw, changed animal behaviour, loss of appetite and

Table 2
Questionnaire responses per country as a proportion of total and farm characteristics in six organic small ruminant production systems (CH = Switzerland, FR = France, NL = Netherlands, LT = Lithuania and UK = United Kindom).

Production system	No. of farms	Proportion (%) total responses	Mean no. stock per farm (min-max)	Mean farm area (ha) (min-max)	Mean no. years since conversion (min-max)
CH dairy goat	58	14	53 (20–150)	20 (5–48)	16 (2–46)
FR dairy goat	21	5	80 (30–200)	52 (9–110)	11 (2–20)
NL dairy goat	27	6	590 (90–1750)	47 (1.5–490)	16 (0.25–40)
CH meat sheep	52	12	73 (20–460)	20 (4–58)	16 (1–40)
LT meat sheep	41	10	161 (20–1139)	35 (5–288)	11 (4–16)
UK meat sheep	226	53	372 (3–2500)	264 (3–3900)	15 (1–50)

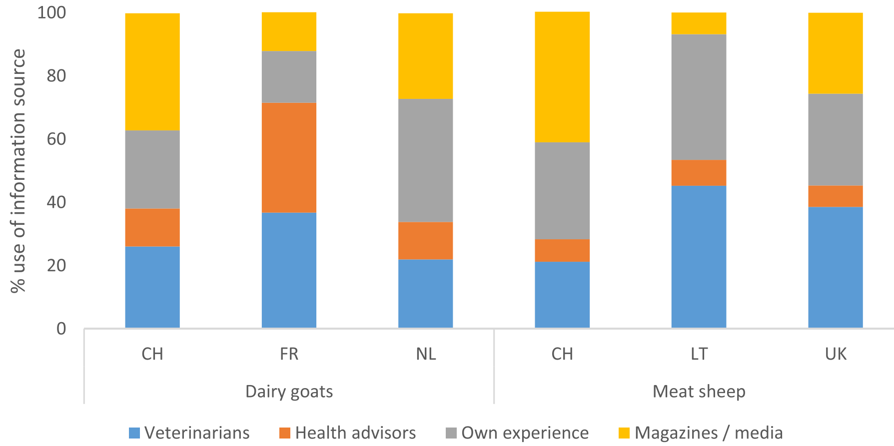

Fig. 1. Information sources used to by farmers to stay updated on the parasite challenge in organic 745 dairy goat (Switzerland = CH, France = FR, Netherlands = NL) and meat sheep (CH, Lithuania = LT, United Kingdom = UK) systems, including: veterinarians (blue), health 746 advisors (orange), farmers own experience (grey), magazines/media (yellow).

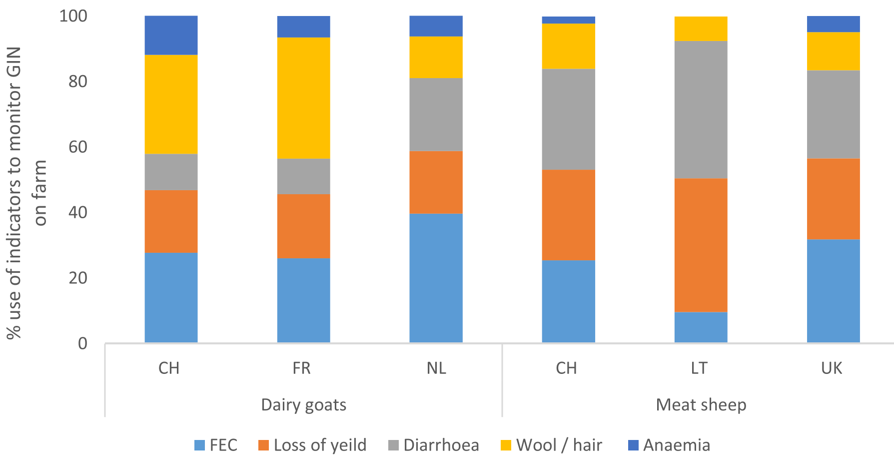

Fig. 2. Indicators used by farmers on organic dairy goat (Switzerland = CH, France = FR, Netherlands = NL) and meat sheep (CH, Lithuania = LT, United Kingdom = UK) systems monitor gastrointestinal nematodes (GIN) on farm. The questionnaire allowed farmers to mark up to three indicators, data reflects the percent each indicator was mentioned. Indicators included FEC (faecal egg counts) (light blue), loss of production yield (orange), diarrhoea (grey), wool/hair quality (yellow), anaemia (dark blue).

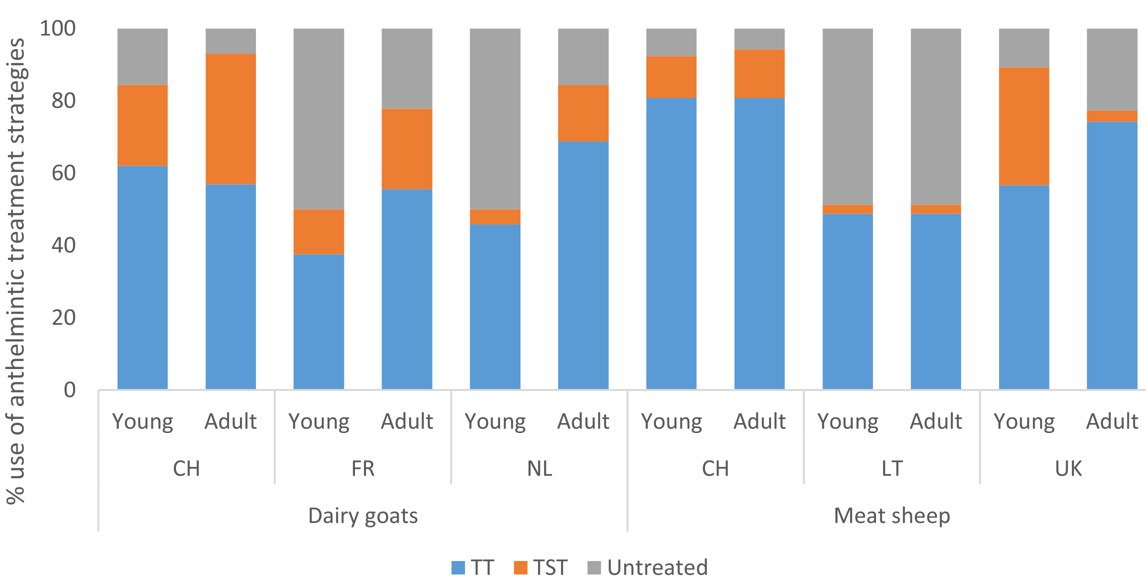

Fig. 3. Anthelmintic treatment strategies used by farmers in organic dairy goat (Switzerland = CH, France = FR, Netherlands = NL) and meat sheep (CH, Lithuania = LT, United Kingdom = UK) systems to treat young and adult stock. Strategies included TT (Targeted Treatment to groups of stock) (blue), TST (Targeted Selective Treatment to individual stock) (orange) and leaving stock untreated (grey).

tapeworm segments in faeces.

3.3. Anthelmintic resistance and treatment strategies

Farmers stated cases of confirmed anthelmintic resistance in all production systems. The highest percentage of farmers stating that anthelmintic resistance occurs on their farms was in UK meat sheep (24%), followed by FR dairy goats (18%), CH dairy goats (16%), NL dairy goats (11%), CH meat sheep (10%) and LT meat sheep (7%).

Farmers in all production systems preferred to use a Targeted treatment (TT) rather than a Targeted selective treatment (TST) (Fig. 3). Targeted treatment (TT) is the treatment of groups of animals during periods of high worm abundance levels. Targeted selective treatment (TST) is the administration of anthelmintics on an individual basis based on the diagnosis of the disease. In dairy goat systems in CH, FR and NL, farmers used TST more frequently in adult stock. The UK was the only meat sheep system to make notable use of TST and applied it 10-fold more frequently in young stock than adult stock. The proportion of farmers who left their meat sheep undrenched varied from 6% (CH) to 22% (UK), except for LT-farmers, who left 49% of the adult sheep as well as lambs untreated. CH and UK-farmers left 8% and 11% of their lambs untreated, respectively. The proportion of dairy goat farms that abstained from anthelmintic treatment ranged from 7% (CH), to 16 (NL) and 22% (FR).

