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Review article

A systematic review and meta-analysis of impact of strongyle parasitism on growth rates in young cattle

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ABSTRACT

Background: To identify any universal impact of strongyle parasite burden on the growth rate of young cattle.
Methods: A meta-analysis and meta-regression of the relationship between differences in strongyle parasite burden between cohorts and average daily weight gain was conducted. Publications were identified from a search of databases applying PRISMA 2020 principles. Eligible studies had at least two groups of growing cattle on the same farm that were identical in composition, management and diet except for parasite exposure and were subject to body weight gain or average daily gain and faecal egg count measurements across the common growing period. The reference group had the lowest growth-period faecal egg count. A meta-regression estimated the impact of strongyle parasitism. The dependent variable was the log of the ratio of average daily gain between comparison groups and the reference group with the predictor variable as the common logarithm of the difference in average faecal egg count (plus 1) between the comparison and the reference groups.
Results: 26 publications containing 85 groups and 59 comparison ratios were analysed. Papers included representatives from dairy and beef industries and from pasture and feedlot production systems and from all cattle-producing continents. The comparison group average daily growth rate was 0.89 (95%CI 0.81–0.97) that of the reference group. Meta-regression identified a 0.131 linear reduction in average daily weight gain ratio for every $\log_{10}$ increase in the difference between comparison and reference group faecal egg count. Direction of effect was consistent across all subset analyses (continent, class of stock and production system). Whilst small faecal egg count differences between the comparison and reference groups often provided similar rates of daily weight gain, the trend was negative with most comparison groups having lower daily weight gains than their reference group.
Conclusions: Strongyle parasitism of growing cattle as measured by faecal egg count is associated with reduced growth across all production systems, geographies and classes of cattle.

1. Introduction

Strongyle parasitism of growing cattle can produce disease and a reduction in productivity (Bisset, 1994; Charlier et al., 2009; Rashid et al., 2019; Sykes, 1994). Productivity impacts include impaired weight gain, reproduction, lactation, feed use efficiency and death (Corwin, 1997). Further, parasite burdens are associated with changes in behaviour of cattle including time spent walking, lying and feeding that indicate discomfort, with welfare implications, even in subclinically-affected cattle (Högberg et al., 2021).

Faecal egg counts are a rapid method of evaluating parasite burdens in grazing animals (Nielsen, 2021). Close correlations between FEC and total worm burden in young cattle have been demonstrated in both warm and cool climates (Bryan and Kerr, 1989; Teixeira et al., 2021). However, other studies suggest that in temperate seasonal grazing systems, worm egg counts, while useful, do not accurately reflect worm burden of animals (Eysker and Ploeger, 2000).

A strong correlation has also been demonstrated between the number of larval worms taken in by cattle on pasture and their average daily gain (Burggraaf et al., 2007), but due to the cost and technical difficulty of conducting pasture larval counts, these are rarely used to make treatment or management decisions for cattle herds (Molento et al.,

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2016).

Charlier estimated the net difference in average daily gain between treated and untreated first-season grazing calves was 150–315 g/head/day (Charlier et al., 2014). However, precise signals for determining the impact or potential economic benefit of treating or not treating young cattle have been unclear, despite the use of various measures including worm egg counts, liveweight measurements and a combination of these (Kenyon and Jackson, 2012).

Parasite treatment and control costs add to (Burggraaf et al., 2007) the economic impact of parasitism (Rashid et al., 2019). There is increasing resistance to anthelmintics (Waller, 2003), and the rate of development of new anthelmintics has slowed since the 1980 s (McKellar and Jackson, 2004), making effective control of parasites in commercial farming challenging (Sangster, 2001). Cattle farming using pastures requires effective and sustainable ways to control strongyle parasitism, especially in young stock (Sutherland and Bullen, 2015). The targeted treatment of livestock combined with maintenance of a pool of untreated (and hopefully susceptible) parasites in refugia has gained much acceptance (Charlier et al., 2009). Novel (non-chemical) controls are of increasing interest (Ketzis et al., 2006). Worm egg counts can be used to predict the level of future pasture larval contamination (Molento et al., 2016; Shaw et al., 1998). The role of grazing management in controlling host-parasite interactions is of increased importance as a management strategy (Hutchings et al., 2003).

This review examines the relationship between strongyle parasite burden (as measured by faecal egg count (FEC)) and average daily weight gain (ADG) in young, growing cattle from across different breeds, current production systems, countries, and between within-farm comparison groups using a meta-analysis. The objectives are to see if a meta-regression can effectively quantify the impact of strongyle parasite burden on growth performance of farmed cattle in a generalisable way, and to estimate impact of modest worm burden on average daily weight gain under modern farming practices. This information is important in that it guides decision making on investment into parasite controls.

2. Material and methods

2.1. Eligibility criteria

The population of interest was weaned eligible cattle less than two years of age (i.e., growing) within current (from 1990 onwards) commercial farming systems, whose weight was measured alongside monitoring for parasitism with strongyles using FEC during the growth period.

2.2. Database search and systematic review

The *Web of Science* portal was used to search multiple reference databases (including CAB Abstracts, BIOSIS Citation Index, Current Contents, MEDLINE and SciELO Citation Index) supplemented by an identical search using *Google Scholar* was undertaken in September 2021. The search query was: (calf or calves or yearling* or heifer or steer or cow* or cattle) AND (FEC or "fecal egg count*" or "faecal egg count*") AND ("weight gain" or "average daily weight gain" or "average daily gain" or ADG or "body weight" or "liveweight gain" or growth or "weaning weight" or weight* or gain" or liveweight") limited to a publication year of 1990 or above.

2.3. Study selection

Publications that measured both animal weight or growth and strongyle parasite burden using FEC during the growing period in this class of cattle were suitable for inclusion in the meta-analysis. The title of publication was examined for relevance. The abstracts of publications potentially meeting eligibility criteria were then examined for compliance with the eligibility criteria. Specifically, the abstracts reporting weights and/or ADGs and strongyle parasite burden measurements of study groups identified papers for examination.

At least two groups of growing cattle were required, which was necessary for the calculation of a) the relative growth performance (ratio of ADG) of each study group to a within-study reference group; and b) the predictor variable, being the difference in FEC between the study and reference group. This approach was used to control for other study-level (confounding) variables that may also impact growth rate — such as breed, production system, supplementary feeding and use of hormone growth promoters — thereby support pooling of results from across studies. The use of anthelmintics was not an eligibility criterion. The strongyle parasite burden was able to be estimated if there was at least one FEC taken from each group within the growing period.

