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Conjunctival mucous membrane colour as an indicator for the targeted selective treatment of haemonchosis and of the general health status of peri-urban smallholder goats in southern Malawi.

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Abstract

The world's growing population is becoming increasingly centred around large cities, affording opportunities for peri-urban food production. Goats are well-suited to conversion of resources that are available in peri-urban settings into meat and occasionally milk. *Haemonchus contortus* has been described as "the nemesis of small ruminant production systems in tropical and subtropical regions"; hence control of haemonchosis through planned animal health management affords a pragmatic first step in improving the production efficiency of peri-urban goats. This study of peri-urban goat production investigated the potential value of targeted selective treatment of haemonchosis. 452 peri-urban goat keepers in southern Malawi were visited during three seasonal periods with relevance to the epidemiology of haemonchosis. 622, 599 and 455 individually identified goats were clinically examined during the dry season, the rainy season, and shortly after the end of the rainy season, respectively. Data were recorded for sex, age, weight, conjunctival mucous membrane colour score (FAMACHA©), body condition score (BCS) and faecal worm egg count (FEC); and where possible for pregnancy and lactation status. Animals with pale ocular mucous membranes were treated with 10 mg/kg albendazole, then re-examined 14 days later. Animals with pink mucous membranes, but FECs ≥250 eggs per gram were also re-examined and treated 14 days later. The results show high variability in growth rates deduced from the ages and bodyweights of each of 999 goats at the time of their enrolment. FAMACHA© scores alone were a poor index for the targeted selective treatment of haemonchosis, because they failed to identify too many animals that would have required treatment at different times of year and using different FAMACHA© and FEC cut-offs. Combining the indices of FAMACHA© scores ≥4, body condition scores ≥2, and age >18 months was more reliable in identifying those animals requiring treatment when different epidemiologically-relevant FEC thresholds for different seasons were taken into account. Inclusion of late pregnancy or

early lactation status would have resulted in very few animals requiring treatment being missed. The use of conjunctival mucous membrane colour scoring in this way provided a valuable insight of the general health status of the peri-urban goats, to create opportunities for planned animal health management to improve productivity. The efficacy of albendazole treatment was poor, putatively due to drug resistance, or poor drug bioavailability in goats. In summary, our study shows opportunities for better production efficiency in peri-urban goats, and demonstrates the value of simple clinical diagnostic indices as decision support tools in planned animal health management.

Introduction

Continuing improvement of agricultural production efficiency through the twenty-first century is a global priority to meet the burgeoning needs of the world's population for nutritious food. However, agricultural sustainability is threatened by a global reduction in available productive land, regional scarcities of replenishable water and the inevitable failure of chemical-dependent disease control, coupled to increasing urbanisation and vulnerability to climate change. Goats are generally efficient in their metabolism and tolerance of poor quality and potentially toxic nutrients and are adaptable to meet food security needs, in particular in seasonally resource-limiting, semi-arid or humid ecological environments. Goat farming is, therefore, a potential solution to the challenge of achieving socioeconomically and environmentally sustainable global food production, while improving the health and wellbeing of the rural poor living in marginal or degraded environments (Sargison, 2020). Different goat breeds and production systems have been developed to suit local resources and exploit the complementary benefits of co-management with other forms of agriculture in seasonally biodiverse environments throughout the world. Small ruminants are further suited to enhancing the livelihoods of the poor, due to their manageable size, relatively low maintenance requirements, low capital investment cost, short generation interval, ease of marketing of animals and products, hence suitability as short-term economic reserves, and resilience to disaster (Lalljee *et al*., 2018). Despite this potential, goat production is frequently uneconomic, or fails to alleviate poverty in an animal welfare-friendly manner (Sargison *et al*., 2017). Applied research findings in the fields of genetics, animal husbandry and disease management must, therefore, be translated into the economically and environmentally sustainable utilisation of natural resources by goats in their target environments.