The six production systems varied in the mean frequency of anthelmintic treatments. Overall, the frequency of anthelmintic treatment across all farms averaged less than two drenches per animal per year (Table 3). Individual farms in each of the countries surveyed reported to not using any anthelmintics, however, there was greater variation in the maximum number of anthelmintic treatments applied. Of note, the maximum number of treatments reached 4.5 for young dairy goats in CH, and up to 7.5 treatments for young meat sheep in the UK. Yet, the average anthelmintic treatment frequency was similar between age classes for all production systems.

3.4. Grazing and pasture management

Most farmers in the meat sheep production systems ($\geq$ 95%) grazed their young and adult stock for 12 – 24 h (Fig. 4). Grazing duration varied across the dairy goat systems; CH was split between using 1 – 12 and 12 – 24 h grazing for both age classes, NL limited stock grazing to 1 – 12 h for both age classes, FR grazed adult stock for 1 – 12 h but young stock was split between 1 and 12 h grazing and housed indoors.

Overall, the farmers in each of the six production systems had a high level of awareness (>81%) of the different grazing management practices specified in the questionnaire (Fig. 5a-d), although there were notable exceptions: 68% of LT meat sheep farmers had never heard of alternate species grazing (Fig. 5b), 35% of FR dairy goat farmers had never heard of grazing young stock in low risk areas (Fig. 5c), and 36% of LT meat sheep and 26% of FR dairy goat farmers had never heard of minimal grazing (Fig. 5d).

Across the six production systems, there was a consistency between the percentage of farmers that tried a grazing management practice and the percentage which continued to use it, although, this was considerably less than the percentage of farmers that had previously heard of the practice (Fig. 5a-d). The use of each grazing management practice varied between the production systems; most used across the six production systems was reduced stocking rate. The least used was minimal grazing; the exception was in the NL dairy goat system, where 72% of farmers routinely used this practice. Alternate grazing was used to varying degrees across the production systems; FR dairy goat and UK meat sheep used it notably more than any of the other systems. Grazing young stock in low-risk areas was also used variably by each of the systems; NL dairy goat and UK meat sheep used it notably more than any of the others.

3.5. Alternative GIN control measures

The six production systems varied in the degree to which they had heard of (14 – 100%), tried (0 – 98%) and used (0 – 69%) the different alternatives specified in the questionnaire (Fig. 6a-f). For each of the alternatives, the percentage of farmers which had heard of them was markedly higher than the percentage which had tried them. In general, the percent of farmers trying an alternative, and the percent which continued to use it were relatively consistent, although there were a few exceptions. The following alternatives incurred a notable drop in the percent of farmers continuing to use it after trial: culling susceptible stock (FR dairy goats) (Fig. 6b), bioactive forages (CH, FR, NL dairy goats, UK meat sheep) (Fig. 6d), homeopathy (CH, FR dairy goats, UK meat sheep) (Fig. 6e) and phytotherapy (FR dairy goats, UK meat sheep) (Fig. 6f).

Bioactive forages were used by each of the dairy goat systems (CH, FR, NL) to varying degrees, but only by UK meat sheep farmers (Fig. 6d). Elevated dietary protein was used by all the production systems, except dairy goats and meat sheep in CH (Fig. 6c). Culling of susceptible stock generally also had high use across all production systems, although FR dairy goat farmers used it relatively less than the others (Fig. 6b). The use of resistant breeds was variable cross the production systems, with the UK meat sheep farmers using them at least twice more than any other (Fig. 6a). Both homeopathy (Fig. 6e) and phytotherapy (Fig. 6f) were used more frequently by dairy goat than meat sheep farmers. The CH dairy goat farmers used it 3-fold more frequently than the CH meat sheep farmers.

Production system specific preferences for the use of alternatives were as follows: CH dairy goat farmers used culling of susceptible stock and phytotherapy the most, FR dairy goat farmers preferred elevated dietary protein and homeopathy, NL dairy goat farmers mixed elevated protein and culling of susceptible stock, CH meat sheep farmers primarily used culling of susceptible stock, LT meat sheep farmers incorporated elevated dietary protein and culling of susceptible stock, and UK meat sheep farmers used a combination of elevated dietary protein, use of resistant breeds and culling susceptible stock. Bioactive forages, homeopathy and phytotherapy were used more by dairy goat farmers than meat sheep farmers.

Table 3
Anthelmintic treatments per year in young and adult stock in six organic small ruminant production systems (CH = Switzerland, FR = France, NL = Netherlands, LT = Lithuania and UK = United Kindom).

Production system	Young stock					Adult stock				
	N	Mean	Median	Min	Max	N	Mean	Median	Min	Max
CH dairy goat	58	1.3	1	0	4.5	58	1.3	1.0	0	4
FR dairy goats	6	NA	0	0	3	20	1.4	1.5	0	2.5
NL dairy goats	27	1.5	0	0	2	22	1.3	1.0	0.5	2
CH meat sheep	52	1.6	2	0	6	52	1.5	1.3	0	5
LT meat sheep	41	0.9	1	0	3	41	0.8	1.0	0	2
UK meat sheep	166	1.7	1.5	0	7.5	186	1.2	1.0	0	5

N = number of farmers that responded to the question. NA, insufficient survey data to calculate representative mean.

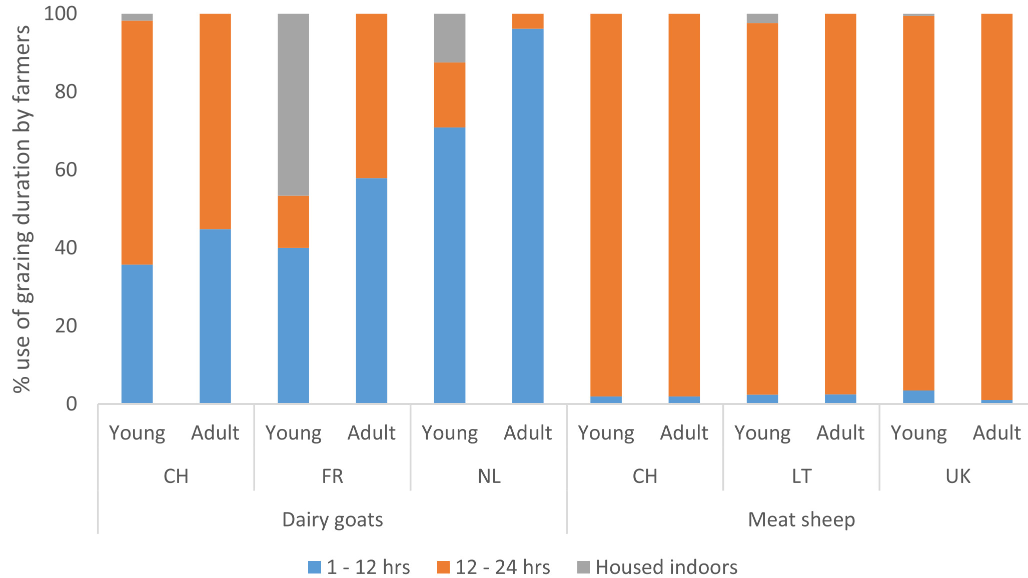

Fig. 4. Grazing durations used by farmers in organic dairy goat (Switzerland = CH, France = FR, Netherlands = NL) and meat sheep (CH, Lithuania = LT, United Kingdom = UK systems for young and adult stock, including 1 – 12 h on pasture (blue), 12 – 24 h on pasture (orange), or housed indoors (e.g. zero grazing) (grey).