The use of ADG provides partial control over differing study durations between studies under the assumption that the ratio in ADG between similarly aged cattle under near-identical conditions is centred on 1 (but can be greater or less than 1). The first weight measurement coinciding with when a FEC was taken was used where possible. If multiple FECs were recorded between weight measurements, the arithmetic average count across each measurement point within the growing period was calculated and this was used in analysis.

Papers reporting more than one study group under similar management and presenting group average weight gain along with the standard deviation of daily weight gain or a standard error of the mean of average daily weight gain and who provided group-level FECs during the growing period were forwarded for meta-analysis. Publications that presented only a pooled standard deviation/standard error from combined study group results were excluded. Studies with multiple replicates, such as farm-level replicates of the study, had each replicate uniquely identified to ensure the most appropriate reference group for ADG ratio and difference in FECs was used.

Publications were assessed for bias in allocation to groups, measurement, losses and attrition and attribution of effect (such as from differences between groups potentially due to confounding exposures, such as differential feeding rates between groups). Publications with non-random allocation to groups, excessive losses and confounding between groups were removed from analysis. Blinding of participants was not considered feasible for most field parasitological studies so this was not used as an exclusion criterion.

2.4. Statistical analysis

The ratio of means method described by Friedrich was used for the meta-regression (Friedrich et al., 2008). The natural logarithm of the ratio of ADG for each comparison group to the reference group within each study (the group with the lowest FEC for the growth period) was the dependent variable for meta-regression. The lower bound of the raw ratio is zero whereas the logarithm of the ratio can extend between negative and positive infinity and so is more suitable for linear regression. The standard deviation of the natural logarithm of the ratio of means was approximated as the sum of the standard deviations of ADG for the comparison and reference group. The key advantage of the ratio of means method is the normalisation of group performance within individual studies (scaled to a common reference ratio of 1 when there is an equivalent growth rate between the comparison and reference group). This approach helps control study-level sources of variation that influence raw growth rate (such as breed, production system or use of hormonal growth promotants) because the ratio of means captures relative performance of each group against the study reference group.

The common logarithm (base 10) difference in FEC between the study and reference group was used as the predictor variable. The difference in FEC between comparison and reference group was chosen over the ratio of FECs because the difference in counts better captures biological effect magnitude than a ratio. The difference in FEC between groups also partly controls for any measurement error arising from technique for estimating egg counts as both groups were assessed using

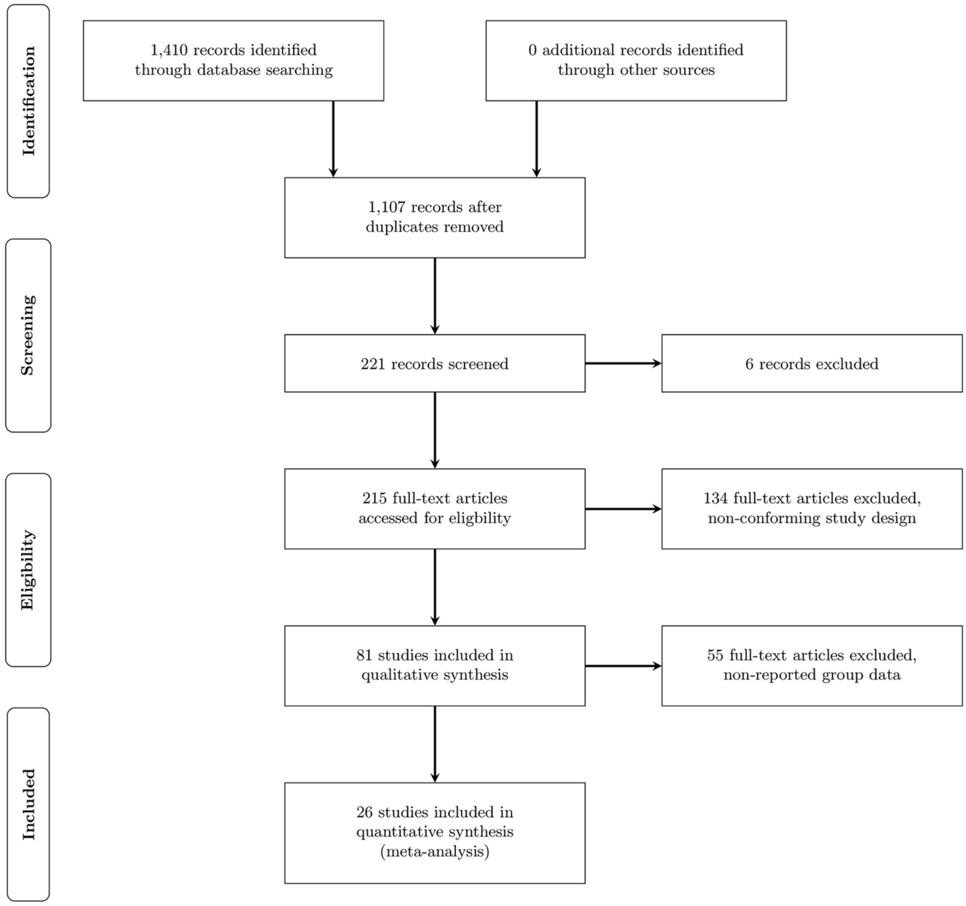

Fig. 1. PRISMA flow chart.

the same method. The common logarithm of the difference between FECs was used because this scale is more amenable to effective communication of results.

The Calc spreadsheet of LibreOffice was used for data entry and basic data manipulation (Foundation, 2020). The R Language and Environment for Statistical Computing was used for analysis (R Core Team, 2012). The R library meta was used for meta-analysis and meta-regression (Balduzzi et al., 2019). Statistical significance was set at $p < 0.05$.

Comparison group (within study) and study were included as random effects in meta-analysis. Heterogeneity was examined by inspection of funnel plots and examination of the Q statistic. The duration of the growth period and any interaction with FEC difference were forwarded to the meta-regression model to adjust for potential confounding effects of developing natural immunity to strongyle infection with increasing age in cattle across studies of differing duration. Linear and curvilinear relationships between predictor and dependent variable were examined for continuous predictor variable. Predictor variables with a statistically significant Wald statistic for the beta coefficient were retained in the model. Predictor variables comprising part of an interaction term with a statistically significant Wald statistic for the beta coefficient were also retained in the model even if the Wald statistic for variables outside of the interaction terms was not statistically significant. A subset analysis of meta-analysis and meta-regression by continent of study was undertaken to examine geographical difference in the relationship between ADG ratio and FEC difference between groups. Linear regression was used to test for funnel plot asymmetry of the final meta-regression model.

Table 1
Publication search and filtering for meta-analysis.