It is estimated that by 2050, about 60% of Africa's human population will be living in cities (United Nations, 2018), creating opportunities for hitherto neglected peri-urban goat production in poverty alleviation and in providing societal benefits through productivity, market participation and provision of nutritious food. This is particularly relevant in those Low and Middle Income Countries (LMICs) where the infrastructures and value chains that are needed to support rural food production are inadequate to meet the needs of urban populations. Peri-urban goats are predominantly looked after by women, affording a means of empowerment, provided that there is capacity for improved production efficiency. Enhancing the efficiency with which peri-urban goats convert natural resources into food for human consumption has the potential to improve the wellbeing of city dwellers, while supporting livelihoods and empowering animal keepers. However, the achievement of these benefits presents complex challenges, such as the risk of spread of zoonotic infections and the frequent dependence on pharmaceutical remedies for the control of production limiting diseases. Innovative, adoptable and adaptable evidence-based tools are required to support management decisions and reduce livestock mortality and morbidity. These systems need to be developed in collaboration with their prospective users within the climatic, geographical and socioeconomic context to which they belong.

Sub Saharan Africa's climatic conditions are conducive for the survival and development of free-living and environmental stages of a range of arthropod, protozoa and helminth parasites, while diverse agricultural management provides opportunities for completion of their life cycles. Gastrointestinal (GI) nematode infections, in particular haemonchosis, are commonplace in goats kept in regions where seasonally warm and wet environmental conditions and livestock management can result in the development of high levels of host larval challenge (Besier *et al*., 2016a). However, knowledge of the importance of GI nematodes as causes of production loss in goats is poor among peri-urban livestock keepers, and there are few examples of rational control strategies. The aim of planned control of GI nematodes is to limit host challenge to a level, which does not compromise performance or welfare, while at the same time enabling the development of protective immunity (Coop *et al*., 1982). This depends on knowledge of the livestock production system and of the relationship between pasture contamination, the availability of infective larvae and the build up of infection in animals. However, the complexity of these principles means that most small ruminant keepers, worldwide, rely upon the use of anthelmintic drugs in an irrational (with reference to the principles of GI nematode control) attempt to eliminate the parasites. Nematode parasites have large genomes, with large numbers of genes and extraordinarily high levels of polymorphism (Laing *et al*., 2013; WormBase ParaSite, 2020), which coupled to high biotic potential make them adaptable to both favourable and hostile conditions afforded by effects of climatic or management changes on free-living stages and exposure of parasitic stages to anthelminitic drugs, respectively. In developed agricultural systems, resistance to anthelmintic drugs used in the control of GI nematodes is now commonplace, and both sheep and goat (small ruminants) farmers and keepers face an immediate challenge to develop new sustainable control strategies (Kaplan and Vidyashankar, 2012). In the absence of monitoring and surveillance, the prevalence of anthelmintic resistance is unknown in many under-developed smallholder agricultural systems. There is a need to develop simple and practical tools to encourage smallholder engagement with these strategies, in particular in regions where infrastructures surrounding animal health services and value chains are inadequate.

The focus of GI nematode control has shifted towards the adoption of management and strategic or targeted anthelmintic drug treatments, aimed at maintaining adequate health standards in the face of a low level of challenge. These strategies exploit the treatment timing and frequency so that only a small proportion of the parasite population is exposed to the anthelmintic drug (Van Wyk, 2001). In summary, the theoretical principle underpinning this concept is that once the numbers of parasite stages in a refuge from drug exposure (either in the environment, or as hypobiotic stages within their host) is reduced to a low level, then the progeny of parasites surviving treatment of their hosts contribute to a significant proportion of the subsequent total parasite population. Thus, if the parasites survive treatment due to their being genetically drug resistant, the frequency of resistant nematodes in the total population increases; followed by an increase in the size of the resistant parasite population as subsequent anthelmintic treatments are ineffective. This eventually leads to disease outbreaks that cannot be controlled using anthelmintic drugs, and impact on the health and welfare of the host animals. This has given rise to the concept of targeting drug treatments towards individual animals that will benefit, or have an epidemiological impact, while leaving others untreated as a source of *refugia* (Hodgkinson *et al*., 2019). A major challenge for *refugia*-based methods, is to decide which animals to treat and which to leave untreated. Weight gain of growing lambs (Greer *et al*., 2010; Busin *et al*., 2014) and milk yield of dairy goats (Gallidis *et al*., 2009) have been developed as indices in temperate climatic conditions where the predominant GI nematode genera are *Teladorsagia* and *Trichostrongylus*.