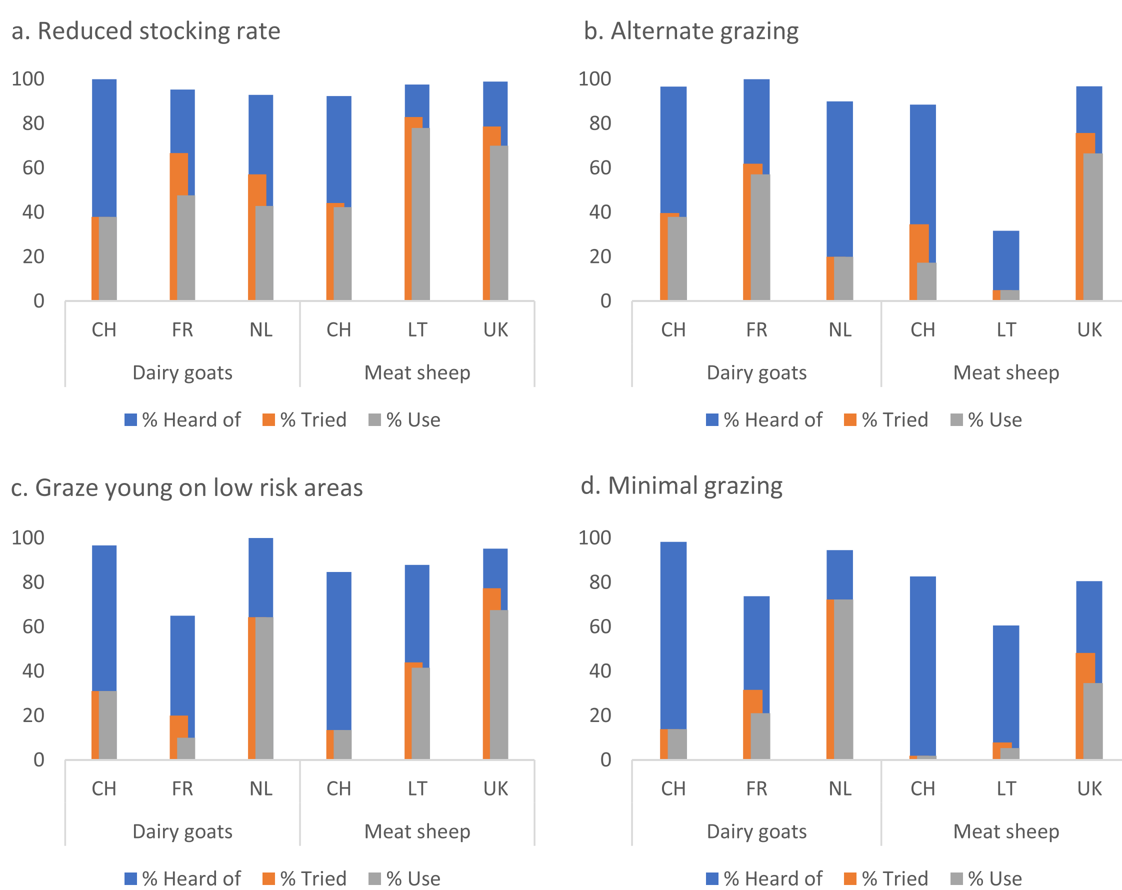

Fig. 5. Grazing management practices in organic dairy goat (Switzerland = CH, France = FR, Netherlands = NL) and meat sheep (CH, Lithuania = LT, United Kingdom = UK) systems. Data reflects the percentage of farmers in each system which had heard of (blue), tried (orange) and use (grey) each practice, including: a) reduced stocking rate, b) alternate species grazing, c) young stock graze low risk areas, d) minimal grazing.

3.6. Determinants of anthelmintic drench frequency in meat sheep and lambs

Of the 28 variables examined in the regression analysis, 12 determinants were identified to significantly impact the frequency of anthelmintic drenches in meat sheep and 14 in lambs (CH, LT, UK) (Table 4). Only 6 determinants were unidirectional in meat sheep and lambs. Using veterinary services, own experience and print media as information source were associated with significantly higher treatment frequencies per animal and year. Using diarrhoea as an indicator to

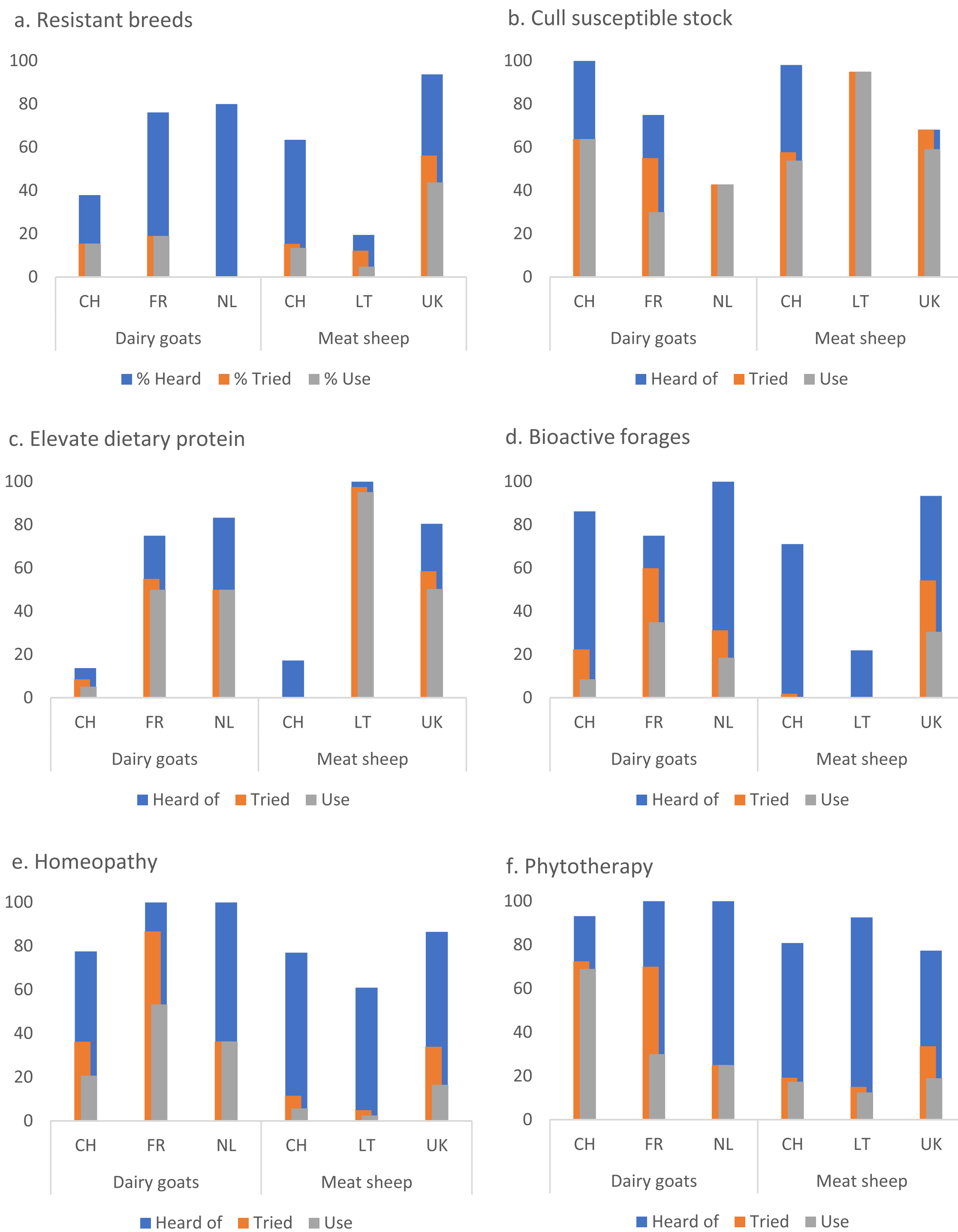

Fig. 6. Alternative gastrointestinal nematode (GIN) control practices in organic dairy goat (Switzerland = CH, France = FR, Netherlands = NL) and meat sheep (CH, Lithuania = LT, United Kingdom = UK) systems. Data reflects the percentage of farmers in each system which had heard of (blue), tried (orange) and use (grey) each alternative, including a) use of GIN resistant breeds, b) culling susceptible stock, c) elevated dietary protein supplementation, d) bioactive forages, e) homeopathy, f) phytotherapy.

monitor worms also seem to increase the number of treatments per animal. Drenching only a part of the flock as well as the use of low-risk areas were associated with a lower number of treatments per animal and year (Table 4).