Reason	No. publications
Total records identified	1410
Total unique publications identified	1107
Title/abstract not suitable	885
Paper not attainable	6
Study design inappropriate	134
No FECs from growth period	1
No group ADG SD/SEM reported	50
Confounded comparator	2
Errors in reported results	3
Included in meta-analysis	26

3. Results

The *Web of Science* and *Google Scholar* searches identified 1410 records of which there were 1107 unique publications whose title and/or abstract suggested they may be useful. Further review of the abstracts identified 221 publications for further examination. Of these, 215 were obtained, of which 81 met study design eligibility requirements. One publication did not have adequate growth-period FECs, and a further 50 did not adequately record group live weight variance/standard deviation and/or provide a standard error of the mean for each group. There was unbalanced confounding in two publications (dissimilar exposures between comparison and reference groups), and three papers likely had errors in reported estimates. A total of 26 publications providing 85 groups satisfied all inclusion criteria and were sent forward for meta-analysis. The *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) flow chart is presented in Fig. 1 with extra detail on

Table 2
Meta-analysis publication summary.

Manuscript	Country	Study description	No. Comp.	Study type
Kennedy (Kennedy, 1990)	Canada	Pasture-based beef cow/calf field trial	1	Treatment (anthelmintic); negative control
Boyles (Boyles et al., 1993)	USA	Feedlot beef field trial	1	Treatment (anthelmintic); negative control
Purvis (Purvis et al., 1994)	USA	Pasture-based beef heifer field trial	5	Treatment (anthelmintic); negative control
Larson (Larson et al., 1995)	USA	Pasture-based beef heifer field trial	1	Treatment (anthelmintic); negative control
Williams (Williams et al., 1995)	USA	Pasture-based cross beef heifer field trial	1	Treatment (anthelmintic); negative control
Agneessens (Agneessens et al., 1997)	Belgium	Pasture-based beef cow/calf field trial	1	Prospective cohort (observational)
Fernandez (Fernandez et al., 1998)	USA	Feedlot beef steer field trial	2	Treatment (anthelmintic); positive + negative controls
Schunicht (Schunicht et al., 2000)	Canada	Feedlot beef yearling field trial	1	Treatment (anthelmintic); positive control
Yamane (Yamane et al., 2000)	Japan	Pasture-based dairy heifer field trial	1	Treatment (anthelmintic); positive control (acaricide)
Elsener (Elsener et al., 2001)	Canada	Pasture-based dairy heifer field trial	2	Treatment (anthelmintic); positive control
Epperson (Epperson et al., 2001)	USA	Pasture-based beef heifer field trial	1	Treatment (anthelmintic); negative control
Cleale (Cleale et al., 2004)	USA	Pasture-based beef heifer and steer field trial	4	Treatment (anthelmintic); negative control
Waruiru (Waruiru, 2004)	Kenya	Pasture-based cross dairy heifer field trial	1	Treatment (anthelmintic); positive control (nutrition)
Mertz (Mertz et al., 2005)	USA	Pasture-based beef field trial	11	Treatment (anthelmintic); negative control
Reinhardt (Reinhardt et al., 2006)	USA	Feedlot beef heifer field trial	2	Treatment (anthelmintic); positive control
O'Shaughnessy (O'Shaughnessy et al., 2014)	Ireland	Pasture-based beef cow/calf field trial	1	Treatment (anthelmintic); positive control
Fazzio (Fazzio et al., 2016)	Argentina	Feedlot beef calf trial	2	Treatment (anthelmintic); positive control
Merlin (Merlin et al., 2016)	France	Pasture-based dairy heifer field trial	3	Cohort (observational)
Edmonds (Edmonds et al., 2018)	USA	Pasture-based beef steer field trial	3	Treatment (anthelmintic); positive + negative controls
Hoglund (Hoglund et al., 2018)	Sweden	Pasture-based dairy and dairy-beef cross field trial	2	Cohort (exposure)
Hogberg (Hogberg et al., 2019)	Sweden	Pasture-based mixed dairy and dairy-beef cross field trial	1	Cohort (exposure)
Canton (Canton et al., 2020)	Argentina	Pasture-based beef male calf field trial	4	Treatment (anthelmintic); positive + negative controls
das Neves (das Neves et al., 2020)	Brazil	Pasture-based dairy-beef cross cow/calf field trial	2	Treatment (anthelmintic); positive + negative controls
Dudley (Dudley and Smith, 2020)	USA	Pasture-based dairy heifer field trial	1	Treatment (anthelmintic); negative control
Kasimanickam (Kasimanickam and Kasimanickam, 2021)	USA	Pasture-based beef field trial	4	Treatment (anthelmintic); positive control
Hogberg b ((Hogberg et al., 2021))	Sweden	Pasture-based dairy steer field trial	1	Cohort (exposure)

Table 3
Meta-analysis publication bias assessment.

Manuscript	Allocation	Losses (attribution bias)
Kennedy	Not described	Nil
Boyles	Random assignment	Nil
Purvis	Random assignment	Nil
Larson	Stratified allocation	Nil
Williams	Randomised block allocation	Nil
Agneessens	Random assignment to exposure group\	Nil
Fernandez	Randomised block allocation	Nil
Schunicht	Random assignment	Reported, but no significant difference in losses between groups
Yamane	Randomised block allocation	Nil
Elsener	Randomised block allocation	Nine accidental losses from negative control group
Epperson	Randomised stratified allocation	3 animals lost ear tags each per group - excluded from analysis
Cleale	Randomised block allocation	2 animals from separate sites lost from treatment group
Waruiru	Weight based (block) allocation	Not reported
Mertz	Random assignment	Not reported
Reinhardt	Random assignment	Reported, but no difference between groups in mortality rate
O'Shaughnessy	Random assignment	Removals reported but groups not stated
Fazzio	Random assignment	Not reported
Merlin	Cohorts determined by exposure within farm	Not reported
Edmonds	Randomised block allocation	Not reported
Hoglund	Block allocation	Not reported
Hogberg	Block allocation	Not reported
Canton	Randomised block allocation	Not reported
das Neves	Block allocation	Not reported
Dudley	Randomised block allocation	Not reported
Kasmanickam	Randomised block allocation	Not reported
Hogberg b	Block allocation	Not reported

paper exclusions in Table 1. The studies included in the meta-analysis are summarised in Table 2 and the bias assessment presented in Table 3. Given most parasitological studies require management of cohorts at group level, blinding of participants was not considered feasible for most studies so this potential bias was not examined.