Conjunctival mucous membrane colour has been developed as an index for the sustainable control of the blood-feeding GI nematode species, *Haemonchus contortus*; and the system, referred to as FAMACHA© (FAffa MAlan CHArt) (Malan *et al*., 2001) has been evaluated by different methods in smallholder farms in South Africa (Van Wyk and Bath, 2002) and Kenya (Ejlertsen *et al*., 2006) and in large-scale sheep and goat farms in parts of Australia, Brazil (Maia *et al*. 2015), the USA (Kaplan *et al*., 2004) and Canada (Westers *et al*., 2016) where haemonchosis is endemic. The strategy is based on the principle that nematodes tend to be over-dispersed in host populations (Sréter *et al*., 1994), that larval stages within the host (L_4) and adult burdens of *H. contortus* are highly correlated to levels of anaemia (Le Jambre, 1995); and that levels of anaemia can be accurately assessed by examination of conjunctival mucous membranes (Van Wyk and Bath, 2002). The simplicity of the method of using a conjunctival mucous membrane colour chart to allocate a score of 1 (red) to 5 (white) to identify anaemic animals requiring treatment and to leave others untreated as a source of *refugia*, has resulted in its widespread adoption; but there are no reports to validate the use of FAMACHA© scoring in individually managed goats (as opposed to those kept in herds), such as those kept in peri-urban environments.

Mass anthelmintic drug administration programmes, as applied by Governments and non-Government organisations (NGOs) in many African and Asian LMICs for the control of human soil-transmitted helminths and schistosomiasis (Webster *et al*., 2008), have also become the mainstay of livestock GI nematode control in these regions (Bessell *et al*., 2018). It is presumed that programmes for the control of human soil transmitted helminths present a low risk for the development of anthelmintic resistance, because parasite populations in *refugia* from treatment tend to be relatively large (Vercruysse *et al*., 2012). However, comparable mass anthelmintic drug administration for the control of GI nematodes infecting livestock might select for anthelmintic resistance if practiced in circumstances where the size of the parasite population in *refugia* is small, or unknown. For example, *refugia* populations may be very low during seasonally hot and dry periods, due to the effects of high temperature and desiccation on survival of free-living stages (Berbigier *et al*., 1990). *H. contortus* has a remarkable propensity to develop anthelmintic resistance (Kotze and Prichard, 2016), that has threatened the economic viability of commercial small ruminant production in developed agricultural systems (Laing *et al*., 2013). This provides a cautionary example of the risks associated with uninformed mass drug administration; that could compromise future attempts to control GI nematodes, especially in tropical and subtropical LMICs where *H. contortus* is the nemesis of small ruminant production systems (Emery *et al*., 2016). Precise evidence-based GI nematode control strategies such as use of simple indices that can be measured by livestock keepers or animal health workers to inform targeted selective treatments might provide a potentially more sustainable alternative to the current widespread practice of mass drug administration in addressing the need for control of haemonchosis in peri-urban goats.

More efficient livestock production is a prerequisite for food security and socioeconomic development in response to human population growth. As a consequence of the rudimentary nature of veterinary infrastructure in Malawi, levels of livestock production efficiency are unknown, while in the absence of active surveillance and diagnostic services, primary animal health constraints such as haemonchosis and zoonotic disease threats are poorly understood. For this study, we used our established working base for paraveterinary education development in the Blantyre district of southern Malawi as our model system; and took the well-known problem throughout sub-Saharan Africa of haemonchosis in goats (Emery *et al*., 2016), along with the recognised priority for sustainable anthelmintic drug use, as a relevant reason for engagement with peri-urban smallholder goat production. We used this to gain practical insight to the health and management of peri-urban goats, and to gauge their keepers' awareness of related challenges.

The aim of this first large-scale study of peri-urban goat production was to evaluate the potential for conjunctival mucous membrane colour scoring in the targeted selective treatment of haemonchosis. We used faecal trichostrongyle egg counts (FECs) to provide an estimate of the GI nematode burdens of up to 600 individual goats kept by peri-urban smallholders, at each of three epidemiologically relevant times of year. Morphological examination of coprocultured third stage GI nematode larvae (L_3) was used to confirm the predominance of *H. contortus*. A mobile data application (App) was used to record the unique identity of each animal, along with its FEC, FAMACHA© score, age, sex, weight and body condition score (BCS). This allowed us to examine the value of FAMACHA© score in predicting GI nematode burdens, and potential confounding effects of other parameters. Analysis of the relationships between each of the convenient to measure clinical parameters and FECs allowed us to evaluate opportunities to improve on FAMACHA© score alone in the targeted selective treatment of haemonchosis. Insight of animal husbandry and management practices allowed us to evaluate risk factors for haemonchosis and consider how these indices and clinical parameters might be applied by animal health professionals and peri-urban goat keepers in the area to the development of sustainable control strategies.

