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A pound for information or a penny for cure: Farmers' economic decisions on testing and treatment of livestock diseases

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Abstract

Livestock productivity and profitability are threatened by livestock diseases. In this study, we examine farmers' revealed preferences for testing and treating gastrointestinal parasites in sheep in Sweden, taking into account the sequential structure of these decisions. We control for preventive measures, as well as the potential impact of wildlife–livestock disease transmission on farmers' decisions. A zero-inflated ordered probit model is used to estimate the determinants of farmers' decisions, and we cross-validate the robustness of the results to alternative model assumptions. Results from the regressions are used to calculate the consequences of these choices for farmers' profits. The results show that treatment decisions are informed by faecal testing, while both testing and treatment are influenced by the grazing practices, the size of the operation and access to information. Contrary to expectations from the conceptual framework, preventive management practices are positively correlated with treatment. Farmers take multiple risk factors into account when deciding on testing, but we do not find that the same factors affect the outcome of treatment. The economic impacts are small and suggest that treatment without prior testing is more profitable for the farmer than informed treatment. If widespread treatment increases drug resistance, this could motivate policies that encourage testing.

KEYWORDS

gastrointestinal (GIN) parasitic nematodes, profits, sheep, wildlife, zero-inflated ordered probit model

JEL CLASSIFICATION
C35, D24, Q12, Q18

1 | INTRODUCTION

Livestock diseases can have a substantial impact on the economic viability of livestock farms (Bennett, 2003; Rich et al., 2012). The productivity and profitability of livestock farms depends on the efficiency of detection, prevention and treatment of microbial diseases, pests and parasites (Corwin, 1997; Seegers et al., 2003). For example, the profitability of sheep production is challenged by parasitic gastrointestinal nematodes (GINs), which are estimated to cause up to a 50% loss in slaughter weight and up to a 21% loss in wool production compared with unaffected animals (Charlier et al., 2014; Mavrot et al., 2015).

Studies on the economic aspects of livestock diseases have strived to quantify the costs of different livestock diseases, and the costs and benefits of different strategies for prevention and treatment, in order to direct policy resources towards their most efficient use. The majority of these studies make use of accounting or modelling frameworks (Bennett, 2003; McInerney et al., 1992; Nieuwhof & Bishop, 2005), whereas relatively few examine farmers' stated or revealed preferences for disease management (Sok et al., 2018; Ugochukwu & Phillips, 2019; Weyori et al., 2020). In spite of several studies considering information acquisition through learning or testing, the role of costly information acquisition for farmers' preferences for management has not been explored. A couple of studies emphasise the risk of disease transmission between domestic and wild animals (Horan et al., 2010, 2018), but the impact of such risks on farmers' actual behaviour has not been studied.

The purpose of this study was to examine farmers' revealed preferences for parasitic gastrointestinal nematodes (GIN) management, including testing and treating parasites in sheep, and the impact of these strategies on farmers' profits. In addition, we examine whether these decisions are affected by the local presence of wildlife. We use a zero-inflated ordered probit model taking into account the hurdle-type structure for decisions on testing and treatment, and the dependence of these decisions on preventive practices and the risk for wildlife–livestock interactions. Data are obtained from an online survey sent out to sheep farmers in Sweden in 2019, and results are cross-validated under different alternative model assumptions. Results show that deworming yields 5% average increase in the number of lambs per ewe. A back-of-the-envelope cost–benefit calculation shows that for the average farmer, deworming without testing is economically more beneficial (a profit of EUR 4.54 per ewe)[1] than informed deworming after testing for and verifying the presence of parasites (yielding a profit of EUR 2.56 per ewe).

The rest of the paper is organised as follows. In Section 2, a brief overview of the studied case and GINs is provided. In Section 3, we discuss the relevant literature. In Section 4, we describe the conceptual framework. In Section 5, the estimation strategy is elaborated, and in Section 5, the survey data are discussed. We present estimation results in Section 6, followed by discussion and conclusions in Section 7.

2 | CASE STUDY

Our study is applied using Swedish data. In 2019, there were 8476 registered sheep farms in Sweden, with a total gross production value of more than EUR 27 million (Swedish Board of Agriculture, 2021b). Charlier et al. (2020) estimated that in Sweden, GINs imply a cost due to decreased productivity equal to EUR 237507 per year, while the treatment cost is estimated to be EUR 314966 per year (Charlier et al., 2020).

[1]EUR = 1.63 AUD = 1.10 USD in January 2024.

Gastrointestinal nematodes are common in small ruminants worldwide. Usually, animals are infected with mixed GIN species representing different genera, in which some are more pathogenic than others (Halvarsson & Höglund, 2021). Although some nematodes in sheep are species-specific, there are also generalists such as *Haemonchus contortus* (commonly known as Barber's pole worm) that may also occur in wild cervids, thus providing opportunities for horizontal transmission between sheep and wild ruminant hosts (Chintoan-Uta et al., 2014). These parasites are expected to be affected by ongoing climate changes, which could increase their abundance and amplify their effect on livestock health (Morgan et al., 2013; Rose et al., 2016).

Farmers' strategies for managing GIN constitute preventive measures as well as diagnostic testing and treatment, which are argued to be effective means of minimising production loss and biosecurity threats. Anthelmintic treatment in combination with grazing management routines is the most common method to control GIN infections in sheep (Jackson & Miller, 2006). However, anthelmintic resistance is an emerging threat (Vineer et al., 2020).[2] In Sweden, it is therefore recommended to sample and diagnose GIN infection levels in sheep herds prior to anthelmintic treatment. Given that testing and treatment are voluntary, it is therefore important to understand whether farmers adhere to these recommendations.

3 | LITERATURE REVIEW

Early empirical economic studies estimated and compared the total cost of different infectious livestock diseases, with the total cost typically defined as the sum of costs due to the impact of disease on the output and the costs for their prevention and treatment at national scale (Bennett, 2003; McInerney et al., 1992; Nieuwhof & Bishop, 2005). This approach has been criticised for providing a limited understanding of optimal prevention and treatment efforts, because the optimal level depends on the marginal costs of the additional effort and the marginal benefit of the associated impact (Mclnerney, 1996; Tisdell, 2006).

Later studies have placed an increasing focus on the role of individual farmers' incentives for prevention and treatment, given that their decisions affect the spread and economic impact of livestock diseases at larger scale. For example, Gramig et al. (2009) investigate how indemnity payments can be designed to encourage producers to invest in prevention and truthfully report infections. Moreover, Wang and Hennessy (2014) model producers' interdependent decisions to join a voluntary livestock disease control program, with subsequent impacts on market premiums for such participation.

Another strand of the literature recognises that the transmission of infectious diseases between wild and domestic animals has become a global concern, potentially affecting not only the economic well-being of farmers but also the food production system and valuable wildlife resources (Cleaveland et al., 2001; Daszak et al., 2000; Horan et al., 2010, 2018). Using bioeconomic modelling, Horan et al. (2010) show that in such situations, disease eradication is not always economically optimal for a social planner. Also, it may not be optimal to aim at upholding an interior steady state. Further, Horan et al. (2018) examine the joint management of wildlife, livestock and a pathogen that can be passed between them, using capital theory to develop a portfolio balancing trade-offs between the animal resources, and the mitigation of and adaptation to disease risks.