There were many potentially useful publications that could not be

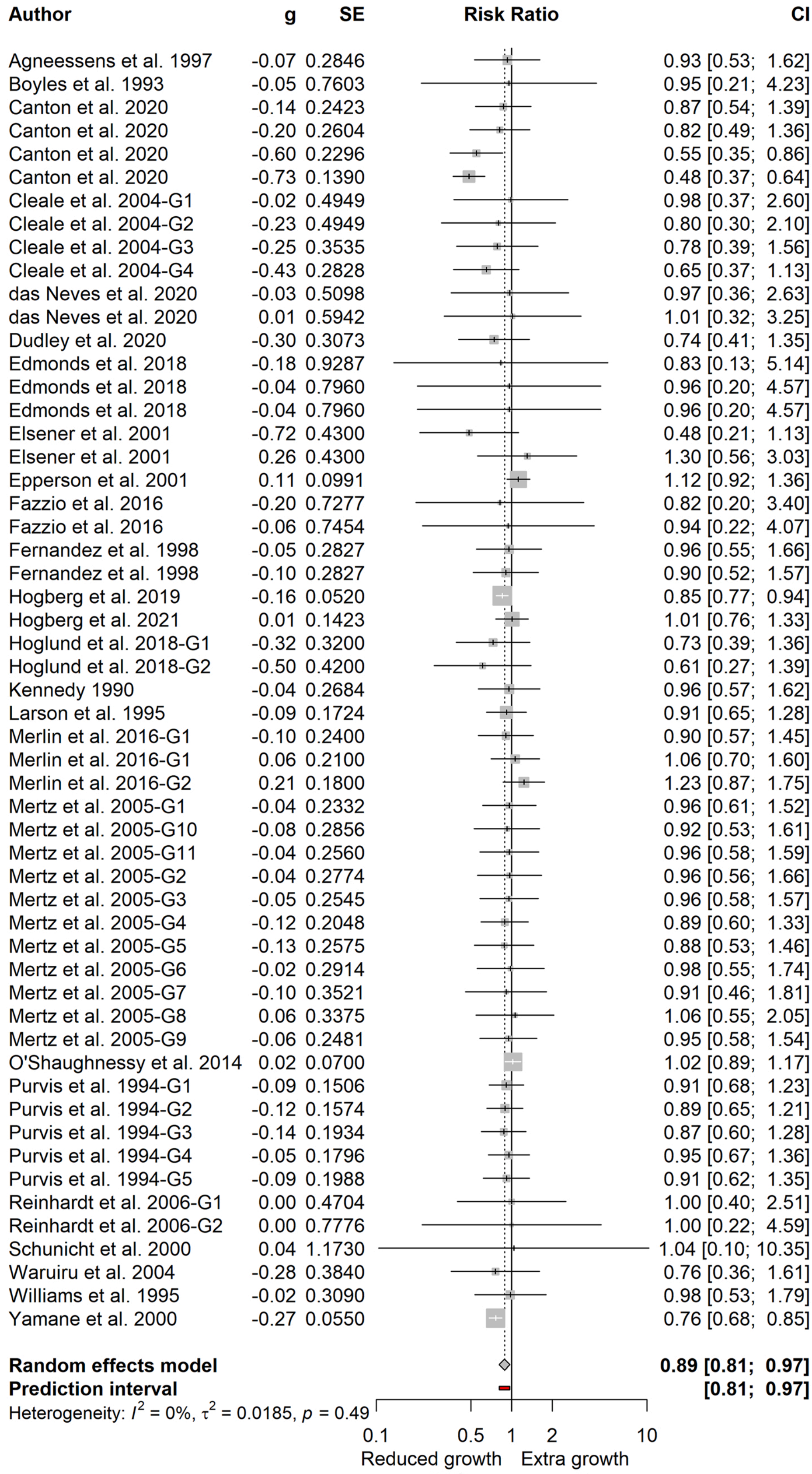

Fig. 2. Forest plot of average daily weight gain ratio meta-analysis.

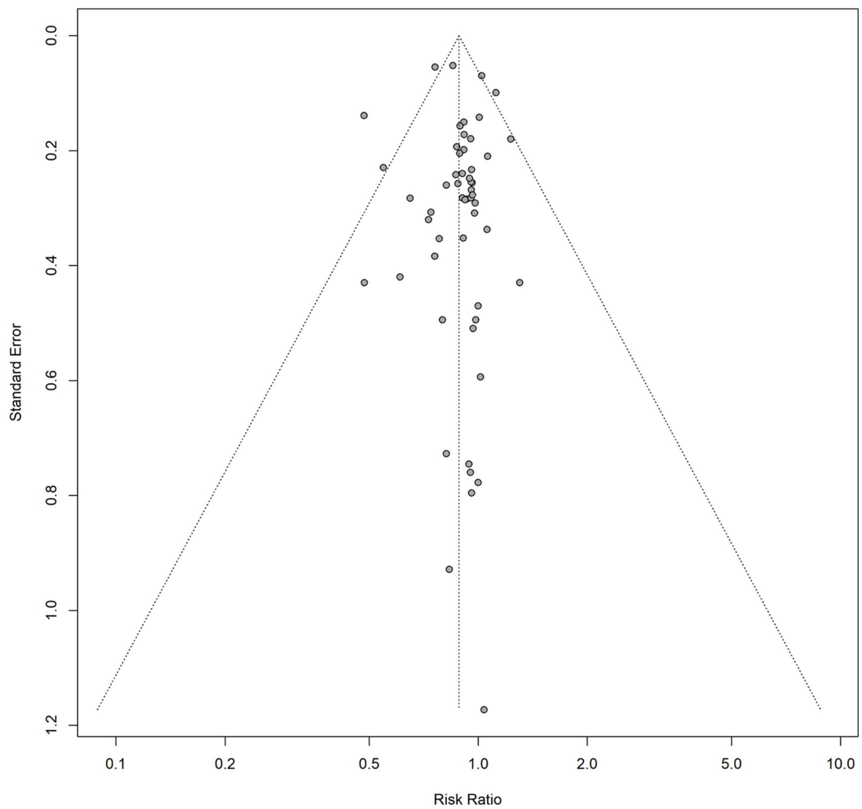

Fig. 3. Funnel plot of average daily weight gain ratio meta-analysis.

included in the meta-analysis. Losses arose primarily from failure to publish standard deviations for ADG or standard errors of the mean for ADG. Some publications did not present FECs in a form suitable for extraction and inclusion in the meta-analysis; mostly only providing FECs graphically. Not all FEC plots were sufficiently distinct to allow data to be reliably harvested using the *WebPlot Digitizer* application. Combined, this resulted in loss of studies and potentially valuable information from the meta-analysis. This was found to be an issue in other reviews of ADG (Baltzell et al., 2015).