The study evaluated FAMACHA© scores for the targeted selective treatment of GI nematodes, and at the same time the usefulness of diagnostic parameters that with basic training can be measured consistently, without requiring otherwise prohibitive specialist equipment, along with relevant background information in a decision support tool for animal health management.

There is a responsibility to ensure that any control measures arising from increased awareness of the importance of GI nematodes are rational and do not present a high risk of selection for anthelmintic resistance (Kaplan and Vidyashankar, 2012). This requires knowledge of the efficacy of anthelmintic drugs that can be used. Therefore in addition, animals with FAMACHA© scores 4 and 5 were treated with a standard goat dose rate of albendazole, and the anthelmintic efficacy was estimated from the reduction in FECs, 14 days post treatment.

Materials and methods

Study sites

Peri-urban communities in the Malawian Government Department of Animal Health and Livestock Development (DAHLD) extension planning areas (EPAs) of Ntonda, Lunzu and Kunthembwe in the Blantyre District of southern Malawi were visited during three periods which were considered to be relevant to the epidemiology of GI nematodes: in the dry season in August/September 2017; during the rainy season in January/February 2018; and shortly after the rainy season in May 2018.

Worm control practices

Survey data were collected from individual goat keepers on animal husbandry and attitudes towards livestock production (reported as a separate study). These included questions about awareness of the importance of parasitic diseases, grazing management with reference to GI nematode infection, and history of anthelmintic drug treatments. Open questions were asked by a paraveterinary Assistant Veterinary Officer (AVO) in the local Chichewa language. Responses were recorded using mobile data recording application (App) developed by the Worldwide Veterinary Service (WVS) and Mission Rabies (MR) (Gibson *et al*., 2018), in which individual goat keepers were anonymously identified. The geographical coordinates for the location of each animal were recorded.

Clinical examination

The App was used to uniquely identify each goat based on knowledge of its owner, its sex, pregnancy (if known), the number of kids sucking adult does, its age (provided by the owner and supported by dentition) and a description of its physical appearance (including face and side photographs stored on the App). The goats were manually restrained to allow immediate evaluation of the colour of the conjunctival mucous membranes using a FAMACHA© card. The conjunctival colour was classified from red (score 1), through red-pink (score 2), pink (score 3) and pink-white (score 4) to white (score 5) (Malan *et al*., 2001). Scores were recorded on the App, alongside a photograph of the conjunctivae and card. Where possible the FAMACHA© scoring was conducted in direct sunlight. Each animal was weighed using a sack and spring balance accurate to $\pm$0.5 kg and body condition scored (BCS) by palpation of the lumbar vertebrae with a range of 1 (thin) to 5 (fat), extrapolating from a system developed for European sheep breeds (Russel, 1984), and using the results only for individual and group comparisons.

Parasitological examination

A sample of about 3 g of faeces was collected freshly voided on to the ground, or per rectum if unavailable in this way (not in small kids), into a disposable glove, and placed directly into an insulated bag containing an ice pack.

Faecal samples were stored at 5^{o}C, and faecal trichostrongyle egg counts were conducted on each individual animal sample within 3 days of collection using a modified McMaster salt floatation method with a detection threshold of 50 epg (MAFF, 1986). The results were uniquely identified to match the individual goat data from the App, and recorded onto a Microsoft Excel (Microsoft Inc., Redmond, WA) spreadsheet. L_3 coprocultures were set up using composite samples left over from the FECs representing the different EPAs, incubated for 14 days at ambient room temperature and processed using standard methods (MAFF, 1986). L_3 were examined and identified to genus level based on their head and sheathed tail morphology (Van Wyk and Mayhew, 2013).

Evaluation of anthelmintic efficacy

Animals with FAMACHA© scores 4 and 5 were treated with 10 mg/kg albendazole (Albandazole 10%, Bajuta International Limited, Tanzania) (in the absence of data sheet recommendations for goats, a dose rate of twice the recommended sheep dose rate was used, in accordance with common practice) by the AVO immediately following clinical examination. A second visit was made 14 days later, during which goats treated at the first visit were re-examined for FAMACHA© score and resampled for FEC. Any goats that had not been treated, but had FECs ≥250 epg (an arbitrary threshold representing a likely production limiting GI nematode burden) at the first visit, were treated during the second visit with 10 mg/kg albendazole and also re-examined for FAMACHA© score and resampled for FEC.