Relatively few economic studies have carried out empirical analysis to evaluate the trade-offs between alternative livestock disease management options. An early example is Chi et al. (2002) who use a regional-level accounting framework to estimate how the prevalence of

[2]Anthelmintic resistance arises locally, but then the main source is animal trade. For example, the first recorded case of ivermectin-resistant *Haemonchus contortus* in Sweden originates from East Friesian Dairy sheep imported from the Netherlands (Höglund et al., 2015).

four output-limiting cattle diseases[3] is affected by different combinations of preventive measures, and calculate the resulting total sectoral costs across 10 different prevention and treatment strategy combinations in order to identify the least-cost strategy. Wang and Hennessy (2014) use their above-mentioned model of voluntary participation in a livestock disease control program to simulate outcomes for bovine Johne's disease in the USA. MacLachlan et al. (2017) analyse the adaptive management of bovine tuberculosis in New Zealand's cattle, using an optimal control model with a Partially Observable Markov Decision Process (POMDP), assuming costly testing is necessary to identify herds for treatment. Cho et al. (2013) use an optimal control model for Johne's disease control in a profit maximising dairy operation, while Pech et al. (2009) use a similar farm-level approach to assess the economic value of refugia for the prevention of intestinal parasites in sheep. Xie and Horan (2009) develop an empirical bioeconomic model for evaluating the economic and ecological impacts of measures addressing the spread of brucellosis from elk to cattle, assuming farmers' decision to vaccinate their herd is determined by the relative profitability of vaccination.

Only few empirical studies investigate the preference of farmers for alternative livestock disease management strategies using farm-level data. Ugochukwu and Phillips (2019) and Sok et al. (2018) both identify farmers' trade-offs using a stated preferences approach, that is, using survey responses to different hypothetical situations. Ugochukwu and Phillips (2019) use choice experiments to identify the willingness-to-pay for the prevention and control of bovine tuberculosis and paratuberculosis in cattle, given farm conditions and the social and informational context. Sok et al. (2018) use a discrete choice experiment to estimate the willingness-to-pay for bluetongue vaccination scheme attributes, showing that moral values and peer behaviour affect the outcome. Weyori et al. (2020) evaluate the impact of a veterinary intervention program on farmers' knowledge, husbandry practices and profits. Gramig et al. (2010) use farm-level data from the US Department of Agriculture (USDA) for the analysis of the impact of bovine leukosis virus (BLV) on US dairy farms, using a two-stage procedure in which they first estimate the disease risk reduction for different livestock health management practices, and subsequently calculate expected economic benefits of these risk reductions and use those as explanatory variables in an econometric model of adoption of the practices. Their results suggest that the economic benefits from disease reduction is statistically significant but of little practical economic importance in adoption decisions. Young and Haantuba (1998) differ from the above by considering both testing and treatment, assuming a probabilistic relationship between the identified number of ticks and the resulting production losses, based on data from two comparable herds with approximately 60 cattle in each. Treatment is assumed to imply a cost, but testing is assumed to be costless, and the economic trade-offs between the two are not explored.

Based on the above survey of the literature, we find that there is a knowledge gap on how farmers understand and make trade-offs in livestock disease management, in particular when it comes to the interlinked decisions to test for and treat livestock diseases, and the economic consequences thereof. In addition, implications of wildlife-induced infection risks for farmers' actual choices on testing and treatment have not previously been empirically investigated. Understanding such choices is necessary for designing efficient policies for livestock disease prevention and management. This study aimed to fill these gaps using farm-level survey data from Sweden.

4 | CONCEPTUAL FRAMEWORK

Livestock diseases can lower the productivity of animals. Farmers' management of such diseases involves economic considerations, as there are trade-offs between prevention efforts,

[3]Bovine viral diarrhoea, enzootic bovine leukosis, Johne's disease and neosporosis.

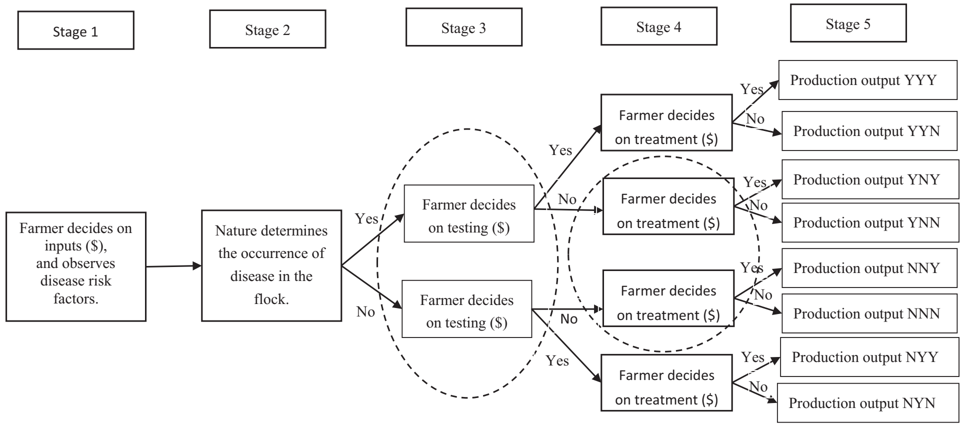

FIGURE 1 Sequence of farmer decisions on inputs, testing and treatment in a given production year. Information sets, in which the farmer does not know whether their flock is infected, are indicated by dashed circles.

efforts to acquire information on infection risks and infection outbreaks in the own flock, and control efforts, and given that all these types of efforts are costly. In the following, we outline our conceptual framework to how these decisions are made at the farm level.

First, we assume that during the production year, farmers take their decisions on livestock management, disease testing and disease control, in a sequential manner, and with the purpose to maximise profits (Figure 1). In the beginning of the production year, that is, Stage 1 in the figure, the farmer observes disease risk factors within and outside the farm and decides on inputs in production. Some risk factors cannot be controlled by the individual farmer in the short term, such as previous instances of infections at the own and neighbouring farms, the quality and size of grazing land on the farm and abundance of wild animals in the neighbourhood, that might potentially carry a contagious disease. However, the farmer's choice of inputs, decided in the beginning of the production year, could potentially affect the risk of infection. For example, the farmer could develop a plan for rotation of grazing between different plots of grazing lands. Moreover, they could decide whether and from where to purchase live animals. They could also decide to sign a contract for regular advisory support from a veterinarian, thereby ensuring that the flock has the best possible health status. We assume that an informed farmer chooses inputs in production considering both their direct impact on output (meat and reproduction) and the indirect impact on the risk of disease occurrence.

In Stage 2, we assume that nature determines whether the flock is either infected or not infected in the given year. However, we assume that farmers cannot know whether their flock is infected in a particular year unless they decide to carry out testing. The farmer's decision to test is taken in Stage 3. The general guidelines suggest that six ewes are tested in small flocks, and 10 per cent of the animals are tested in large flocks, and that the test is carried out before the ewes are let out in the spring. Hence, the recommended testing aims to prevent infections, and it is not required that there are clinical signs of infections found before testing. A second test could be carried out at the time of weaning. Testing is voluntary. We assume that the farmer's choice to test the animals is determined by the expected costs and benefits that follow from this decision. If testing is costly, then the farmer will be less willing to undertake this effort, but if the informational benefits from the test are large, they will be more willing to bear the expenses. The informational benefits are higher if the probability of an infection is at an intermediate level, than if the likelihood is very large or very small. If the probability of an infected flock is very large, the farmer could save costs by treating the flock without prior testing, while if the probability is very low, they could be better off by neither testing nor treating. In addition, the informational benefits from testing are higher if treatment is expensive, because this implies that there will be large cost savings from only treating infected individuals.