For publications that only presented FECs graphically, the application *WebPlot Digitizer* was used to estimate the point values from plots (Rohatgi, 2021). The arithmetic average FEC for the growth period was calculated from these estimates.

Fifteen studies were undertaken in North America, with six studies conducted in Europe, three studies in South America and with Asia/Oceania and Africa each contributing a single study providing a total of 26 studies, comprising 59 comparison ratios.

The meta-analysis forest plot is presented in Fig. 2. Groups with high strongyle burdens, as indicated by elevated FECs, had lower ADGs than groups with lower worm burdens. The mean ratio of ADG for high worm burden group in comparison to low worm burden group was 0.89 (95% CI: 0.81–0.97). There was minimal heterogeneity ($Q = 53.82$, on 58 degrees of freedom; p-value = 0.63). The meta-analysis funnel plot is presented in Fig. 3. The linear regression test for funnel plot asymmetry was not significant ($t = 0.67$, $p = 0.51$).

The common logarithm of the FEC difference between the comparison and reference group (plus 1) was the predictor variable of interest. The duration of the study (growth) period in months was offered to the model along with an interaction with the common logarithm of FEC difference. This was to control for any potential confounding effect of development of resistance to strongyle parasites with increasing exposure, however the duration of study was not a significant predictor. There was no significant effect of continent, industry (dairy or beef), production system (pasture or feedlot) on the outcome. The use of the logarithm of the ratio of means within study is a measure of relative performance of groups within each study and this likely controlled any effect of these between-study confounders in analysis. The final model included only the common logarithm of FEC difference (plus 1) and is summarised in Table 4. The common log of the difference in FEC between comparison and reference group (plus 1) was associated with a 0.131 reduction in the log of the ratio of ADG between comparison and reference groups. The meta-regression plot is presented in Fig. 4. The predicted impact of increasing difference in FEC between groups on relative daily growth rate performance is presented in Fig. 5. Table 5.

Table 4
Meta-regression of $\log_{10}$ of faecal egg count difference on log of average daily gain ratio.

	Estimate	S.E.	Z-value	p-value
Intercept	0.041	0.063	0.649	0.52
Log_{10} difference FEC (+1)	-0.131	0.040	-3.310	0.001

The geographical subset analysis is summarised in Table 3. All continents had meta-analysis risk-ratios less than one and all had negative meta-regression beta coefficients for the common logarithm of difference in FEC between comparison and reference groups (plus 1).

4. Discussion

Whilst some residual heterogeneity remained after combining studies in the meta-analysis, subset analysis indicated that the direction of effect of elevated FEC on reducing ADG was consistent across continents, animal class and production systems. The generalisable impact of strongyle parasitism, as measured by FEC, on daily weight gain of growing cattle is negative and this is independent of continent and production system. Reduced ADG was often present when the

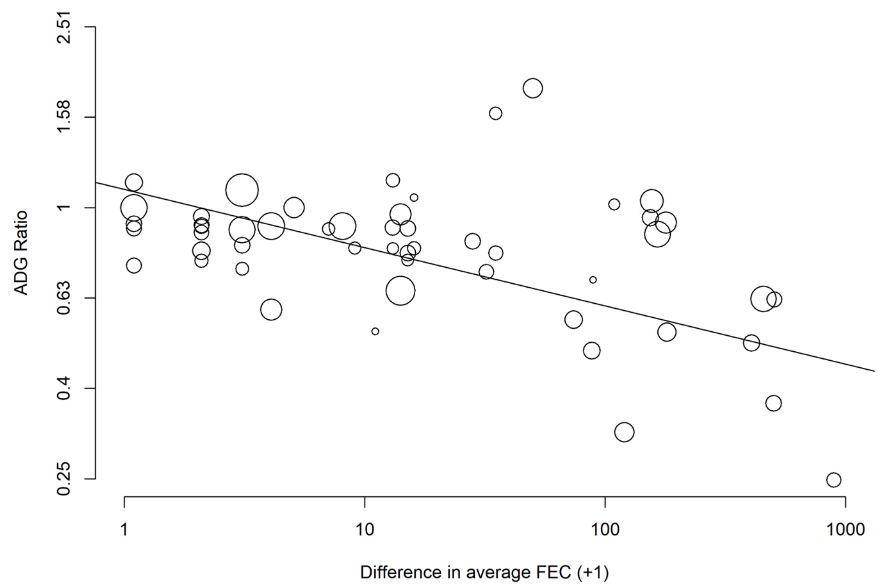

Fig. 4. Meta-regression of $\log_{10}$ faecal egg count difference (+1) between groups on the log of the ratio of average daily weight gain. Point size is linked to the size of the standard error of the ratio, which is determined by the number of animals within each group and the variation in growth rate between individuals within the group.

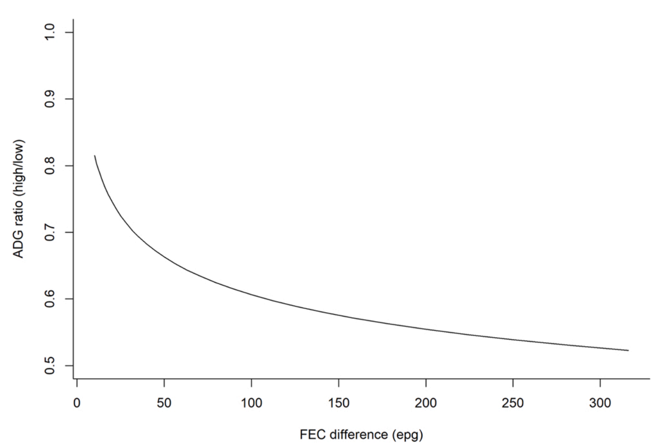

Fig. 5. Predicted average daily weight gain ratio (ADG) by faecal egg count (FEC) difference between comparison and reference group.

Table 5
Meta-analysis and meta-regression geographical breakdown.

Continent	No. studies	No. comp.	Risk ratio	95% CI	Beta	S. E.	P-value
Nth America	15	40	0.87	0.76–0.99	-0.149	.07	0.03
Europe	6	9	0.98	0.84–1.06	-0.180	.08	0.03
Sth America	3	8	0.67	0.52–0.88	-0.378	.15	0.01
Asia/ oceania	1	1	0.76	0.68–0.85	NA	NA	NA
Africa	1	1	0.76	0.36–1.61	NA	NA	NA
All	26	59	0.88	0.82–0.95	-0.131	.04	< 0.01

differences in the faecal egg count was only 50 or less between reference and comparison groups. It should be noted that for several observations a higher ADG was recorded in the comparison group (the group with the higher FEC). However, this effect was not observed when the difference in faecal egg count was 100 or more between the comparison and reference groups.