Consistency of data collection

All data were collected by a team consisting of an AVO and Mission Rabies (MR) data recorder, with periodic researcher support to affirm consistency in methods. Each team was allocated to one of the three EPAs throughout the study.

At the start of the study, the three AVOs and three researchers responsible for the different districts each independently assessed the FAMACHA© scores of 17 goats kept close to the city of Blantyre (chosen as a convenience sample) to determine the degree of agreement. An independent person slowly moved the FAMACHA© card twice, directly under the exposed conjunctival mucosa. The order in which the observers evaluated each goat was consistent to compensate for any changing effect of stress on FAMACHA© score during the time for which the animals were restrained.

The three AVOs responsible for the different EPAs each independently scored the same 17 goats for BCS to determine the degree of agreement.

Quantitative data analyses

H. contortus L_4 and adults in the abomasum of their host may each remove up to 30 μl of blood per day, causing anaemia. Where *H. contortus* is the sole or predominant cause of anaemia, scoring of conjunctival mucous membrane colour using FAMACHA© can be used to provide an indirect index for *H. contortus* burdens. FECs are used as a proxy to estimate GI nematode burdens in live host animals. The FEC and FAMACHA© score data were first analysed to describe the extent and seasonal pattern of GI nematode parasitism and anaemia in the peri-urban goats. The data were then examined to identify and describe any direct relationship between the two parameters, overall and during each sampling period. Cross sectional and longitudinal data were described separately.

A previous report used a FAMACHA© score threshold of ≥4 to determine the need for anthelmintic treatment of South African goats (Vatta et al., 2001). Therefore, for the purposes of this study, we used FAMACHA© scores of 4 and 5 to target and select those goats requiring anthelmintic treatment. In order to evaluate the correctness of the decisions to treat these goats, or not, we first used the combined data from each of the three sampling periods to test the ability of FAMACHA© scores of 4 and 5 to predict treatment thresholds of FECs ≥250, ≥500 and ≥1,000 epg. These arbitrary thresholds were chosen to represent low, moderate and high GI nematode burdens which might be epidemiologically significant during the different sampling periods. Next, we evaluated whether or not having used a lower FAMACHA© score threshold of ≥3 as described for Canadian sheep (Westers et al. 2016) to determine the need for anthelmintic treatment could have improved the percentages of correct decisions to treat goats or not.

The relative importance of decisions to selectively treat, or not treat animals that require, or do not require treatment will vary between seasons. For example, the size of GI nematode *refugia* populations will be much smaller during the mid-dry season than during the mid-rainy season due to effects of temperature and desiccation on developing and infective larval stages (Besier *et al*., 2016a). Hence having a higher FEC threshold and higher percentage of untreated animals because they do not require treatment could be important during the mid-dry season; while a lower FEC threshold and lower percentage of untreated animals that do not require treatment could be necessary during the mid-rainy season. We therefore used the data collected during each of the three sampling periods to evaluate the correctness of the decisions to treat goats, or not, using FAMACHA© scores of ≥4 or ≥3, and FEC thresholds of ≥250, ≥500 and ≥1,000 epg.

To illustrate the complexity surrounding FAMACHA© score phenotypes, we investigated the effects of goat related factors including age, sex, BCS and FECs, for which we had collected quantitative data, on the odds of a goat having a FAMACHA© score ≥3 or ≥4 during the three sampling periods. The associations that were identified were then used to inform investigation the value of combined FAMACHA© score ≥4, BCS ≤2 and age ≥18 months as practical indices in predicting FECs of individual goats during each of the three study periods. These parameters were selected due to the ease and consistency of measurement; the age of goats ≥18 months can be determined simply and with reasonable accuracy by examination of the stage of eruption of the central incisor teeth (Holst and Denney, 1980).

The standard *in vivo* method to evaluate anthelmintic efficacy involves a faecal egg count reduction test (FECRT), whereby the mean FECs of co-managed groups of 10 or more animals are compared before and 14 days after drug treatment, administered effectively at the correct recommended dose rate (Coles *et al*., 2006). Fourteen days is longer than the ovicidal effect of the anthelmintic drug, but within the minimum GI nematode pre-patent period of 17 days; hence the percentage reduction in FEC reflects drug efficacy. The sensitivity of the FECRT can be improved by attributing drug efficacy to gastrointestinal species, determined by pre and post treatment group L_3 coprocultures (McKenna, 1996). The goats in the present study were individually owned and none was managed in a group of 10 or more, hence it was not possible to conduct a standard FECRT. Instead, we evaluated the pre- and 14 days post-treatment reductions in FEC of individual goats to describe the efficacy of the benzimidazole anthelmintic drug group.