After deciding on whether to test the flock, the farmer is assumed to decide on treatment, as in Stage 4 in the figure. The farmer will treat the flock if the expected benefits in terms of enhanced production exceed the costs for treatment. Whenever the farmer has tested the animals, and the test showed that the flock was infected, the veterinarian prescribes treatment when he or she judges that this will be beneficial from a veterinary perspective.[4] The expected economic benefits of treatment are larger when there is a known infection than if the sheep have not been tested. This is because in the latter case, the flock might be uninfected, implying that treatment will not affect output. In practice, farmers could treat their flock without having obtained a prescription, for example, by purchasing anthelmintics on the internet. The difference between the informed decision and the uninformed decision, with respect to the expected benefits from treatment, will be larger when there is a low probability that the flock is infected. Similarly, if there is a high probability that the flock is infected, there is a large difference in the expected benefits from not treating, depending on whether the decision not to treat is informed or uninformed. The resulting output from production will be determined by the presence of the infection in the flock, and the treatment choice, and it is realise in Stage 5 (Figure 1).

Based on the above, farmers' decisions on testing and treatment, and the resulting output, depend on disease risks that can be identified in the beginning of the production season, the measures undertaken to prevent such risks, and testing and treatment of a disease. In our empirical analysis below, we first investigate how input choices and risk factors from Stage 1 affect the decision to test the flock in Stage 3. This is followed by an examination of how the same factors (from Stage 1) affect treatment choices, given that the farmer has chosen whether to test the flock, or not. We also explore the impact of informed and uniformed treatment, and treatment intensity on output. Thereby, the empirical approach captures the major aspects of the above-described model, although there are some simplifications that are motivated by our focus on the decisions to test for and treat a disease, and the consequences for the final output, in combination with data limitations. For example, there are no data available on the presence of nematode infections at the farms other than the test results; thus, it is not possible to distinguish between infected and noninfected herds for farms that have not carried out tests with respect to the output. Moreover, some input decisions related to disease prevention could potentially be taken after the decision to test; for example, the farmer might decide to stable sheep during the grazing season after a positive test result. However, the main determinant of the timing of stabling in the end of the grazing season is the cost of winter feed, and it is therefore unlikely that sheep are stabled based on the pure suspicion of a parasite infection. In addition, we do not have farm-specific data on prices paid for testing and treatment, but veterinarians are likely to charge the same amount independently of farm size. These simplifications should still be borne in mind.

5 | EMPIRICAL METHOD

We examine factors that determine farmers' sheep disease control choices using outcome variables that reveal farmers' testing and treating practices. The first outcome variable is derived from a survey question that asked farmers about their GIN testing practices. As outlined in the conceptual framework, this variable informs farmers' decisions on treatment when a farmer has chosen to test. The survey question asked respondents ‘How often do you perform a diagnostic

[4]Anthelmintics are only legally available by prescription since 2007, motivated by the risk of increased resistance.

fecal test?'. The response has three categories ordered from no testing to the highest frequency of testing: 'Never or rarely', 'Yes – but only some years' and 'Yes – regularly every year'.

Subsequently, we study farmers' treatment choices using an outcome variable that was constructed from a survey question that asked, 'Were the sheep dewormed this year?' The response has three categories ordered from the most reluctant approach to the most cautious: 'They were not dewormed', 'They were dewormed due to proven parasite presence in the stool sample' and 'They were dewormed as a safety precaution'.

The nature of the two outcome variables allows empirical analysis using both ordinal and categorical outcome models. We conduct the main analysis based on a model assumption that decision outcomes are generated by a two-stage choice mechanism, which is described using the zero-inflated ordered probit model presented below. We cross-validate the robustness of the results to alternative model assumptions. The first alternative model assumption is that the categories of the outcome variables are unordered, which is described using a multinomial logistic model. The second alternative model assumption is that the categories of the outcome variables are ordered, but the categories do not represent the distance between them. The latter model assumption results in an ordered logistic model. A brief description of the alternative model specifications and the associated results are presented in Section S2. Cross-validation based on the three model assumptions shows that the results discussed in the main analysis are not sensitive to the model assumption.

5.1 | Zero-inflated ordered probit model

In a zero-inflated ordered probit model, an ordered choice is generated by a two-stage process in which the first stage is category zero, which is an actual value of zero or the lowest outcome category. In the first stage, a sheep farmer decides whether to choose faecal testing in the case of the first outcome variable defined above, and whether to deworm in the case of the second outcome variable defined above. In the second stage, the sheep farmer chooses from the choices that are different from zero (i.e., the lowest outcome category). This implies a hurdle-type structure in which the sheep farmer must pass through the first stage of choices before choosing among different alternatives in the second stage, as outlined in the conceptual framework. This structure allows investigating whether the choice between the zero category and nonzero category is determined by different factors than the choices between nonzero alternatives. This model also allows examination of the two processes in the same model (Greene & Hensher, 2010; Harris & Zhao, 2007). The concentration of observations in the lowest category, that is zero inflation, indicates that a potential two-stage process generates the data.

A farmer might choose not to conduct a faecal test because they do not expect a parasite problem in their sheep herd, because they are not aware that it would be economically beneficial to conduct a test, or because conducting faecal tests might not be economically viable given the value of the information that can be obtained. A farmer might choose not to deworm for the same reasons as choosing not to perform a faecal test; in addition, a faecal test might have indicated the absence of parasites, implying that the value of treatment may be low. All these reasons lead to inflated lowest category, as shown in the summary statistics in Section 5, Figure S1 and Table S1.

The zero (or lowest outcome) category contains two types of farmers. The first type is farmers who would never participate in deworming. These farmers have perfectly inelastic demand to prices and income. The second type is farmers who will participate at the right price and income. The farmers in the second category behave in the same way as farmers who report nonzero participation and will also respond to economic factors. However, the two categories of farmers cannot be distinguished when they have chosen the zero category. We present an abbreviated *zero-inflated ordered probit model* in this study's context as follows (for details, see Greene and Hensher (2010), Harris and Zhao (2007) and Maddala (1986)):

Let a latent variable r^* represents the propensity to participate in testing or deworming:

$$r^* = \alpha Z + \varepsilon, \tag{1}$$

where Z is a vector of explanatory variables that determine the choice between participation and nonparticipation, α is a vector of unknown coefficients and the error term is $\varepsilon \sim N(0, 1)$. The latent variable r^* is related to a dichotomous variable r that indicates two regimes with $r = 0$ for non-participants and $r = 1$ for participants. The latent variable r^* is related to the observed r through the mapping: $r = 1$ for $r^* > 0$ and $r = 0$ for $r^* \ll 0$ (Harris & Zhao, 2007). Then, the probability of an individual being in the participating regime ($r = 1$) is as follows:

$$\Pr(r = 1 | Z) = \Pr(r^* > 0 | Z) = \Phi(\alpha Z), \tag{2}$$

where $\Phi(\alpha Z)$ is the cumulative distribution function (c.d.f.) of the univariate standard normal distribution.