The relationship between the log of the ratio of ADG and the common logarithm of the difference in FEC was linear. This means the relationship is curvilinear on the original scale. Strongyle parasitism reduces ADG with the lowest growth rates occurring in groups with the highest FEC burden. The reduction in ADG due to increasing strongyle parasite burden identified in this review is consistent with other findings (Beltrán et al., 2020; Charlier et al., 2009; Merlin et al., 2017; Sutherland and Bullen, 2015; Vercruysse and Claerebout, 2001). A meta-analysis of studies across western Europe showed that in untreated first season grazing calves, 53 mobs considered 'clinical' (mean peak of 275 epg) had ADG of 375 g/head/day compared to 32 'subclinical' mobs (mean peak of 100 epg) at 530 g/head/day (Shaw et al., 1997).

Although the egg output of different gastrointestinal nematodes varies (Bailey, 2008), it was beyond the scope of this investigation to quantify the impact on ADG attributable to different species of parasites. A recent meta-analysis identified a negative impact of gastrointestinal nematode infections on weight gain of growing sheep (Mavrot et al., 2015). This study also described a negative correlation between FEC and ADG, regardless of the worm species identified.

This study shows that WEC differences of 100 epg in young grazing cattle are associated with a material depression in ADG (see Fig. 5). The impact of parasite burdens showing worm egg counts below 100epg have previously been demonstrated (George et al., 2020; Stromberg et al., 2012). Practitioners and producers will determine their own thresholds for intervention, depending on the cost of mustering and treatment or other interventions such as supplementing feed, compared with the costs associated with depressed growth rates and pasture larval contamination. Effective control of strongyle parasite burden in growing cattle provides growth benefits. Identifying sustainable and cost-effective strongyle parasite controls remains an important objective for effective management and production of cattle globally. This paper provides evidence to justify investment in interventions for young cattle to minimise exposure to the larvae of, as well as treating excessive burdens of, gastrointestinal nematodes and in doing so improve both productivity and welfare.

Declarations

Ethics approval is not applicable. No animal or human experimentation was undertaken.

Consent to publication is not applicable for the reasons listed above.

All data generated or analysed during this study are available from referenced published articles (meta-analysis).

RWS has no competing interests.

RWS received funding from Zoetis Australia to undertake this work.

RWS undertook the literature review, meta-analysis. All authors contributed to study design and writing of the manuscript.

CRediT authorship contribution statement

RWS co-designed the study, undertook the systematic literature review, conducted the analysis and authoring of the manuscript, ASH, MP and SO contributed to study design, assisted with result interpretation and co-authored the paper.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Richard Shephard reports financial support was provided by Zoetis Australia Pty Limited.

References

Agneessens, J., Dorny, P., Hollanders, W., Claerebout, E., Vercruysse, J., 1997. Epidemiological observations on gastrointestinal nematode infections in grazing cow-calf pairs in Belgium. Vet. Parasitol. 69, 65–75. https://doi.org/10.1016/S0304-4017(96)01116-8.

Bailey, J., 2008. The integration of grazing management and anthelmintic treatment to provide clean lambing paddocks in the northern tablelands region of NSW, Australia. (Doctoral Thesis). University of New England, Armidale, NSW.

Balduzzi, S., Rücker, G., Schwarzer, G., 2019. How to perform a meta-analysis with R: a practical tutorial. Evid.-Based Ment. Health 153–160.

Baltzell, P., Engelken, T., O'Connor, A.M., 2015. A critical review and meta-analysis of the magnitude of the effect of anthelmintic use on stocker calf production parameters in Northern US States. Vet. Parasitol. 214, 2–11. https://doi.org/10.1016/j.vetpar.2015.09.019.

Beltrán, D., Couto, L., Heller, L., Cavalcante, A., Nicaretta, J., Cruvinel, L., Maciel, W., Teixeira, W., Felippelli, G., Gomes, L., Ferreira, L., Costa, A., Borges, F., Lopes, W., 2020. Association between fecal egg count and weight gain in young beef cattle. Livest. Sci. 244, 104335 https://doi.org/10.1016/j.livsci.2020.104335.

Bisset, S.A., 1994. Helminth parasites of economic importance in cattle in New Zealand. null 21, 9–22. ⟨https://doi.org/10.1080/03014223.1994.9517972⟩.

Boyles, S., Johnson, L., Slanger, W., Kreft, B., Kirsch, J., 1993. The effect of deworming naturally infected heifers on liveweight gain, reproductive-performance and fecal egg counts. Can. J. Anim. Sci. 73, 287–293. https://doi.org/10.4141/cjas93-031.

Bryan, R.P., Kerr, J.D., 1989. The relation between the natural worm burden of steers and the faecal egg count differentiated to species. Vet. Parasitol. 30, 327–334. https://doi.org/10.1016/0304-4017(89)90102-7.

Burggraaf, V.T., Brooky, A.R., Boom, C.J., 2007. Response of beef calves to different levels of postweaning ingestion of gastrointestinal parasite larvae. Aust. J. Exp. Agric. 47, 1297–1303.

Canton, C., Ceballos, L., Dominguez, M.P., Fiel, C., Liron, J.P., Moreno, L., Canton, L., Bernat, G., Lanusse, C., Alvarez, L., 2020. Impact on beef cattle productivity of infection with anthelmintic-resistant nematodes. N. Z. Vet. J. 68, 187–192. https://doi.org/10.1080/00480169.2019.1698999.

Charlier, J., Hoglund, J., von Samson-Himmelstjerna, G., Dorny, P., Vercruysse, J., 2009. Gastrointestinal nematode infections in adult dairy cattle: impact on production, diagnosis and control. Vet. Parasitol. 164, 70–79. https://doi.org/10.1016/j.vetpar.2009.04.012.

Charlier, J., van der Voort, M., Kenyon, F., Skuce, P., Vercruysse, J., 2014. Chasing helminths and their economic impact on farmed ruminants. Trends Parasitol. 30, 361–367.

Cleale, R.M., Hart, K.B., Hutchens, D.E., Johnson, E.G., Paul, A.J., Smith, L.L., Tucker, C., Yazwinski, T.A., Doscher, M.E., Grubbs, S.T., Wulster-Radcliffe, M., Amodie, D.M., 2004. Effects of subcutaneous injections of a long acting moxidectin formulation in grazing beef cattle on parasite fecal egg reduction and animal weight gain. Vet. Parasitol. 126, 325–338. https://doi.org/10.1016/j.vetpar.2004.08.010.