Statistical analyses

Data were analysed using the R statistical software (Gamer *et al*., 2019) and Microsoft Excel (Microsoft Inc., Redmond, WA). The percentage of both absolute agreement, and agreement within 1 score difference, between observers was estimated for both FAMACHA© score and BCS using R package irr (Cicchetti, 1994). The intraclass correlation coefficient (Shrout *et al*., 1979) for each was estimated using R package psych (Revelle, 2018).

Multivariable logistic regression models were built using FAMACHA© score more than or equal to 3 or 4 as the dependent variable. Explanatory variables included information about the goat such as sex, age, BCS and FEC < 250. Models including all possible variable combinations were considered using the package *MuMIn* (Bartoń, 2019). Three-fold cross-validation was used in order to assess each model's predictive ability based on the area under the curve (AUC) using package *vtreat*

(Mount and Zumel, 2019). The final model was chosen based on the best combination of highest AUC and the lowest Akaike information criterion (AIC). The AUC for each model was calculated using package pROC (Robin *et al*., 2011). Using the final model selected, odds ratios and 95% confidence intervals for each predictor variable were estimated.

Approval and consent

Goat keepers provided informed verbal consent and were always present during the evaluation of their animals. The experimental protocol was reviewed and approved by the University of Edinburgh Veterinary Ethnics Review Committee (VERC 90.17) and Human Ethics Review Committee (HERC_140_17). Permission for the pilot study and to publish the results was granted by the Ministry of Agriculture, Irrigation and Water Development, Department of Animal Health and Livestock Development, Malawi (Ref. No 15/10/32a).

Results

Data collection

The size of the study population was chosen to give an appropriate balance between practicality and analytical power. A total of 452 smallholders participated in the study. The aim had been to study about 200 goats in each of the three study districts longitudinally through each of the three sampling periods. However, of the 622 goats examined and sampled during the first dry season study period, only 359 were present during the second rainy season study period and 198 during the third post rainy season period. The missing animals were reported to have been traded, gone missing, or used as loans, consistent with their role as financial reserves. When possible, missing animals were replaced by goats that the smallholders had acquired in their place, resulting in a total 999 individual animals being represented in the study as a whole. Furthermore, it was not possible to revisit all of the goats in the Kunthembwe EPA during the third study period due to an outbreak of foot and mouth disease and consequent biosecurity restrictions. Numbers of goats examined in each study district and each study period and their locations are shown in Supplementary Fig. 1.

The smartphone mobile application proved to be efficient and practical in terms of data management, and contributed greatly to the smooth running of the study.

Worm control practices

Understanding of how animal husbandry and management might influence the epidemiology of GI nematodes is a prerequisite for the development of sustainable control strategies. Almost all of the goats were tethered along the sides of tracks, on unfarmed ground, or around the margins of cultivated arable land during the daytime, where they browsed on shrubs or grazed short herbage. The animals were all housed at night, most in their keepers' homes, and a few larger herds in raised kholas (slatted-floored and covered outdoor pens). Few of the peri-urban goat keepers regarded animal production *per se* as being important, and none attributed signs of ill thrift, anaemia or diarrhoea to GI parasitism or causes of production loss. None had knowingly managed their animals for worm control, or previously administered anthelmintic drugs. All of the goat keepers were intrigued by the process of FAMACHA© scoring and interested in the reasons for doing so.

Between observer agreement in FAMACHA© and body condition scoring

Knowledge of the consistency in FAMACHA© and body condition scoring was important in the analysis of data collected by different observers. Consistency in measuring clinical indices is a prerequisite for their practical application. The FAMACHA© scores assigned to each goat by each of the six observers to evaluate the consistency of data collection are shown in Supplementary Fig. 2A. No goats were assigned a score of 4 or 5. Among the six participants, the inter-observer variation in agreement of FAMACHA© score was 23%. However, when the FAMACHA© score was evaluated to within a +/-1, the agreement increased to 94%. The intraclass correlation coefficient was estimated as 0.47, indicating that there was reasonable, albeit imperfect, inter-observer agreement. These factors should be considered when interpreting the value of conjunctival mucous membrane colour for the targeted selective treatment of GI nematodes, or in predicting the general health of goats. The FAMACHA© score tended to decrease by 1 unit following restraint of the animals for more than one minute.