Conditional on $r = 1$, participation levels are represented by a discrete variable $\widetilde{y} = 0, 1, 2$ that is generated by an ordered probit model via a second underlying latent variable $\widetilde{y}^*$:

$$\widetilde{y}^* = \beta X + u \tag{3}$$

where X is a vector of covariates, β is a vector of unknown coefficients and u is an error term, $u \sim N(0, 1)$. The covariates in X may or may not overlap with the covariates in Z. The linear equations describing the latent variables in Equations (1) and (3) represent observations obtained from the same individual. Thus, it is likely that ε and u are correlated. It is assumed that (ε, u) follows a bivariate normal distribution with the correlation coefficient ρ and unit variance. Then, $\rho = 0$ would indicate independence of the two error terms. The mapping between the observed and latent variables of the dependent variables is given by:

$$y = r\widetilde{y} = \begin{cases} 0 \; if \; (r^* \ll 0) \; or \; \left(r^* > 0 \; and \; \%\tilde{y}^* \ll 0\right) \\ 1 \; if \; \left(r^* > 0 \; and \; \mu_0 < \%\tilde{y}^* \ll \mu_1\right) \\ 2 \; if \; \left(r^* > 0 \; and \; \mu_1 < \%\tilde{y}^*\right) \end{cases} \tag{4}$$

where μ_0, μ_1 are boundary parameters. In this paper's set-up, $\mu_0 = 0$. The full probabilities for y are given by

$$\Pr(y) = \begin{cases} \Pr(y = 0 | X,\ Z) = [1 - \Phi(\alpha Z)] + \Phi_2(\alpha Z, -\beta X; -\rho) \\ \Pr(y = 1 | X,\ Z) = \Phi_2\left(\alpha Z, \mu_1 - \beta X; -\rho\right) - \Phi_2\left(\alpha Z, \mu_0 - \beta X; -\rho\right) \\ \Pr(\mathrm{y} = 2 | X, \mathrm{Z}) = \Phi_2\left(\alpha Z, \beta X - \mu_1; \rho\right) \end{cases} \tag{5}$$

where $\Phi_2(.,.;l)$ is the cumulative distribution function of the standardised bivariate normal distribution with the correlation coefficient l between the univariate random elements of ε and u (Harris & Zhao, 2007).

For a sample of N from the population $\left(y_i, Z_i, X_i\right), i = 1, \ldots, N$, maximum likelihood criteria can consistently and efficiently estimate the parameters $\theta = (\alpha, \beta, \mu, \rho)'$ (Harris & Zhao, 2007). The log-likelihood function is

$$\ell(\theta) = \sum_{i=1}^{N} \sum_{j=0}^{3} h_{ij} \ln[\Pr(y_i = j \mid X_i, Z_i, \theta] \tag{6}$$

where the indicator function h_{ij} is

$$h_{ij} = \begin{cases} 1 \text{ if individual } i \text{ chooses outcome } j, (i = 1, \ldots, N; j = 0, 1, 2) \\ 0 \text{ otherwise} \end{cases} \tag{7}$$

The marginal effects are derived from Equation (6) as the change in Pr(y) with respect to the different covariates, as detailed in Harris and Zhao (2007).

5.2 | Economic value of deworming

We examine the economic value of deworming using two outcome variables: the number of lambs per ewe and weights of the lambs (in kilograms) at slaughter. We estimate a linear relationship:

$$Y_{ij} = \beta X_{ij} + \alpha_j + \varepsilon_{ij} \tag{8}$$

where Y_{ij} is the number of lambs per ewe or weight (in kilograms) of the lambs at slaughter for farmer i located in municipality j, and X_{ij} is the list of explanatory variables discussed in Section 5 that include the farmers' deworming choice, farmer characteristics, grazing characteristics, sheep breed and sheep interaction with wild cervids. The term α_j indicates municipality fixed effects that account for observed and unobserved characteristics shared by all farmers located within a municipality, such as geographic suitability for sheep rearing and ease of parasite transmission due to, among other things, long-term mean weather suitability, altitude and mean temperature.[5] The term ε_{ij} is an idiosyncratic error term.

6 | SURVEY DATA AND DESCRIPTIVE STATISTICS

An online questionnaire was designed and distributed using a web-based service. Prior to release, the questionnaire was sent to (i) veterinarians at the organisation Farm & Animal Health, (ii) a farm advisor at the organisation Happy Sheep and (iii) two producers for pretesting and commenting.[6,7] The questionnaire included questions concerning (i) farm structure, (ii) general husbandry practices, (iii) production data, (iv) potential wildlife interactions and (v) producers' views on the impact of parasites and deworming practices. Most questions were close-ended with specific response alternatives, a few were open-ended and some questions included the option of replying 'other' or 'do not know'. In case any questions were answered with a 'No', subsets of related questions were not shown.

The survey was sent out via email to individuals who have been registered as sheep producers at the Swedish Board of Agriculture. The surveyed farmers received the invite through email in an online questionnaire system. The invite contained information regarding the aim of the project and a link to the online questionnaire. Three reminders were sent out. Farmers were anonymous in the questionnaire. We received responses from 3949 farmers, which is equivalent to 46.6% of the 8476 sheep farmers registered in 2019 by the Swedish Board of Agriculture (2021b).

[5]See E. Morgan and Van Dijk (2012) for the relationship between climate and gastrointestinal nematode infections in sheep.

[6]The Happy Sheep is a translation of the Swedish name of the organisation Glada Fåret. Farm & Animal Health is a translation of the Swedish name of the organisation Gård & Djurhälsan. These two organizations do not have official names in English.

[7]In 2020, Farm & Animal Health had approximately 2000 members who are sheep farmers and approximately 4000 sheep farmers subscribed to receive information about sheep disease.

Descriptive statistics of the survey data (Table 1) show that approximately 40% of farmers who responded to the survey indicated that they never or rarely perform faecal tests, 22% give their sheep faecal tests in some years and 38% regularly test their herd. More than half of the farmers (55%) did not deworm their sheep flock during the survey year, which correlates with the inflated zero category assumption of the model discussed in Section 4. The remaining farmers dewormed their sheep in the same year. The cross-tabulation between testing and treating is presented in Table S1.

Summary statistics presented in Table 1 show that approximately 81% of the farmers are above the age of 40 years, and a farmer owns, on average, 52 sheep, in which the lamb-to-ewe ratio is 1.1. At the time of slaughter, the average sheep weighs 18.14 kg. Among the survey respondents, 49% of farmers described their main production sector as 'Hobby/Environmental Protection', and 42% were meat, skin and wool producers. Of all farmers, 88% are organic producers, and on average, sheep contribute 16% to the respondents' total agricultural income. Most farmers' sheep flock consists of more than one purebred sheep and one mixed-breed sheep. Among farmers whose sheep flock consists of only one pure breed, 19% have Gotland sheep, 5% have Swedish Finull ('Fine Wool') sheep, 7% have Texel sheep and 6% have Gute sheep.

When farmers were asked about their reliance on information for decision-making, only 5% responded 'Not important to me', and almost 95% indicated that they obtained information from veterinarian and other sources, including the animal and health association Farm & Animal Health and district veterinarians, and looking for information by themselves. Grazing practices are relevant to GIN infections, 65% of the farmers rotate pastures and 61% use a combination of old and new pastures. Moreover, 22% of farmers have changed pastures, and 9% have stabled sheep during the grazing season over the past 3 years due to weather conditions, insects/tics, intestinal parasites, predator attacks or other reasons. Out of the total sheep feed, 31% is purchased forage. Also, 69% of the farmers buy live animals. Approximately 42% of the farmers graze their sheep on natural land, forests and mountainsides, while 58% use a mix of natural and arable pastures. In addition, almost 90% of the respondents replied 'yes' to the question, 'Have you seen wild cervids (Moose, Deer, Red deer, Fallow deer, or Mouflon) in your pasture?', in which the question aims to capture the possibility that GIN parasites might be passed between wild cervid and livestock.

7 | ESTIMATION RESULTS

In this section, we first present the estimation results for faecal testing, followed by results for treatment. Thereafter, we present the impacts of different combinations of testing and treatment on output in terms of meat per lamb and number of lambs per ewe and estimate the net impacts on farmers' profits.