3.7. Farmers attitudes on the future of GIN control

The farmer attitudes to six statements on GIN control are summarised in Fig. 7. Overall, there was a high level of agreement across all six production systems that AR would worsen in the future, although LT and NL expressed some uncertainty (Fig. 7a), and that farmers would accept alternative controls that had greater costs (Fig. 7d) or labour requirements (Fig. 7e). Opinion on accepting reduced production due to less anthelmintic treatments to minimise AR was varied across and within the systems (Fig. 7b), where CH dairy goat and CH and LT meat sheep farmers agreed with the statement, FR and NL dairy goat farmers and UK meat sheep farmers expressed uncertainty, with a high proportion of NL and FR dairy goat farmers also disagreeing with it. If AR

Table 4
Determinants impacting frequency of anthelmintic treatments in meat sheep production systems.

Determinants (units)	*Sheep*			*Lambs*		
	IRR	*RSE*	*Sig.*	*IRR*	*RSE*	*Sig.*
General characteristics						
Organic (years)	0.991	0.003	***	0.992	0.012	
Farm size (ha)	0.961	0.038		0.970	0.046	
Permanent pasture (ha)	0.999	0.000	**	1.000	0.000	
Pers. attitude (index)	0.748	0.173		0.640	0.118	**
Livestock management						
Grazing up to 12 h (1 =yes)	0.726	0.181		3.452	1.245	***
Grazing up to 24 h (1 =yes)	1.746	0.431	**	1.333	0.243	
Transhumance (1 =yes)	0.926	0.069		0.901	0.092	
Reduced stocking rate (1 =yes)	1.007	0.098		0.763	0.092	**
Alternate grazing (1 =yes)	1.076	0.092		1.246	0.045	***
Use low risk areas (1 =yes)	0.851	0.016	***	0.946	0.019	***
Minimal grazing (1 =yes)	1.089	0.046	**	0.915	0.020	***
Information sources						
Magazines (1 =yes)	1.257	0.090	***	1.243	0.110	**
Veterinary services (1 =yes)	1.310	0.047	***	1.379	0.214	**
Other advisory services (1 =yes)	0.918	0.084		0.911	0.072	
Own experience (1 =yes)	1.223	0.095	***	1.276	0.114	***
Monitoring methods						
Faecal samples (1 =yes)	0.986	0.096		1.122	0.175	
Diarrhoea (1 =yes)	1.087	0.017	***	1.245	0.060	***
Fur quality (1 =poor)	1.013	0.028		1.122	0.113	
Weight loss (1 =yes)	0.790	0.028	***	0.971	0.051	
Anaemia (1 =yes)	0.945	0.051		0.806	0.185	
Alternative control methods						
Bioactive plants as feed (1 =yes)	1.116	0.060	**	1.025	0.024	
Increased protein sup. (1 =yes)	0.821	0.171		0.841	0.168	
Resistant breeds (1 =yes)	0.883	0.058		0.835	0.025	***
Vuln. animals culled (1 =yes)	1.119	0.067		1.061	0.026	**
Partial drenching (1 =yes)	0.846	0.063	**	0.843	0.046	***
Individual drenching (1 =yes)	1.007	0.144		0.873	0.114	
Homoeopathy (1 =yes)	0.941	0.104		1.391	0.739	
Phytotherapy (1 =yes)	0.794	0.182		0.817	0.075	**
Constant	1.029	0.193		1.287	0.676	
Observations (n)	234			223		
Log pseudolikelihood	3340			3624		

Note: Significance (Sig.) levels are ***$p < 0.01$ and **$p < 0.05$. Coefficients are shown as incidence rate ratios (IRR).
The variability is shown as robust standard error (RSE).

became a serious problem, farmers across the production systems differed in their attitudes towards seeking exemption to house stock indoors (Fig. 7e). The FR dairy goat farmers showed a high level of agreement for this, and to a lesser degree, NL dairy goat and LT meat sheep farmers agreed. A proportion of the LT meat sheep farmers also expressed uncertainty at the prospect whereas the other production systems predominantly disagreed. Farmer opinion on the prospect of industry developing improved treatments or vaccines before AR became a problem was also very divided (Fig. 7c). The only polarised response was with LT meat sheep farmers who were largely uncertain. Attitudes within the other production systems were otherwise very variable. The attitude index was created by principal component analysis and transformed by z-score ranging from zero to one with a mean of 0.585 and a standard deviation of 0.201.

4. Discussion

The aim of this research was to gain insight into the current GIN control practices used by organic farmers of small ruminants in five European countries, their attitudes towards AR and alternative sustainable control methods and identify determinants of anthelmintic drenching frequency. Four key findings emerged from our survey: i) The frequency of anthelmintic treatments was stated to be lower than 2 per animal per year in all production systems; ii) Overall, organic farmers appear to be well informed on the availability of alternative GIN control methods, but not many practiced them; iii) TST is not commonly incorporated by organic farmers; iv) Despite operating under national and EU organic regulations, each of the organic dairy goat (CH, FR, NL) and meat sheep (CH, LT, UK) production systems developed distinct approaches for GIN control.

Anthelmintic resistance is one of the greatest limitations to effective GIN control in small ruminant production systems worldwide. The regulated use of anthelmintics in the organic farming system, compared with their unmitigated use in conventional production, should serve to reduce the selection pressure on the spread of AR. Although all six of the organic production systems surveyed reported confirmed AR on farm, ranging from 7% in LT to 24% in the UK, this contrasts sharply with reports of AR in conventional farming systems in New Zealand (Waghorn et al., 2006), Australia (Playford et al., 2014) and in the UK (Mitchell et al., 2006; Bartley, 2008; McMahon et al., 2013), which range from 64% to 96% (reviewed by Muchiut et al., 2018). Concerning Europe, Ploeger and Everts (2018) reported also widespread anthelmintic resistance with ivermectin resistance found in 78% and moxidectin resistance found in 47% of observed herds. However, no information was given about the type of production (organic/conventional). From a survey including Faecal egg count reduction tests in Belgium, resistance against benzimidazoles in all eight evaluated farms and resistance against macrozyclic lactones in 7 out of 20 evaluated farms (Claerebout et al., 2020) have been revealed, but also no information on production type was mentioned. Halvarsson et al. (2022) found no differences in the general use of anthelmintics between Swedish conventional and organic sheep farmers. However, the proportion of farmers applying routine drenching was four time higher in conventional compared to organic producers. It is important to note that there is currently no obligation under organic regulations for farmers to monitor AR on farm and the prevalence of AR reported by the farmers in the present study may be underestimated. On the other hand, the possibility that AR prevalence may be over-estimated cannot be excluded, as confounding factors may impact FECRT and no details are available on how the tests were performed (Morgan et al., 2022).