The BCS assigned to each goat by each of the three observers to evaluate the consistency of data collection are shown in Supplementary Fig. 2B. No goats were assigned a score of 1 or 5. Among the 3 participants, the inter-observer variation agreement in BCS was 53%. However, when BCS was evaluated to within a +/-1, the agreement increased to 100%. The intraclass correlation coefficient was estimated as 0.40, indicating that there was reasonable inter-observer agreement.

Clinical examination

In the context of countries with limited veterinary infrastructures such as Malawi, it is important to ensure that clinical parameters (indices) are practical and simple to measure, without the need for expensive equipment or specialist expertise. Conducting a full clinical examination on each of the goats involved in the study would have been impractical, and the subjective nature of the findings would have prevented their meaningful analyses. Instead, age (which can be practically estimated from incisor dentition), sex, known pregnancy status, weight, body condition score and FAMACHA© score were used as objective clinical parameters. None of the goats appeared to be sick or injured.

All of the goats were of an unimproved, indigenous breed. The bodyweights and ages of each of 999 goats when first recruited to the study provide a proxy for growth rates as shown in Fig. 1. The data suggest that on average the peri-urban goats in the study areas take about 3 years to reach mature weights of about 30 kg. Comparison of individual animal data with the best-fit prediction for weight vs. age ± 95% confidence intervals shows that many underperform in relation to their peers and within the environment in which they are kept.

The mean (±SEM) ages, body weights and BCS data of goats with different FAMACHA© scores recorded throughout the study are shown in Supplementary Fig. 3A, B and C. There are trends towards higher (pale) FAMACHA© scores with increased age and decreased BCS. Bodyweight is influenced by both age and BCS in addition to anaemia, hence would not be expected to show a direct relationship with FAMACHA© scores.

FAMACHA© scores and FECs

The value of FECs in predicting GI nematode burdens is influenced by factors such as faecal dry matter, the immune status of the host, the proportions of different nematode species present, patency of infection and the sensitivity of the method used (Sargison, 2013). These factors were considered in the interpretation of results, albeit between sample variations in faecal consistency and GI nematode species proportions were considered to be consistent within sampling periods. The modified McMaster method with a detection threshold of 50 epg was chosen for this study to give an optimal balance between practicality and sensitivity in the comparison of different GI nematode populations.

The mean (±SEM) FECs and FAMACHA© scores of each goat sampled during the first visit of each of the three study periods are shown in Supplementary Fig. 3D. The mean (±SEM) FECs of all of the goats sampled throughout the study were 123 (±14) epg, 741 (±45) epg, and 300 (±33) epg during the first visit of the dry season, the first visit of the rainy season and shortly after the rainy season, respectively. 46 of 508 of the FECs of goats sampled during the first visit of the rainy season were above 2,000 epg, with the highest value being 8,300 epg. The mean FECs of the goats increased with increasing FAMACHA© scores of 2 (red-pink), 3 (pink) and 4 (pink-white), but there were insufficient animals with scores of 1 (red) or 5 (white) to extend the analysis and attribute meaningful statistical significance. The trend was clearest during the rainy season, corresponding with the highest *Haemonchus* burdens, when the mean (±SEM) FECs of goats with FAMACHA© scores of 2, 3 and 4 were 572 (±65), 702 (±65) and 1,038 (±113) epg, respectively. The trend was present to a lesser degree shortly after the rainy season, where the mean (±SEM) FECs of goats with FAMACHA© scores of 2, 3 and 4 were 229 (±50), 291 (±47) and 402 (±368) epg, respectively.

Owing to a high turnover of goats, inability to visit the Kunthembwe EPA for the whole of the May 2018 sampling period, and the impracticality of collecting a faecal sample from every animal during each sampling period, complete longitudinal FEC data were only available for 133 goats. The mean (±SEM) FECs of these animals were 78 (±13), 818 (±91) and 190 (±39) epg during the dry season, during the rainy season and at the start of the dry season, respectively. As anticipated, FECs of individual goats during one sampling period could not be used to predict their FECs during the next sampling period. The seasonal trends in FECs of 75, 31 and 27 individual goats in the Ntonda, Lunzu and Kunthembwe EPAs were similar, albeit there were differences in the values, as shown in Supplementary Fig. 4.