7.1 | Faecal test choice

We start by presenting estimation results on factors that affect how often farmers choose to perform faecal tests. Table 2 shows marginal effects from a maximum likelihood estimation. The main estimation table is provided in Table S4. As mentioned above, we also applied alternative model assumptions, for which the results are presented in Tables S2 and S3. Comparing with the results presented in Table 2, the estimated marginal effects are robust to model assumptions.

The estimation results shown in Table 2 show that a farmer's choice to test for GIN infection in sheep is affected by farmer age, which can act as a proxy for their experience. The

TABLE 1 Summary statistics.

	Categories	Obs.	Per cent	Mean (std. dev.)
Dependent variables				
Output variables				
Number of lambs per ewe		3865		1.1 (0.82)
What was the average weight at slaughter, in kg?		4635		18.14 (3.80)
Control: testing				
How often do you perform faecal testing?	Never or rarely	1510	39.98	
	Yes—but only some years	835	22.11	
	Yes—regularly every year	1432	37.91	
Control: treatment				
Were the sheep dewormed this year?	Not dewormed	2091	55.36	
	Dewormed due to proven parasite presence in the stool sample	827	21.90	
	Dewormed as a safety precaution	859	22.74	
Explanatory variables				
Age	18–39	749	18.85	
	40–59	1959	49.31	
	>60	1265	31.84	
Number of sheep		4635		52.37 (178.77)
How much forage is bought during the stable season 2018/2019? (%)		3820		31.1 (41.18)
How much do sheep contribute to income from agricultural activities? (%)		3999		16.25 (25.62)
Production type	Breeding, milk production and other	331	8.26	
	Meat, skin and wool	1693	42.27	
	Hobby/environmental protection	1981	49.46	
Organic producer	No	3515	87.79	
	Yes	489	12.21	
How do you get veterinary advice?	Not important to me	201	5.32	
	From veterinarian and other sources	3576	94.68	
Do you buy live animals?	No	1240	31.03	
	Yes	2756	68.97	
How do sheep graze?	Grazing on the same field	1307	35.49	
	Changing pasture	2376	64.51	
What type of pastures are used?	Mix of natural and arable pasture	2104	57.52	
	Mainly natural, forest and mountain	1554	42.48	

TABLE 1 (Continued)

	Categories	Obs.	Per cent	Mean (std. dev.)
How long have the pastures been used by sheep?	Old pasture, at least 5 years old	1435	39.19	
	Combination of old and new	2227	60.81	
Has land use for grazing changed over the past 3 years due to weather conditions, insects/tics, intestinal parasites, predator attacks or other?	No	3594	77.54	
	Yes	1041	22.46	
Sheep stabled due to weather conditions, insects/tics, intestinal parasites, predator attacks or other	No	3250	90.93	
	Yes	324	9.07	
Have you seen wild cervid on pasture? Moose, deer, Red deer, fallow deer and mouflon	No	362	10.13	
	Yes	3211	89.87	
Sheep breed				
Gotland sheep		4635	18.73	
Swedish Finull sheep		4635	4.79	
Texel sheep		4635	7.29	
Gute		4635	6.36	
Mixed		3962	34.60	

probability of never or rarely performing a faecal test for farmers in the age groups 40–59 years and older than 60 years is 5% and 16% lower, respectively, than the same probability for farmers in the age group 18–39 years. Farmers in the age groups 40–59 years and older than 60 years are also 6% and 16% less likely, respectively, to perform faecal tests regularly every year than farmers in the age group 18–39 years.

A one per cent increase in the number of sheep in the flock is associated with an 8% increase in the probability that a farmer will perform faecal tests regularly every year and reduces the probability that a farmer will rarely perform faecal tests by 7%. Similarly, a one per cent increase in the percentage of forage bought is associated with a 1.8% increase in a farmer regularly performing faecal tests and a 1.7% decrease in a farmer never or rarely performing faecal tests.

Farmers who depend on sheep for most of their income from agriculture are more likely to test their sheep flock for GIN infection. This is revealed in the estimation results, which show that a one per cent increase in the sheep share of agricultural income is associated with a 1.9% decrease and a 1.8% increase in farmers that never or rarely perform faecal tests and farmers who regularly perform faecal tests, respectively.

Compared with breeding and milk producers, hobby/environmentally motivated farmers are 8% more likely to never or rarely perform faecal tests and 12% less likely to perform faecal tests regularly every year. In contrast, organic producers are 13% more likely to perform faecal tests regularly every year and 12% less likely to never or rarely perform faecal tests than nonorganic producers. Obtaining veterinary advice is associated with a reduction in farmers' practice of never or rarely performing faecal tests by 26% and an increase in the probability that farmers perform faecal tests some years by 5% and regularly every year by 21%.

Farmers who buy live animals are 9.6% less probable and 7.6% more likely to perform faecal tests never or rarely and regularly, respectively, than farmers who do not buy live animals. Furthermore, grazing practices that could be utilised as preventive measures against GIN

TABLE 2 How often do you perform faecal tests? Marginal effects.

Explanatory variables	Categories	Zero-inflated ordered probit model: Never or rarely (1)	Yes—but only some years (2)	Yes—regularly every year (3)
Age	40–59, vs. 18–39	0.0459** (0.0185)	0.017 (0.0119)	−0.0629*** (0.0199)
	>60, vs. 18–39	0.1581*** (0.0208)	0.0076 (0.0119)	−0.1657*** (0.0205)
Log number of sheep		−0.0731*** (0.0080)	−0.004 (0.0074)	0.0770*** (0.0100)
Log forage bought		−0.0175*** (0.0036)	−0.0005 (0.0018)	0.0181*** (0.0034)
Log share of agricultural income		−0.0187*** (0.0060)	0.0007 (0.0033)	0.0181*** (0.0057)
Production type	Meat, skin and wool vs. breeding and milk production	0.0572 (0.0374)	−0.0139 (0.0438)	−0.0433 (0.0335)
	Hobby/environmental protection vs. breeding and milk production	0.0799** (0.0353)	0.0442 (0.0452)	−0.1241*** (0.0359)
Organic production	Yes vs. no	−0.1190*** (0.0197)	−0.0117 (0.0152)	0.1306*** (0.0266)
How do you get veterinary advice?	From veterinarian and other sources vs. not important to me	−0.2631*** (0.0387)	0.0502** (0.0223)	0.2129*** (0.0261)
Do you buy live animals?	Yes vs. no	−0.0961*** (0.0187)	0.0192 (0.0141)	0.0769*** (0.0173)
How do sheep graze?	Rotational grazing vs. grazing on the same field	−0.0769*** (0.0172)	0.0248* (0.0143)	0.0521*** (0.0181)
What type of pastures are used?	Mainly natural, forest and mountain vs. mix of natural and arable pasture	0.0365** (0.0153)	−0.0157** (0.0076)	−0.0208 (0.0142)
How old is the pasture?	Combination of old and new vs. old pasture	−0.0149 (0.0147)	−0.0161 (0.0099)	0.0309** (0.0149)
Pasture change	Yes vs. no	−0.0717*** (0.0152)	0.007 (0.0090)	0.0647*** (0.0158)
Sheep stabled	Yes vs. no	−0.0670* (0.0383)	−0.0471 (0.0372)	0.1141*** (0.0274)
Have you seen wild cervids on pasture?	Yes vs. no	−0.0447* (0.0231)	0.0103 (0.0126)	0.0344 (0.0232)
Observations		3514		

Note: Robust standard errors in parenthesis.
*$p<0.1$; **$p<0.05$; ***$p<0.01$.

infection are also associated with significant effects. Farmers who practice changing pastures are 5% more likely to perform faecal tests regularly every year, 2% more likely to perform faecal tests some years and 7.6% less likely to never or rarely perform faecal tests than farmers who use the same grazing field for a long time. Combination and rotational grazing are associated with a 3% higher probability of taking faecal tests than grazing using old pastures. Letting sheep mainly graze in natural pastures, forests and mountains is associated with a 3% lower probability of taking faecal tests than letting sheep graze on a mix of natural and arable pastures. Farmers' behaviour of changing pasture and stabling sheep during the grazing season due to weather conditions, insects/tics, intestinal parasites and predator attacks is associated with an increased probability of performing faecal tests regularly every year by 6% and 11%, respectively, and a reduced probability of never or rarely performing faecal tests by 7% and 6%, respectively. In addition, seeing wild cervid on pasture is associated with a 4% lower probability of never or rarely performing faecal tests.