In production systems that reported a higher prevalence of AR, the main source of information farmers used to stay updated on the parasite challenge was from veterinarians. Results from the regression analyses further indicate that the reliance on veterinarians may be associated with increased drench frequency. The relative cause and effect of this relationship on AR requires further investigation as the data are open to contradictory interpretations. On one hand, the increased interaction with veterinarians could increase farmer accessibility to anthelmintics, their relative inputs and consequent pressure on AR. On the other, regular contact with the veterinarians may facilitate AR testing and thereby the number of confirmed AR cases may appear to be higher in such farms. Small ruminant production may be less economically significant compared to other production systems in some countries, such as CH, NL, FR and LT, and may represent only a small part of a veterinarian's clientele. As such, there is a risk that veterinarians may not be adequately informed of the problems with anthelmintic resistance and management practices to slow down resistance development specific to

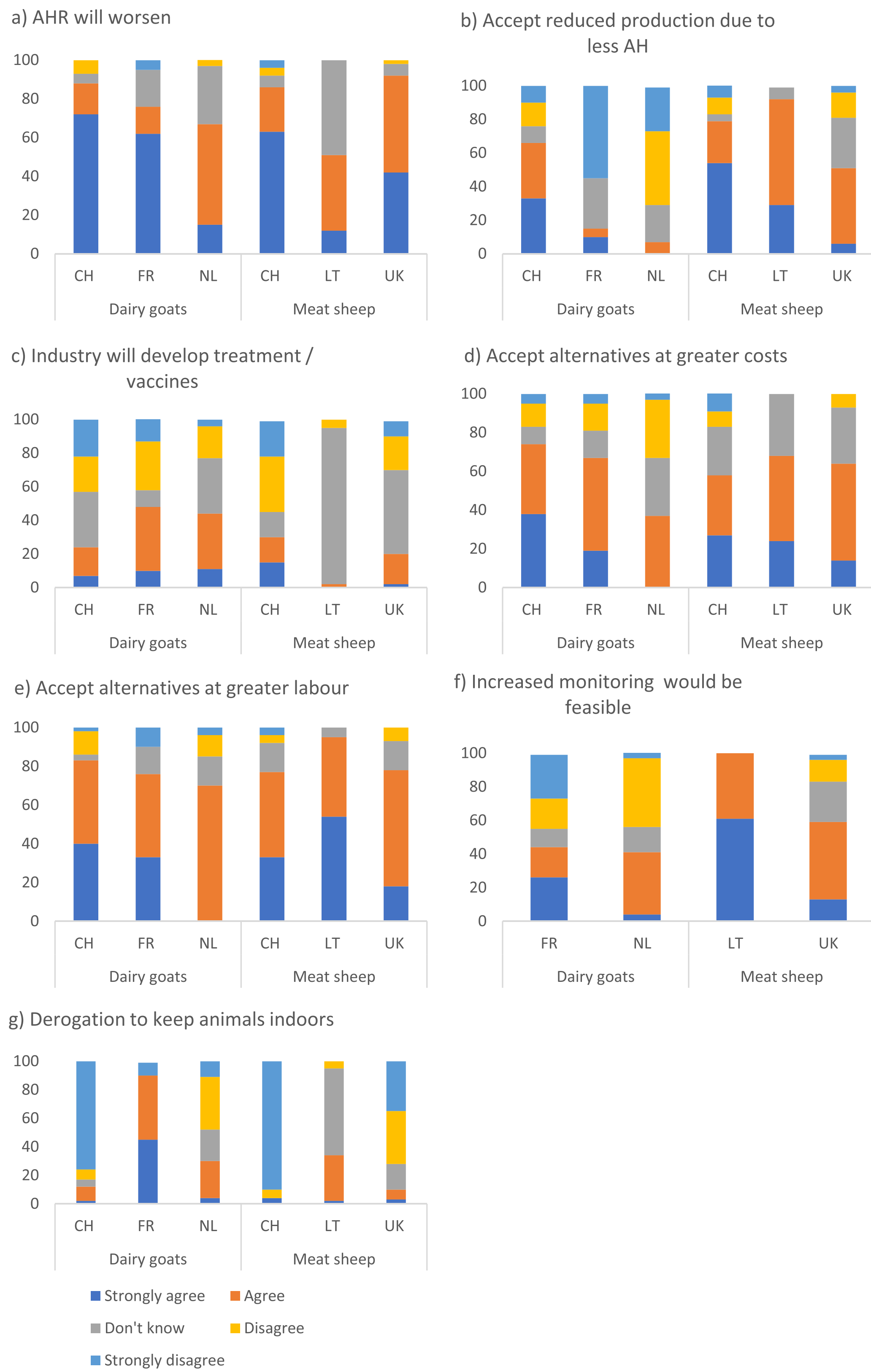

Fig. 7. Farmer attitudes on the future of gastrointestinal nematode (GIN) control in organic dairy goat (Switzerland = CH, France = FR, Netherlands = NL) and meat sheep (CH, France = FR, Netherlands = NL) systems. Data reflects farmer responses to seven statements measured on a 5-point Likert scale, from strongly agree (dark blue), agree (orange), don't know (grey), disagree (yellow), strongly disagree (light blue). The statements included: a) AR will worsen in the future, b) to prevent further AR, farmers may have to accept reduced production due to less anthelmintic treatments, c) industry will develop improved treatments/vaccines before AR becomes a problem, d) I would accept alternative control methods that may incur greater costs e.g. monitoring, products or new equipment, e) I would accept alternative control methods that may incur greater on farm labour input e.g. sample collection, animal monitoring, f) Increased focus on monitoring and treating individual animals is a feasible worm control strategy, g) If AR becomes a serious problem, derogation is needed to keep the animals permanently indoors.

small ruminants. This might be indicated by the significantly increased number of treatments per animal and year in all three analysed livestock categories.

Veterinary parasitologists have placed considerable emphasis on the benefits of incorporating drenching strategies which reduce the input of anthelmintics, and consequent pressure on AR, either by TT of groups of animals during periods of high worm abundance levels using diagnostic information, or preferably by TST which lowers anthelmintic inputs even further by drenching stock on an individual basis (Kenyon et al., 2017). In the present study however, TST was not commonly used, and preference instead was given to a TT approach across all production systems. While TT may reduce the anthelmintic drench frequency compared to mass treatment of the whole flock, groups of animals are still drenched concurrently which may give rise to bottlenecks in the GIN population and result in selection for AR (Kenyon et al., 2017). Improving the uptake of TST is widely considered to have the potential to reduce drench frequency even further than TT, while counter-selecting for AR and without any negative effects on productivity (Kenyon et al., 2013; Busin et al., 2014). This is the first known study to report on the low uptake of TST amongst organic farmers, although similar findings have been documented for conventional farming systems (Cabaret et al., 2009; Kenyon et al., 2017; Vande Velde et al., 2018). The increased time and resources needed to assess stock on an individual basis has been sighted as potential hinderance to uptake (Cabaret et al., 2009), especially given the appropriate diagnostic indicators and treatment thresholds of TST must be adapted to local farm conditions (Höglund et al., 2013; Chylinski et al., 2015; Merlin et al., 2016). Indeed, the opinion of the organic farmers in the present study was divided when asked if increased monitoring and treating of individual animals was a feasible worm control strategy. On the other hand, our data suggest that farmers already make use of indicators (Fig. 2) to monitor GIN infections on farm, such as loss of performance and to a much lesser extent of anaemia, but it is not clear if these are used to inform drenching decisions directly. These finding are in support of a recent survey (Chylinski et al., 2021) where organic UK farmers identified the same monitoring GIN infection tools and used them to inform their drenching decisions. The beforementioned indicators have shown to be useful parameters in identifying animals in need of treatment (Kenyon et al., 2013; Notter et al., 2017). Given the majority of the farmers stated that they would accept greater labour input that might come with an alternative control option (Fig. 7e), drenching decisions associated with animal performance or FAMACHA (FAffa MAlan CHArt) in regions where the haematophagous GIN *Haemonchus contortus* is endemic might be accepted by a major part of the farmers. Although not surveyed here, random treatment may offer an alternative solution to circumvent the monitoring requirements of TST, where studies have demonstrated drenching 20% of the stock at random can achieve similar levels of worm control as mass treatment while counter selecting from AR (Gaba et al., 2012).

The frequency of anthelmintics treatment for each of the production systems was lower than two drenches per animal, per year. Although a couple of organic farmers reached up to 5 drenches per animal in adult stock (CH and UK meat sheep) and even 7 in young stock (UK meat sheep) per year, the average number of drenches per year was much lower to that used in conventional farms. Amongst conventional farms, where anthelmintic use is unmitigated, the frequency of anthelmintic treatments is reportedly higher; in the UK for example, drenching in lambs can average 4 treatments per year (Learmount et al., 2016). A recent survey of organic inspectors reported similar findings in the frequency of anthelmintic treatment from across 16 European countries (Varga et al., 2022); a similar frequency of around 2 treatments per animal per year was recently reported by organic UK farmers (Chylinski et al., 2021).