R. Core Team, 2012. R: A Language and Environment for Statistical Computing. Vienna, Austria.

Corwin, R.M., 1997. Economics of gastrointestinal parasitism of cattle. Vet. Parasitol. 72, 451–460. https://doi.org/10.1016/S0304-4017(97)00110-6.

das Neves, J.H., Carvalho, N., Talamini do Amarante, A.F., 2020. Gastrointestinal nematode infections do not hinder the development of Simmental X Nellore crossbred calves raised with a nutritionally enhanced diet. Rev. Bras. Parasitol. Vet. 29, e015819 https://doi.org/10.1590/S1984-29612020006.

Dudley, H.B., Smith, G.W., 2020. Efficacy and production benefits following use of eprinomectin extended-release injection in pastured dairy heifers. Vet. Parasitol. 282, 109157 https://doi.org/10.1016/j.vetpar.2020.109157.

Edmonds, M.D., Vatta, A.F., Marchiondo, A.A., Vanimisetti, H.B., Edmonds, J.D., 2018. Concurrent treatment with a macrocyclic lactone and benzimidazole provides season long performance advantages in grazing cattle harboring macrocyclic lactone resistant nematodes. Vet. Parasitol. 252, 157–162. https://doi.org/10.1016/j.vetpar.2018.02.009.

Elsener, J., Villeneuve, A., DesCoteaux, L., 2001. Evaluation of a strategic deworming program in dairy heifers in Quebec based on the use of moxidectin, an endectocide with a long persistency. Can. Vet. J.-Rev. Vet. Can. 42, 38–44.

Epperson, W.B., Kenzy, B.D., Mertz, K., Hildreth, M.B., 2001. A single pasture limited treatment approach to estimate production loss from gastrointestinal nematodes in grazing stocker cattle. Vet. Parasitol. 97, 269–276. https://doi.org/10.1016/S0304-4017(01)00408-3.

Eysker, M., Ploeger, H.W., 2000. Value of present diagnostic methods for gastrointestinal nematode infections in ruminants. Parasitology 120, S109–S119.

Fazzio, L.E., Streitenberger, N., Galvan, W.R., Sanchez, R.O., Gimeno, E.J., Sanabria, R.E.F., 2016. Efficacy and productive performance of moxidectin in feedlot calves infected with nematodes resistant to ivermectin. Vet. Parasitol. 223, 26–29. https://doi.org/10.1016/j.vetpar.2016.04.003.

Fernandez, M.I., Woodward, B.W., Stromberg, B.E., 1998. Effect of diatomaceous earth as an anthelmintic treatment on internal parasites and feedlot performance of beef steers. Anim. Sci. 66, 635–641. https://doi.org/10.1017/S1357729800009206.

Foundation, T.D., 2020. LibreOffice Calc.

Friedrich, J.O., Adhikari, N.K., Beyene, J., 2008. The ratio of means method as an alternative to mean differences for analyzing continuous outcome variables in meta-analysis: a simulation study. BMC Med. Res. Methodol. 8, 32. https://doi.org/10.1186/1471-2288-8-32.

George, M., George, M., Kotzke, A., 2020. Production impacts and resistance of gastrointestinal parasites in feedlot cattle (No. B.FLT.3002). Meat & Livestock Australia, Sydney, Australia.

Hogberg, N., Lidfors, L., Hessle, A., Arvidsson Segerkvist, K., Herlin, A., Hoglund, J., 2019. Effects of nematode parasitism on activity patterns in first-season grazing cattle. Vet. Parasitol. X 1. https://doi.org/10.1016/j.vpoa.2019.100011, 100011.

Hogberg, N., Hessle, A., Lidfors, L., Baltrusis, P., Claerebout, E., Hoglund, J., 2021. Subclinical nematode parasitism affects activity and rumination patterns in first-season grazing cattle. Animal 15, 100237. https://doi.org/10.1016/j.animal.2021.100237.

Högberg, Niclas, Hessle, Anna, Lidfors, Lena, Baltrušis, Paulius, Claerebout, Edwin, Höglund, Johan, 2021. Subclinical nematode parasitism affects activity and rumination patterns in first-season grazing cattle. Animal 15, 8.

Hoglund, J., Hessle, A., Zaralis, K., Arvidsson-Segerkvist, K., Athanasiadou, S., 2018. Weight gain and resistance to gastrointestinal nematode infections in two genetically diverse groups of cattle. Vet. Parasitol. 249, 88–91. https://doi.org/10.1016/j.vetpar.2017.11.011.

Hutchings, M.R., Athanasiadou, S., Kyriazakis, I., Gordon, I, J., 2003. Can animals use foraging behaviour to combat parasites? Proc. Nutr. Soc. 62, 361–370. https://doi.org/10.1079/PNS2003243.

Kasimanickam, R.K., Kasimanickam, V.R., 2021. Association of gastrointestinal parasite burden, serum cytokines and hormones concentrations, and pregnancy in Angus-cross beef cows. Vet. Parasitol. 295, 109464 https://doi.org/10.1016/j.vetpar.2021.109464.

Kennedy, M., 1990. Effect of ivermectin on weight-gain of calves on pasture in Alberta. Can. Vet. J.-Rev. Vet. Can. 31, 589–590.

Kenyon, F., Jackson, F., 2012. Targeted flock/herd and individual ruminant treatment approaches. Vet. Parasitol. 186, 10–17. https://doi.org/10.1016/j.vetpar.2011.11.041.

Ketzis, J.K., Vercruysse, J., Stromberg, B.E., Larsen, M., Athanasiadou, S., Houdijk, J.G.M., 2006. Evaluation of efficacy expectations for novel and non-chemical helminth control strategies in ruminants. Vet. Parasitol. 139, 321–335. https://doi.org/10.1016/j.vetpar.2006.04.022.

Larson, R., Corah, L., Spire, M., Cochran, R., 1995. Effect of treatment with ivermectin on reproductive-performance of yearling beef heifers. Theriogenology 44, 189–197. https://doi.org/10.1016/0093-691X(95)00168-8.

Mavrot, F., Hertzberg, H., Torgerson, P., 2015. Effect of gastro-intestinal nematode infection on sheep performance: a systematic review and meta-analysis. Parasit. Vectors 8, 557. https://doi.org/10.1186/s13071-015-1164-z.

McKellar, Q.A., Jackson, F., 2004. Veterinary anthelmintics: old and new. Trends Parasitol. 20, 456–461. https://doi.org/10.1016/j.pt.2004.08.002.

Merlin, A., Chauvin, A., Madouasse, A., Froger, S., Bareille, N., Chartier, C., 2016. Explaining variability in first grazing season heifer growth combining individually measured parasitological and clinical indicators with exposure to gastrointestinal nematode infection based on grazing management practice. Vet. Parasitol. 225, 61–69. https://doi.org/10.1016/j.vetpar.2016.05.006.