7.2 | Choice to deworm

In this subsection, we investigate whether testing affects deworming practices and whether the variables that capture farmer, sheep grazing and input-related characteristics discussed in the previous sections play a role in a farmer's choice of deworming. We base interpretations and discussions on the calculated marginal effects presented in Table 3 and provide the full estimation results in Table S5. In Table S5, marginal effects under alternative model assumptions are presented. The results in Table S5 are similar to those in Table 3, in terms of the estimated coefficients signs and magnitude, indicating that the estimated marginal effects are robust to the model assumption.

Evidently, taking a faecal test informs farmers about the presence of GINs, which could affect the farmer's decision to deworm sheep. The estimation results presented in Table 3 show that farmers who perform faecal tests some years are 11% more likely to deworm due to proven parasite presence and 10% less likely to deworm for safety reasons than farmers who never or rarely perform faecal tests. Farmers who perform faecal tests regularly every year are 16% less likely to not deworm, 38% more likely to deworm due to proven parasite presence and 21% less likely to deworm for safety reasons than farmers who never or rarely perform faecal tests.

The numbers of sheep that a farmer owns could indicate the relevance of the sheep to the farming business, and thus, the farmer could be more concerned about the health of the sheep flock. In the estimation results presented in Table 3, a one per cent increase in the number of sheep is associated with a farmer being 9% less likely to not deworm the sheep and 7% more likely to deworm the sheep due to proven parasite presence. An increase in the number of sheep is also associated with an increased probability of deworming for safety by 2%.

A one per cent increase in the share of sheep in agricultural income is associated with a 2% higher probability of not deworming and a 1% lower probability of deworming for safety, indicating a higher economic awareness. Meat, skin and wool producers are 6% less likely to not deworm and 5% more likely to deworm for safety than breeding and milk producers. Organic producers have a 12.5% higher probability of not deworming, a 3% lower probability of deworming due to proven GIN parasites and a 9% lower probability of deworming for safety than nonorganic (conventional) producers. Asking for veterinary advice is associated with a 7% reduced probability of not deworming and a 6% increased probability of deworming due to proven parasites.

Farmers' choice of grazing is significantly correlated with deworming behaviour. Changing pastures, which could be considered a preventive measure against GIN infection, is correlated with a 6% lower probability of not deworming, a 3% higher probability of deworming due to proven parasites and a 3% higher probability of deworming for safety than using the same

TABLE 3 Were the sheep dewormed this year? Marginal effects.

Explanatory variables	Categories	Zero-inflated ordered probit model: Not dewormed (1)	Dewormed due to proven parasite presence (2)	Dewormed for safety (3)
How often do you perform faecal test?	Yes—but only some years vs. never or rarely	−0.009 (0.022)	0.109*** (0.014)	−0.100*** (0.020)
	Yes—regularly every year vs. never or rarely	−0.166*** (0.021)	0.377*** (0.015)	−0.210*** (0.018)
Age	40–59 vs. 18–39	0.001 (0.022)	0.01 (0.014)	−0.01 (0.017)
	>60 vs. 18–39	−0.033 (0.024)	0.018 (0.015)	0.015 (0.019)
Log number of sheep		−0.091*** (0.009)	0.071*** (0.006)	0.020*** (0.007)
Log forage bought		0.004 (0.004)	−0.001 (0.003)	−0.004 (0.003)
Log share of agricultural income		0.018*** (0.007)	−0.008* (0.005)	−0.010* (0.005)
Production type	Meat, skin and wool vs. breeding and milk production	−0.059* (0.031)	0.007 (0.020)	0.052** (0.023)
	Hobby/environmental protection vs. breeding and milk production	−0.05 (0.031)	0.023 (0.021)	0.027 (0.023)
Organic production	Yes vs. no	0.125*** (0.023)	−0.034** (0.015)	−0.091*** (0.016)
How do you get veterinary advice?	From veterinarian and other sources vs. Not important to me	−0.076** (0.037)	0.062** (0.026)	0.014 (0.033)
Do you buy live animals?	Yes vs. no	−0.003 (0.019)	0.019 (0.013)	−0.016 (0.016)
How do sheep graze?	Changing grazing vs. grazing on the same field	−0.064*** (0.018)	0.034*** (0.012)	0.030** (0.015)
What type of pastures are used?	Mainly natural, forest and mountain vs. mix of natural and arable pasture	0.01 (0.017)	−0.01 (0.011)	−0.001 (0.013)
How old is the pasture?	Combination of old and new vs. old pasture	0.015 (0.017)	−0.013 (0.011)	−0.002 (0.013)
Pasture change	Yes vs. no	−0.045** (0.018)	0.034*** (0.012)	0.011 (0.014)
Sheep stabled	Yes vs. no	0.091*** (0.027)	−0.056*** (0.017)	−0.035 (0.021)
Have you observed wild cervids on pasture?	Yes vs. no	0.01 (0.027)	0.022 (0.020)	−0.033 (0.024)
Observations		3514		

Note: Robust standard errors are shown in parenthesis.

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$.

pasture throughout the whole season. Similarly, changing pastures due to weather conditions, insects/tics, intestinal parasites and predator attacks is correlated with a reduced probability of not deworming by 4.5% and an increased probability of deworming due to proven parasite presence by 3%. Together, these results indicate that farmers with GIN issues in the herd undertake treatment- and grazing-related prevention measures simultaneously. In contrast, stabling sheep for the same reasons is correlated with an increased probability of not deworming of 9% and a decreased probability of deworming for safety of 5.6%, potentially indicating lower infection risks for farms with production practices involving more extensive stabling.

7.3 | Economic value of nematode prevention

Table 4 presents the results from a linear regression estimation (Equation 8) of the relationship between the two economic outcomes measured in number of lambs per ewe and average weight at slaughter and covariates. We examine the economic impact of deworming practices using the variable that describes the deworming choice discussed in the previous sections as well as an additional variable that describes the frequency of deworming. This allows us to compare outcomes across nontreatment and different treatment intensities. In Columns (1) and (4), the effect of farmers' deworming choice on the economic outcomes is assessed. In Columns (2) and (5), the economic impact of deworming frequency is further examined. In Columns (3) and (6), we extend the model to capture the effect of interactions between deworming choice and deworming frequency on the two economic outcome variables (number of lambs per ewe and weight at slaughter). The estimated effects of deworming choice and frequency are presented in Table 4, and the full estimation results showing the estimated effects of the control variables are presented in Table S6.