Even though several variables were significantly associated with the drenching frequency, only six variables were common between sheep and lambs. Of these six, the following four variables were associated positively (increased drenching): using print media, veterinarians and own experience as information source and using diarrhoea as monitoring method. Only two variables indicate a negative association with the drenching frequency in adult sheep as well as in lambs: the use of low risk areas and TT. The increased drenching frequency associated with veterinarians may be explained by a better availability of anthelmintics. As diarrhoea is not specific to parasite infection, it may be misinterpret followed by unnecessary drenching after it was observed by the farmers. Other pasture management strategies, information sources, indicators to monitor infection and alternative GIN controls were significantly associated with anthelmintic treatment frequency in the sheep or lamb category. Unexpectedly, some of the drivers that are designed specifically to reduce GIN infections in stock (i.e. pasture management strategies) and/or the requirement for anthelmintics directly (i.e. TT, alternative controls) showed a positive association with treatment frequency. For example, one may expect lower treatment frequencies if animals are grazed for up to 12 h only compared to 24 h. This result has to be taken with care, as less than 3% of farmers of all three sheep systems stated that they do graze their sheep and lambs up to 12 h only, resulting in small numbers of observations in this category. The positive correlation of alternate or mixed grazing and increased drench frequency stands out in particular, as it is generally accepted that e.g. cograzing sheep and cattle usually reduced the exposure to parasites in sheep, resulting in lower nematode numbers and improved weight gain (d'Alexis et al., 2014; Jordan et al., 1988). As more than half of the UK sheep farmers and 17% of the CH sheep farmers stated that they include alternate grazing in their grazing management, the number of observations is sufficient. The question remains if the used proportion of the other livestock species and their integration in mixed grazing was sufficient to make an effect. Many other significant associations show expected direction of interaction. For example, the observed reduced drenching frequencies when applying management techniques such as reduced stocking rate, minimal grazing and use of low risk areas.

In addition to factors that drive frequency of treatment, key differences in the approach to GIN control were observed between the organic dairy goats and meat sheep production systems. Firstly, there was a clear distinction in the grazing duration; where meat sheep grazed almost exclusively for 12 – 24 h, grazing in the dairy goat systems was much more limited, particularly amongst young stock. Although organic regulations emphasise outdoor access for all livestock, limiting the grazing duration of young kids may by help protect them whilst their immune systems are still developing and their susceptibility to GIN infection is greater. While goats and sheep are infected by the same species of GIN, differences in anthelmintic metabolization, immunology and behaviour mean that goats are not only more susceptible to GIN infection than sheep, but that AR is also more prevalent in goats (Hoste et al., 2008; Jackson et al., 2012). Secondly, the approach to drenching varied more between the young and adult stock in dairy goats, whereas they were more similar across age classes in the meat sheep. This may reflect divergent priorities in the production outputs of each systems; where dairy goat production will likely prioritise GIN control in their milking does and their interest in offspring will be limited to the female kids as future replacements, meat sheep production profits from both adult breeding stock and the young lambs to sell at market.

Pasture management offers a non-chemotherapeutic control option that can minimise exposure to GIN transmission stages by interrupting their life cycle (Morgan and Wall, 2009; Bennema et al., 2010; Charlier et al., 2010; Van Dijk et al., 2010). The four pasture management practices specified in the questionnaire were implemented to varying degrees by the six production systems, which is likely associated with availability of grassland, scale of production, the husbandry customs adapted to local climate and epidemiological knowledge of the GIN (Vande Velde et al., 2018; Takeuchi-Storm et al., 2019). Reducing the stocking rate reduces the density of infective GIN transmission stages on pasture (Aumont et al., 1991) and was the most used pasture management technique by all six production systems. Minimising grazing for the livestock was the least used, except amongst the NL dairy goat system, where 72% of the farmers made use of the practice, which could be attributed to their greater susceptibility to GIN infection and AR than sheep (Hoste et al., 2008; Jackson et al., 2012) or to the limited grazing areas available compared to other countries. The pasture management technique of alternating the grazing livestock species works on the premise that specific GIN species show little cross-infectivity (Maqbool et al., 2017), although some authors have reported limited cross-infection between sheep and cattle, with few studies looking at goats (Achi et al., 2003; Amarante et al., 1997; Jacquiet et al., 1998; Riggs, 2001). Our data indicate that alternate grazing was used variably across each of the six production systems. Interestingly, in systems where it was used most, such as FR dairy goats and UK meat sheep, there seems to be a higher prevalence of AR. Although the relationship cannot be exclusive, it has been suggested that alternate species grazing may reduce the requirement for anthelmintic drenching by reducing the infection intensity on pasture, but may not significantly impact AR development if the remaining GIN on pasture has previously survived anthelmintic treatment and contributed significantly to the next generation of worms (Michel, 1985; Barger, 1997).

The organic farmers in this study were generally well informed on the availability of the six alternative GIN control measures specified, with only a few notable exceptions. The degree to which they have tried or actively used any of these alternatives however was much lower and varied across the production systems. When farmers tried an alternative, they often continued using it thereafter, implying a degree of satisfaction with the method. For example, in LT meat sheep, 98% of farmers stated to have tried the use of dietary protein supplementation and 95% continued to use it, in NL dairy goats, 36% of farmers who had tried homeopathy 36% continued to use it, in CH dairy goats, 71% of farmers who had tried phytotherapy 69% and continued to use it. It is interesting to observe that a relatively large proportion of the farmers use homeopathy, despite the lack of scientific evidence to support that it serves as an effective alternative to anthelmintics.

Getting the alternatives to trial may thereby be key to improving overall uptake amongst organic farmers. Kenyon et al. (2017) suggest that tailoring advice to specific audiences and situations can enhance their uptake by improving farmer confidence in the method. Production system also had an impact; homeopathy, phytotherapy and bioactive forages were more commonly integrated by the dairy goat systems, where again, differences in the susceptibility to GIN infection and AR (Hoste et al., 2008; Jackson et al., 2012) may motivate greater use of the alternatives. Some of the production systems however, exhibited a drop in the continued use of an alternative after trial; for example, bioactive forages (CH, FR, NL dairy goats, UK meat sheep), culling of susceptible stock (FR dairy goats), homeopathy (CH, FR dairy goats, UK meat sheep) and phytotherapy (FR dairy goats, UK meat sheep). Closer investigation is required to determine why farmers in these systems did not continue with the alternatives. One possible assumption might be that the farmers did not pursue the measures further because they were not effective or showed poor cost/benefit ratio. In this work, we have pooled all measures that are used by organic farmers to control GIN in the section 'alternatives' to strategic drenching. The aim was to get an idea of what organic farmers use to control GIN, irrespective of proven effectiveness of the applied measure (e.g. homeopathy).

Information regarding the control of livestock parasites is available from a wide range of actors (veterinarians, other farmers, agricultural merchants, farm advisors, pharmaceutical industry, levy boards, researchers and the farming press to name a few) in an array of formats (journals, internet, social media, books, leaflets, scientific and popular press articles, newsletters, websites) (Kenyon et al., 2017). Yet, optimising the implementation of anthelmintic treatment strategies, such as TST, or the uptake of alternative controls, may benefit from country specific approaches to knowledge transfer. This study identified specific preferences in the productions systems' preferred information source to stay updated on the parasite challenge. Similar findings were documented across EU organic dairy and beef cattle farmers in different countries, highlighting the need for system specific approaches when designing actions to improve GIN control in the future (Takeuchi-Storm et al., 2019). Specifically, print and other media appear to be the most effective manner to disseminate information amongst the dairy goat farmers in CH and NL, and meat sheep farmers in CH and LT, whereas UK meat sheep farmers could be informed by veterinarians, as could FR dairy goat farmers, along with health advisors. Incentivising veterinarians and health advisors to keep updated on the most recent advances in GIN control, however, may arguably be more complicated than periodic bulletins in print or other media. Currently in NL for example, there is a national online advisory tool that is getting frequently used by farmers, informing on the practical benefits of incorporating FEC, with supporting advice on anthelmintic treatments, and information on good practice (i.e. TT and TST) and alternative control strategies (Verkaik personal communication). Similar country-specific approaches could facilitate improved parasite across the EU.