Merlin, A., Chauvin, A., Lehebel, A., Brisseau, N., Froger, S., Bareille, N., Chartier, C., 2017. End-season daily weight gains as rationale for targeted selective treatment against gastrointestinal nematodes in highly exposed first-grazing season cattle. Prev. Vet. Med. 138, 104–112. https://doi.org/10.1016/j.prevetmed.2017.01.011.

Mertz, K.J., Hildreth, M.B., Epperson, W.B., 2005. Assessment of the effect of gastrointestinal nematode infestation on weight gain in grazing beef cattle. J. Am. Vet. Med. Assoc. 226, 779–783. https://doi.org/10.2460/javma.2005.226.779.

Molento, M.B., Buzatti, A., Sprenger, L.K., 2016. Pasture larval count as a supporting method for parasite epidemiology, population dynamic and control in ruminants. Livest. Sci. 192, 48–54.

Nielsen, M.K., 2021. Parasite faecal egg counts in equine veterinary practice. Equine Vet. Educ. https://doi.org/10.1111/eve.13548.

O'Shaughnessy, J., Earley, B., Mee, J.F., Doherty, M.L., Crosson, P., Barrett, D., Macrelli, M., de Waal, T., 2014. Nematode control in spring-born suckler beef calves

using targeted selective anthelmintic treatments. Vet. Parasitol. 205, 150–157. https://doi.org/10.1016/j.vetpar.2014.07.009.
Purvis, H., Whittier, J., Boyles, S., Johnson, L., Ritchie, H., Rust, S., Faulkner, D., Lemenager, R., Hendrix, K., 1994. Weight-gain and reproductive-performance of spring-born beef heifer calves intraruminally administered oxfendazole. J. Anim. Sci. 72, 817–823. https://doi.org/10.2527/1994.724817x.
Rashid, M., Rashid, M.I., Akbar, H., Ahmad, L., Hassan, M.A., Ashraf, K., Saeed, K., Gharbi, M., 2019. A systematic review on modelling approaches for economic losses studies caused by parasites and their associated diseases in cattle. Parasitology 146, 129–141. https://doi.org/10.1017/S0031182018001282.
Reinhardt, C.D., Hutcheson, J.P., Nichols, W.T., 2006. A fenbendazole oral drench in addition to an ivermectin pour-on reduces parasite burden and improves feedlot and carcass performance of finishing heifers compared with endectocides alone. J. Anim. Sci. 84, 2243–2250. https://doi.org/10.2527/jas.2005-598.
Rohatgi, A., 2021. Webplotdigitizer: Version 4.5.
Sangster, N.C., 2001. Managing parasiticide resistance. Vet. Parasitol. 98, 89–109. https://doi.org/10.1016/S0304-4017(01)00425-3.
Schunicht, O.C., Guichon, P.T., Booker, C.W., Jim, G.K., Wildman, B.K., Ward, T.I., Bauck, S.W., Gross, S.J., 2000. Comparative cost-effectiveness of ivermectin versus topical organophosphate in feedlot yearlings. Can. Vet. J.-Rev. Vet. Can. 41, 220–224.
Shaw, D.J., Vercruysse, J., Claerebout, E., Agneessens, J., Dorny, P., 1997. Gastrointestinal nematode infections of first-season grazing calves in Belgium: general patterns and the effect of chemoprophylaxis. Vet. Parasitol. 69, 103–116. https://doi.org/10.1016/S0304-4017(96)01105-3.
Shaw, D.J., Vercruysse, J., Claerebout, E., Dorny, P., 1998. Gastrointestinal nematode infections of first-grazing season calves in western Europe: general patterns and the effect of chemoprophylaxis. Vet. Parasitol. 75, 115–131. https://doi.org/10.1016/S0304-4017(97)00214-8.
Stromberg, B.E., Gasbarre, L.C., Waite, A., Bechtol, D.T., Brown, M.S., Robinson, N.A., Olson, E.J., Newcomb, H., 2012. Cooperia punctata: effect on cattle productivity. Vet. Parasitol. 183, 284–291. https://doi.org/10.1016/j.vetpar.2011.07.030.
Sutherland, I.A., Bullen, S.L., 2015. Parasite control in pasture-grazed dairy cattle: are we at the edge of a precipice? Anim. Prod. Sci. 55, 916–921.
Sykes, A.R., 1994. Parasitism and production in farm animals. Anim. Sci. 59, 155–172. https://doi.org/10.1017/S0003356100007649.
Teixeira, W.F.P., Gomes, L.V.C., Felippelli, G., Buzzulini, C., Zapa, D.M.B., Cavalcante, A. S. de A., Borges, D.G.L., Ferreira, L.L., Santos, T.R., dos, Soares, V.E., Arnhold, E., Costa, A.J. da, Borges, F. de A., Lopes, W.D.Z., 2021. Investigation of fecal egg counts versus worm burden and helminth fauna in cattle treated or not with macrocyclic lactones in a tropical region. Vet. Parasitol. 300, 109618 https://doi.org/10.1016/j.vetpar.2021.109618.
Vercruysse, J., Claerebout, E., 2001. Treatment vs non-treatment of helminth infections in cattle: defining the threshold. Vet. Parasitol. 98, 195–214. https://doi.org/10.1016/S0304-4017(01)00431-9.
Waller, P.J., 2003. The future of anthelmintics in sustainable parasite control programs for livestock. Helminthologia 40, 97–102.
Waruiru, R.M., 2004. The influence of supplementation with urea-molasses blocks on weight gain and nematode parasitism of dairy calves in central Kenya. Vet. Res. Commun. 28, 307–315. https://doi.org/10.1023/B:VERC.0000026670.64936.18.
Williams, J.C., Loyacano, A.F., Broussard, S.D., Coombs, D.F., DeRosa, A., Bliss, D.H., 1995. Efficacy of a spring strategic fenbendazole treatment program to reduce numbers of Ostertagia ostertagi inhibited larvae in beef stocker cattle. Vet. Parasitol. 59, 127–137. https://doi.org/10.1016/0304-4017(94)00745-X.
Yamane, I., Arai, S., Nakamura, Y., Hisashi, M., Fukazawa, Y., Onuki, T., 2000. A clinical trial to evaluate the effects of flumethrin or ivermectin treatment on hemoparasites, gastrointestinal parasites, conception and daily weight gain in a dairy farm in Japan. Prev. Vet. Med. 43, 203–210. https://doi.org/10.1016/S0167-5877(99)00096-3.