The results presented in Table 4 Column (1) show that deworming due to proven parasite presence increases the number of lambs per ewe by 4.1% compared with not deworming. Deworming as a safety precaution increases the number of lambs per ewe by 4.8% compared with not deworming. Similarly, the results presented in Column (2) show that deworming once increases the number of lambs per ewe by 5.4% compared with not deworming. In Column (3), the interaction term shows that deworming once in response to proven parasites increases the number of lambs per ewe by 5.1% and deworming once for safety increases the number of lambs per ewe by 5.6% compared with not deworming. In contrast, we do not observe a significant gain in weight at slaughter due to deworming choices.

The full estimation results presented in Table S6 show the impact of other factors on the number of lambs per ewe and weight at slaughter. The size of a farmer's sheep flock is positively and significantly associated with the number of lambs per ewe, which indicates that farmers with larger sheep flock are more productive, which could be because they pay more attention to the economic viability of the livestock. The estimation results show that a one per cent increase in the number of sheep is associated with an increased number of lambs per ewe of 15.8% (Table S6 Column [1]). Similarly, farmers who mainly produce their own forage report having higher weights at slaughter per sheep, supported by the result that a one per cent increase in forage bought decreases weight at slaughter by approximately 1% (Table S6 Column [4]). This could be explained by the cost and quality of forage. A one per cent increase in the sheep share of agricultural income is associated with a 1.4% increase in the number of lambs per ewe (Table S6 Columns [1] and [4]). This could be because farmers whose income depends mainly on sheep take sheep rearing more seriously.

Similarly, the results presented in Table S6 Columns (1) and (4) show that farmers who buy live animals have 8% more lambs per ewe than farmers who do not. Changing pastures is associated with 5.3% more lambs per ewe. Farmers who let their sheep graze on mainly natural, forested and mountain pastures experience a 4.3% lower weight at slaughter than farmers who let their sheep graze on a mixture of natural and arable pastures. Using a combination of old and new pastures

TABLE 4 Fixed effects estimation result of the economic value of deworming.

		Log number of lambs per ewe			Log weight at slaughter		
Explanatory variables	**Categories**	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Were the sheep dewormed this year?	Dewormed due to proven parasite presence vs. not dewormed	0.041** (0.017)			0.002 (0.012)		
	Dewormed for safety vs. not dewormed	0.048*** (0.016)			0.012 (0.014)		
How often were the sheep dewormed?	Dewormed once vs. not dewormed		0.054*** (0.015)			0.004 (0.011)	
	Two times vs. not dewormed		0.02 (0.022)			0.022 (0.015)	
	Three or more times vs. not dewormed		−0.067 (0.051)			−0.036 (0.036)	
Interaction	Dewormed due to proven parasite once vs. not dewormed			0.051*** (0.019)			−0.004 (0.012)
	Dewormed due to proven parasite twice vs. not dewormed			0.022 (0.026)			0.021 (0.019)
	Dewormed due to proven parasite three or more times vs. not dewormed			−0.111 (0.068)			0.001 (0.030)
	Dewormed for safety once vs. Not dewormed			0.056*** (0.017)			0.013 (0.015)
	Dewormed for safety twice vs. not dewormed			0.015 (0.034)			0.022 (0.023)
	Dewormed for safety three or more times vs. not dewormed			0.007 (0.064)			−0.094 (0.072)
Observations		3405	3405	3405	1964	1964	1964

Note: $*p<0.1$; $**p<0.05$; $***p<0.01$. Standard errors presented in parentheses are clustered at the municipality level. All estimations contain control variables and fixed effects. The full estimation table is provided in Table D1 of the Supplemental Appendix.

TABLE 5 Marginal economic impacts of GIN treatment, costs and revenues per ewe.

	Increased number of lambs per ewe	
	Deworming once due to proven parasite presence	**Deworming once for safety**
	(1)	**(2)**
Revenue per ewe	4.83	5.31
Costs per sheep in flock for testing, treatment and veterinarian advice	2.27	0.77
Profit per ewe	2.56	4.54

Note: All values are shown in 2019 euro.

and rotational grazing is associated with 3.3% more lambs per ewe than grazing on old pastures. Farmers' behaviour of changing pastures due to weather conditions, insects/tics, intestinal parasites and predator attacks is associated with 3% fewer lambs per ewe. Among the different breeds of sheep that farmers rear, farmers whose entire sheep flock contains only one breed of Gotland, Swedish Finull, Texel or Gute sheep report more lambs per ewe than farmers whose entire sheep flock contains mixed breeds.[8] Farmers who rear only Texel sheep races also report having heavier lambs at slaughter, and farmers who have only Gotland or Gute races report having lighter lambs at slaughter than farmers with mixed sheep races.

Using the marginal effects reported in Table 4, we conduct a back-of-the-envelope cost–benefit calculation. In the calculation, we interpret the marginal effects, conventionally, as the effect of a farmer's deworming choice on one more sheep. We use the marginal effects from Table 4 in combination with summary statistics in Table 1, price data from the Swedish Board of Agriculture (2021a) and data on the costs of veterinary advice, testing and treatment from Farm and Animal Health (2021). Although testing is not mandatory to carry out deworming treatment, it is mandatory to obtain veterinarian advice to be able to treat the sheep regardless of faecal testing. The calculated benefits and costs are presented in Table 5. The details of the calculation, including the data used, are provided in Section S5 in which the back-of-the-envelope cost–benefit calculation and the calculated profit per ewe for the average farmer are presented in Table S7.

The results presented in Table 5 show that, accounting for the costs of testing and treating, deworming due to proven parasite presence provides a net gain of EUR 2.56 per ewe for the average farmer. Deworming once for safety reasons, implying that the farmer avoids the cost of testing, results in a profit of EUR 4.54 per ewe and year due to the increased number of lambs per ewe.

7.4 | Robustness

The empirical exercises in Sections 7.1, 7.2 and 7.3 present results that are robust to model assumptions. Comparing the main results with the results presented in Section S2 shows that the estimated coefficients and their statistical significance are not sensitive to the assumptions of the data-generating process. In the regressions, we control for important factors including farm and farmer characteristics, input choices and fixed effects. Furthermore, distribution of each covariate across the categories of the dependent variables is balanced. In the Figure S2 panels (A) to (D), we show that farmers' sheep flock size and dependence on income from sheep are balanced across the categories of testing and treating. Or equivalently, the categories of the dependent variables are similarly distributed across flock size and extent of farmers

[8]Farmers who have mixed sheep breeds have two or more of Gotland sheep, Swedish Finull, Texel, Gute, Suffolk, Leicester Longwool, East Frisian dairy sheep, Landrace breeds and mixed breeds.

income dependence on sheep. Based on consistencies of these diagnostics, we argue that the research design and the empirical exercises enable inferring the direction and magnitude of the estimated coefficients. However, we cannot rule out that unobserved factors might influence the estimation results. Where we assess the relationship between testing and treating choices (results presented in Table 3), the testing variable might be endogenous. Where we assess the economic impact (Table 4), the deworming variables might be endogenous.

Econometric methods that are potentially suitable for solving endogeneity in the context of this study are instrumental variable method and methods that rely on instruments such as control function approach. However, because testing and treating are very closely related outcome variables, an instrumental variable that fulfils exclusion restriction criteria, that is, the instrumental variable affects the outcome variable only through instrumented variable, is challenging to come by. For instance, consider a weather variable such as temperature or precipitation. For a weather variable to be a valid instrument, it should affect treating behaviour only through its effect on testing behaviour. When a farmer perceives that weather conditions are favourable for parasite transmission, she/he is more likely both to test and treat the sheep flock, implying a violation of exclusion restriction criteria.