5. Conclusion

In conclusion, this study showed that the organic dairy goat (CH, FR, NL) and meat sheep (CH, LT, UK) production systems had distinct approaches and attitudes to GIN control. Organic farmers appear to have some awareness of their AR problem and are willing to try various alternatives to work towards reducing it. A recent study on the use of synthetic medicines across the UK organic livestock sector documented that anthelmintics for the treatment of GIN in small ruminants accounted for the greatest proportion of total allopathic inputs (Chylinski et al., 2021) and as such increasing the uptake of practices such as TST, or alternative controls and pasture management by small ruminant farmers, could have a particularly profound impact on reducing the input of veterinary medicines into the EU organic system as a whole. To achieve this, initiatives that promote research dissemination, farmer participatory and knowledge transfer activities at national level would be desirable.

CRediT authorship contribution statement

Caroline Chylinski: Writing – original draft, Visualization, Validation. **Spiridoula Athanasiadou**: Writing – review & editing, Supervision, Project administration, Funding acquisition, Validation, Investigation. **Susann Thüer**: Data curation, Validation, Investigation. **Christian Grovermann**: Formal analysis, Methodology, Writing – review & editing. **Simon Moakes**: Conceptualization, Software, Formal analysis, Investigation. **Hervé Hoste**: Conceptualization, Investigation, Writing – review & editing. **Saulius Petkevicius**: Investigation, Writing – review & editing. **Cynthia Verwer**: Conceptualization, Investigation, Validation, Writing – review & editing. **Jan Verkaik**: Conceptualization, Investigation, Validation, Writing – review & editing. **Steffen Werne**: Conceptualization, Formal analysis, Writing – review & editing, Validation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Financial support for this project was provided by transnational funding bodies, being partners of the FP7 ERA-net project (ProPara), CORE Organic Plus, and the co-fund from the European Commission (Grant agreement No. 618107). SRUC acknowledges funding by the Scottish Government. We also acknowledge the acquisition of survey data by Florence Arsonneau (FiBL-France).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.vetpar.2022.109864.

References

Achi, Y.L., Zinsstag, J., Yeo, N., Dorchies, P., Jacquiet, P., 2003. Host specificity of *Haemonchus* spp. for domestic ruminants in the savannain northern Ivory coast. Vet. Parasitol. 116, 151–158.
Amarante, A.F.T., Bagnola Jr., J., Amarante, M.R.V., Barbosa, M.A., 1997. Host specificity of sheep and cattle nematodes in Sao Paulo state, Brazil. Vet. Parasitol. 73, 89–104.
Aumont, G., Gruner, L., Berbigier, P., 1991. Dynamique des populations des stades infestants de strongles gastrointestinaux des petits ruminants en mileu tropical humide: conséquences sur la gestion des pâturages. Rev. Elev. Med. Vet. Pays Trop. 123–131.
Barger, I., 1997. Control by management. Vet. Parasitol. 72, 493–506.
Bartley, D.J., 2008. Prevalence, characterisation and management of anthelmintic resistance in gastrointestinal nematodes of Scottish Sheep. PhD Thesis. University of Edinburgh. Available: 〈https://www.semanticscholar.org/paper/Prevalence%2C-characterisation-and-management-of-in-Bartley/8113b85f8471a0c2daaecdd8a763eace4e087a15〉.
Bennema, S.C., Vercruysse, J., Morgan, E., Stafford, K., Höglund, J., Demeler, J., von Samson-Himmelstjerna, G., Charlier, J., 2010. Epidemiology and risk factors for exposure to gastrointestinal nematodes in dairy herds in northwestern Europe. Vet. Parasitol. 173, 247–254.
Busin, V., Kenyon, F., Parkin, T., McBean, D., Laing, N., Sargison, N.D., Ellis, K., 2014. Production impact of a targeted selective treatment system based on liveweight gain in a commercial flock. Vet. J. 200, 248–252.
Cabaret, J., Benoit, M., Laignel, G., Nicourt, C., 2009. Situation and management of internal parasites for conventional and organic meat sheep farmers in central France: how does it fit for targeted selective treatments? Vet. Parasitol. 164, 21–29.
Charlier, J., Demeler, J., Höglund, J., von Samson-Himmelstjerna, G., Dorny, P., Vercruysse, J., 2010. *Ostertagia ostertagia* in first-season grazing cattle in Belgium, Germany and Sweden: general levels of infection and related management practices. Vet. Parasitol. 171, 91–98.
Chylinski, C., Cortet, J., Neveu, C., Cabaret, J., 2015. Exploring the limitations of pathophysiological indicators used for targeted selective treatment in sheep experimentally infected with *Haemonchus contortus*. Vet. Parasitol. 207, 85–93.
Chylinski, C., Borthwick, M., Michie, D., Athanasiadou, S., 2021. Towards reducing the input of allopathic medicines in UK organic livestock. Vet. Rec., e947 https://doi.org/10.1002/vetr.947.
Claerebout, E., De Wilde, N., Van Mael, E., Casaert, S., Velde, Vande, F., Roeber, F., Veloz, P.V., Levecke, B., Geldhof, P., 2020. Anthelmintic resistance and common worm control practices in sheep farms in Flanders, Belgium. Vet. Parasitol. Reg. Stud. Rep. 20, 100393 https://doi.org/10.1016/j.vprsr.2020.100393.
Council regulation No 834/2007, Official Journal of the European Union. Available: 〈https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007R0834&from=EN〉.
d'Alexis, S., Sauvant, D., Boval, M., 2014. Mixed grazing systems of sheep and cattle to improve liveweight gain: a quantitative review. J. Agric. Sci. 152, 655–666.
Donelli, D., Antonelli, M., 2021. Homeopathy and psychological therapies. Enzyclopedia 1, 57–64.
Escribano, A.J., 2016. Organic livestock farming — challenges, perspectives, and strategies to increase its contribution to the agrifood system's sustainability — a review. Organic Farming - A Promising Way of Food Production. IntechOpen, London, United Kingdom (Available). 〈https://www.intechopen.com/chapters/49129〉.
Gaba, S., Cabaret, J., Chylinski, C., Sauvé, C., Cortet, J., Silvestre, A., 2012. Can efficient management of sheep gastro-intestinal nematodes be based on random treatment? Vet. Parasitol. 190, 178–184.
Halvarsson, P., Gustafsson, K., Höglund, J., 2022. Farmers' perception on the control of gastrointestinal parasites in organic and conventional sheep production in Sweden. Vet. Parasitol. Reg. Stud. Rep. 30. https://doi.org/10.1016/j.vprsr.2022.100713.
Höglund, J., Dahlström, F., Sollenberg, S., Hessle, A., 2013. Weight gain-based targeted selective treatments (TST) of gastrointestinal nematodes in first-season grazing cattle. Vet. Parasitol. 196, 358–365.
Hoste, H., Torres-Acosta, J.F.J., Aguilar-Caballero, A.J., 2008. Nutrition-parasite interactions in goats: is immunoregulation involved in the control of gastrointestinal nematodes? Parasite Immunol. 30, 79–88.
Jackson, F., Varady, M., Bartley, D.J., 2012. Managing anthelmintic resistance in goats – can we learn lessons from sheep? Small Rumin. Res. 103, 3–9.
Jacquiet, P., Cabaret, J., Thiam, E., Cheikh, D., 1998. Experimental and natural *Haemonchus* spp. Cross infections of domestic ruminants in Sahelian West Africa. Ann. N. Y. Acad. Sci. 849, 465–469.
Jordan, H.E., Phillips, W.A., Morrison, R.D., Doyle, J.J., McKenzie, K., 1988. A 3-year study of continuous mixed grazing of cattle and sheep: parasitism of offspring. Int. J. Parasitol. 18, 779–784.
Keatinge, R., 2004. Control of internal parasites in organic livestock without the use of pharmaceutical anthelmintics (Project OF0185). ADAS Consulting Ltd. Redsedale. Final report to Defra. Available: 〈http://www.defra.gov.uk/science/project_data/DocumentLibrary/OF0185/OF0185_2215_FRP.doc〉.
Kenyon, F., Hutchings, F., Morgan-Davies, C., van Dijk, J., Bartley, D.J., 2017. Worm control in livestock: bringing science to the field. Trends Parasitol. 33, 669–677.
Kenyon, F., McBean, D., Greer, A.W., Burgess, A.G.S., Morrison, A.A., Bertlet, D.J., Bartlet, Y., Devin, L., Mintu, N., Jackson, F., 2013. A comparative study of the effects of four treatment regimes on ivermectin efficacy, body weight and pasture contamination in lambs naturally infected with gastrointestinal nematodes in Scotland. Int. J. Parasitol. Drugs Drug Resist. 3, 77–84.
Kolenikov, S., Angeles, G., 2004. The Use of Discrete Data in PCA: Theory, Simulations, and Applications to Socioeconomic Indices. CPC/MEASURE Working Paper 85. Available: 〈https://measureevaluation.org/resources/publications/wp-04-85.html〉.
Learmount, J., Stephens, N., Boughtflower, V., Barrecheguren, A., Rickell, K., 2016. The development of anthelmintic resistance with best practice control of nematodes on commercial sheep farms in the UK. Vet. Parasitol. 299, 9–14.
Lindqvist, Å., Ljungström, B., Nilsson, O., Waller, P.J., 2001. The dynamics prevalence and impact of nematode parasite infections in organically raised sheep in Sweden. Acta Vet. Scand. 42, 377–389.
Maqbool, I., Wani, Z.A., Shahardar, R.A., Allaie, I.M., Shah, M.M., 2017. Integrated parasite management with special reference to gastrointestinal nematodes. J. Parasit. Dis. 41, 1–8.
McArthur, M.J., Reinemeyer, C.R., 2014. Herding the U.S. cattle industry toward a paradigm shift in parasite control. Vet. Parasitol. 204, 34–43.
McMahon, C., McCoy, M., Ellison, S.E., Barley, J.P., Edgar, H.W.J., Hanna, R.E., Malone, F.E., Brennan, G.P., Fairweather, I., 2013. Anthelmintic resistance in Northern Ireland (III): uptake of "SCOPS" (Sustainable Control of Parasites in Sheep) recommendations by sheep farmers. Vet. Parasitol. 193, 179–184.
Merlin, A., Chauvin, A., Madouasse, A., Froger, S., Bareille, N., Chartier, C., 2016. Explaining variability in first season grazing heifer growth combining individually measured parasitological and clinical indicators with exposure to gastrointestinal nematode infection based on grazing management practices. Vet. Parasitol. 225, 61–69.
Michel, J.F., 1985. Strategies for the use of anthelmintics in livestock and their implications for the development of drug resistance. Parasitology 90, 621–628.
Mitchell, S., Hunt, K., Wood, R., McLean, B., 2006. Anthelmintic resistance in sheep flocks in Wales. Vet. Rec. 159, 860.
Moore, H., Pandolfi, F., Kyriazakis, I., 2016. Familiarity with and uptake of alternative methods to control sheep gastro-intestinal parasites on farms in England. Vet. Parasitol. 221, 1–8.
Morgan, E.R., Wall, R., 2009. Climate change and parasitic disease: farmer mitigation? Trends Parasitol. 25, 308–313.
Morgan, E.R., Coles, G.C., 2010. Nematode control practices on sheep farms following an information campaign aiming to delay anthelmintic resistance. Vet. Rec. 166, 301–303.
Morgan, E.R., Lanousse, C., Rinaldi, L., Charlier, J., Vercruysse, J., 2022. Confounding factors affecting faecal egg count reduction as a measure of anthelmintic efficacy. Parasite 29, 20. https://doi.org/10.1051/parasite/2022017.
Morgan, E.R., Hosking, B.C., Burston, S., Carder, K.M., Hyslop, A.C., Pritchard, L.J., Whitmarsh, A.K., Coles, G.C., 2012. A survey of helminth control practices on sheep farms in Great Britain and Ireland. Vet. J. 19, 390–397.
Muchiut, S.M., Fernández, A.S., Steffan, P.E., Riva, E., Fiel, A.C., 2018. Anthelmintic resistance: management of parasite refugia for *Haemonchus contortus* through the replacement of resistant with susceptible populations. Vet. Parasitol. 254, 43–48.
Notter, D.R., Burke, J.M., Miller, J.E., Morgan, J.L.M., 2017. Association between FAMACHA scores and fecal egg counts in Katahdin lambs. J. Anim. Sci. 95, 1118–1123.
Playford, M.C., Smith, A.N., Love, S., Besier, R.B., Kluver, P., Bailey, J.N., 2014. Prevalence and severity of anthelmintic resistance in ovine gastrointestinal nematodes in Australia (2009 – 2012). Aust. Vet. J. 92, 464–471.
Ploeger, H.W., Everts, R.R., 2018. Alarming levels of anthelmintic resistance against gastrointestinal nematodes in sheep in the Netherlands. Vet. Parasitol. 262, 11–15.
Riggs, N.L., 2001. Experimental cross-infections of *Haemonchus placei* (Place, 1983) in sheep and cattle. Vet. Parasitol. 94, 191–197.
Scheaffer, R.L., Mendenhall, III, W., Ott, R.L., Gerow, K.G., 2012. Elementary Survey Sampling, seventh ed. Brooks/Cole, Boston.
Silva, J.B., Fagundes, G.M., Soares, J.P.G., Finseca, A.H., Muir, J.P., 2014. A comparative study of production performance and animal health practices in organic and conventional dairy systems. Trop. Anim. Health Prod. 46, 1287–1295.
Takeuchi-Storm, N., Moakes, S., Thuer, S., Grovermann, C., Verwer, C., Verkaik, J., Knubben-Schweizer, G., Höglund, J., Petkevičius, S., Thamsborg, S., Werne, S., 2019. Parasite control in organic cattle farming: management and farmers' perspectives from six European countries. Vet. Parasitol. Reg. Stud. Rep. 18, 100329 https://doi.org/10.1016/j.vprsr.2019.100329.
Teuscher, E., Melzig, F., Lindequist, U., 2012. Biogene Arzneimittel, seventh ed. Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart.
Van Dijk, J., Sargison, N.D., Kenyon, F., Skuce, P.K., 2010. Climate change and infectious disease: helminthological challenges to farmed ruminants in temperate regions. Animal 4, 377–392.

Vande Velde, F., Charlier, J., Claerebout, E., 2018. Farmer behaviour and gastrointestinal nematodes in ruminant livestock – uptake of sustainable control approaches. Front. Vet. Sci. 5, 255. https://doi.org/10.3389/fvets.2018.00255.

Varga, K., Fehér, J., Trugly, B., Drexler, D., Leiber, F., Verrastro, V., Magid, J., Chylinski, C., Athanasiadou, S., Thuerig, B., László, A., Ladányi, M., Moeskops, B., Herforth-Rahmé, J., Tamm, L., 2022. The state of play of copper, mineral oil, external nutrient input, anthelmintics, antibiotics and vitamin usage and available reduction strategies in organic farming across Europe. Sustainability 14, 3182. https://doi.org/10.3390/su14063182.

Waghorn, T.S., Leathwick, D.M., Rhodes, A.P., Lawrence, K.E., Jackson, R., Pomroy, W. E., West, D.M., Moffat, J.R., 2006. Prevalence of anthelmintic resistance on sheep farms in New Zealand. N. Z. Vet. J. 54, 271–277.