Although the estimated coefficients might be affected by endogeneity, implying that the results should be interpreted as associations and with caution, we argue that the empirical exercise is relevant and informative. Future research based on independent measures of nematode infection and empirical designs that enable inferring causal relationships, such as quasi-experimental methods, will add to the field.

8 | DISCUSSION AND CONCLUSIONS

In this study, we assess factors that determine farmers' choices in the detection of GIN parasites through faecal testing and in the treatment through deworming and examine the economic consequences. Using farm survey data from Sweden, we present results from a zero-inflated ordered probit model cross-validated with a multinomial logistic model and an ordered logistic model. The three models rely on varying assumptions about the data-generating process, and our analysis shows that the estimation results are not sensitive to these assumptions. Furthermore, the economic value of the detection and treatment choices is explored through examination of the impact of treatment choices on lamb and meat productivity.

Our results show that the decision to deworm and the intensity of treatment are informed by conducting faecal tests. As can be expected, informed deworming, that is, after confirmed parasite presence, is higher among farmers who carry out irregular as well as regular faecal testing than those who never or rarely carry out faecal testing. Additionally, farmers who carry out faecal testing more rarely abstain from deworming or deworm for safety. This result is consistent with farmers testing more frequently when the actual occurrence of parasite infections is higher but could also be observed if a significant number of infected flocks is left untreated.

In our estimations, we attempted to control for the risk of parasite infections by considering foraging practices, whether organic or conventional farming practices are applied, the purchase of live animals, grazing practices and the likelihood of interactions with wild cervids. We find, as expected, a significant and positive relationship between testing frequency and purchases of forage, buying live animals and organic farming, thus indicating that those are perceived by the farmers to increase infection risks. Additionally, we find a significant negative relationship between sheep grazing on natural pastures or in forests and the frequency of testing, which was expected, as well as a significant negative relationship between the occurrence of wild cervids on pastures and testing, which was contrary to expectations. When analysing treatment choices, the only significant variable out of the above variables is organic farming, which is negatively related to treatment. Together, these results suggest that farmers take multiple risk factors into account when deciding on testing, but there is no strong evidence of the actual effects of the same factors on the need for treatment, except for the case of organic farming practices.

Our conceptual framework theorised trade-offs between control (in terms of testing and treatment) and the use of preventive inputs such as grazing management and stabling. The empirical results show that routinely changing grazing fields, combining new and old pastures, and changing pastures or stabling due to the occurrence of specific problems (weather conditions, insects/tics, intestinal parasites or predator attacks) are all associated with higher testing frequency. Moreover, changing pastures due to specific problems is associated with a higher treatment frequency, while stabling due to specific problems is associated with a lower treatment frequency. Thus, we do not see the expected trade-off between control and inputs as expected in the case of stabling due to specific problems. One possible explanation is that farmers do not make such trade-offs because they have a strong preference for disease control, therefore using all available tools when infection risks are seen as high. The trade-off that we find between stabling, and treatment could also potentially be due to different production systems being applied, in which, for example, stabling could be more common among milk producers; therefore, we do not believe that it provides any strong support for the presence of trade-offs being made between control and input use.

The implications of deworming decisions on output are that deworming once due to proven parasites and deworming once for safety are both associated with a positive gain in the number of lambs per ewe. It is interesting to observe that informed and uninformed treatment on a single occasion in a year is associated with approximately the same positive impact on the number of lambs per ewe, suggesting that there might not be any economic benefits from testing. This is contrary to expectations, as one would expect that uninformed deworming could be applied to both infected and uninfected flocks, with a lower average treatment effect. Other deworming choices, for example, deworming three or more times, do not result in significant economic gain. In addition, it can be noted that routinely changing pastures also leads to increased output. Thus, it is not obvious that this inputs measure, which could help to reduce infection risks, generates net costs to the farmer. Instead, it could be the case that the net gains from improved fodder availability and reduced infection risks outweigh the costs of undertaking the measure. In contrast, changing pastures or stabling due to the occurrence of specific problems reduces output and is thus costly to the farmer. Thus, voluntary pasture changes are only made if they are profitable, while changes in grazing practices made in an emergency situation are not necessarily associated with a net economic gain.

Farmers with many sheep and those who rely more heavily on sheep farming for their income might consider faecal testing and deworming more seriously than those with fewer sheep due to the economic importance of the decision (cf., e.g., Ugochukwu and Phillips (2019)). This is observed in our estimation, in which both factors are associated with more frequent faecal testing. Consequently, a larger flock implies that it is more likely that farmers deworm due to the proven presence of parasites and less likely not to deworm. A larger sheep flock and greater dependency on the income from sheep rearing obviously increase the economic importance of the sheep to the farmer. This might encourage farmers to put more effort into measures that enhance sheep productivity. Our estimations show that more sheep in the flock and a larger share of sheep in the total agricultural income are both positively associated with the number of lambs per ewe, confirming higher productivity.

Farmers have differing incentives to deworm their sheep depending on the purpose of production. In our survey data, we classified production activities into three broad groups: breeding and milk production; meat, skin and wool; and hobby/environmental protection. The estimation results show that meat, skin and wool producers and hobby/environmental protectionists are less likely to perform faecal testing but more likely to deworm than breeding and milk producers. This could indicate that infections are controlled more effectively in the larger two farmer categories. Farmers who identify themselves as organic producers are likely to pay extra attention to the environmental impact of their production activities. For example, GIN treatment medications are known to have toxic characteristics and affect biodiversity (Beynon, 2012), which could motivate environmentally oriented farmers to bear a higher cost of livestock disease (Rushton, 2009). In line with that, our results show that organic producers are more likely to conduct faecal tests regularly every year; however, they are less likely to deworm due to proven parasite presence or for safety and less likely to deworm than conventional producers.

Information available to farmers is another factor that could govern their faecal testing and deworming decisions (Garforth et al., 2013; Kaler & Green, 2013). In our survey data, farmers are categorised into two groups depending on how they obtain veterinarian advice. The first group are those who obtain advice from the animal health advisory organisation Farm & Animal Health or district veterinarians or search and obtain information from several different sources. The second group includes farmers who answer that they do not attach much importance to veterinary advice. The first group, who plausibly make informed decisions, is more likely to perform faecal tests and less likely to deworm their flock, supporting the observation in Ugochukwu and Phillips (2019) that qualified advice increases farmers' willingness-to-pay for disease prevention and control. The two groups do not differ with respect to productivity, and it is therefore not obvious that farmers' efforts to obtain information pay off in economic terms.

Our study contributes to the literature by studying farmers' actual decisions concerning livestock disease control using survey data on farmers' actual decisions on GIN management in sheep. Compared with the earlier literature, which predicts that farmers make trade-offs between direct control of the disease and preventive measures, our study shows that such trade-offs may not be a priority consideration by farmers. Instead, we find a positive correlation between the use of direct control and preventive measures, which might be due to farmers' strong preferences for reducing infections. Moreover, while acquiring more information through testing and advisory services could be valuable for the purpose of controlling infections, our results raise doubts on whether such information is actually profitable for farmers. Dynamic effects over time are largely unexplored and thus open areas for future research. Future studies that track farmers' decisions over time will be able to capture the dynamic interaction between market factors, climate change and GIN control choices.

With respect to policy, our results show that it is more profitable to treat without prior testing. This can be a problem as it could result in overuse of anthelmintics, potentially resulting in increasingly drug resistant parasites. In order to avoid this, policymakers could provide a subsidy for testing, and this can be expected to increase testing and avoid unnecessary treatment.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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