Larval coprocultures were set up on pooled faecal samples, to give an indication of the GI nematode species present. All of the L_3 coprocultures set up during the dry season sampling period failed, while only those set up during the rainy season sampling period yielded sufficient L_3 for speciation. Post treatment and untreated control coprocultures set up during the rainy season sampling period yielded between 90% and 95% *Haemonchus*, based on L_3 head and sheathed tail morphology. Small numbers of *Trichostrongylus* were also identified in each of the coprocultures.

Appropriateness of decisions based on FAMACHA© scores as overall indices for targeted selective treatment of GI nematodes

Overall, when combining all of the data, FAMACHA© scores alone provided a poor index for the targeted selective treatment of GI nematodes in the study population of peri-urban goats.

Combining the three sampling periods of this study resulted in 1,398 samples. Of these, a total of 251 samples had FAMACHA© scores of 4 and 5 and, therefore, these goats were targeted and selectively treated with 10 mg/kg albendazole. A total of 1147 samples had FAMACHA© scores of 1, 2 and 3 and, therefore, these goats were not treated immediately. From the 251 samples with FAMACHA© scores of 4 and 5, 135 (54.0%), 94 (37.6%) and 52 (20.8%) had FECs ≥250, ≥500 and ≥1,000 epg, respectively. 363 (31.6%), 217 (18.9%) and 118 (10.2%) samples with FAMACHA© scores of 1, 2 and 3 had FECs ≥250, ≥500 and ≥1,000 epg, respectively.

Using an arbitrary threshold of FECs ≥250 epg as an example, decisions to treat, or not to treat were correct for 65.7% of the 1,398 samples. These arbitrarily correct decisions comprised of 135 samples with FAMACHA© scores of 4 and 5 and FECs ≥250 epg, indicative of a need to treat, and 784 samples with FAMACHA© scores of 1, 2 or 3 and FECs <250 epg, indicative of animals that did not require treatment and were not treated. Of the incorrect decisions, 26.0% were not to treat animals that arbitrarily required treatment, comprising of 363 samples with FAMACHA© scores of 1, 2 or 3 and FECs ≥250 epg. Goats with FECs ≥250 epg and FAMACHA© scores of 1, 2 or 3 were treated with 10 mg/kg albendazole 14 days later, on the second visit of the dry season and rainy season sampling periods.

Using FAMACHA© scores of 4 and 5 as indices to predict and selectively treat goats with arbitrary FEC thresholds of ≥500 and ≥1,000 epg would have increased the correct decisions to 73.3% and 77.4%, respectively These comprised of 94 and 52 samples with FAMACHA© scores of 4 or 5 and FECs ≥500 and ≥1,000 epg, and 930 and 1029 samples with FAMACHA© scores of 1, 2 or 3 and FECs <500 and <1,000 epg. Of the incorrect decisions, 15.5% and 8.4% would have been not to treat animals that required treatment, comprising of 217 and 118 samples with FAMACHA© scores of 1, 2 or 3 and FECs ≥500 and ≥1,000 epg. The predictive value of FAMACHA© scores ≥4 for the targeted selective treatment of GI nematodes, therefore, depends on the desired treatment threshold, being best in circumstances where a high FEC threshold is epidemiologically appropriate.

Reducing the FAMACHA© score treatment threshold to ≥3 would have reduced the correct decisions to 51.5%, comprising of 369 samples with FAMACHA© scores of 3, 4 or 5 and FECs ≥250 epg, and 351 samples with FAMACHA© scores of 1 or 2 and FECs <250 epg. Of the incorrect decisions, 25.1% would have been not to treat animals that required treatment, comprising of 351 samples with FAMACHA© scores of 1 or 2 and FECs ≥250 epg. Use of a FAMACHA© score treatment threshold of ≥3 would, therefore, have been unhelpful in the study population of peri-urban goats.

Appropriateness of decisions based on FAMACHA© scores as seasonal indices for targeted selective treatment of GI nematodes

The value of FAMACHA© scores of ≥4 or ≥3 to predict FECs ≥250, ≥500 and ≥1,000 epg varied between the three sampling periods. The two-way frequency tables used to calculate these values are shown in Supplementary Fig. 5A. The predictive values of FAMACHA© scores during the dry season, during the rainy season, and shortly after the rainy season are summarised in Table 1A. As expected (Vatta *et al*., 2001), changing the FAMACHA© score cut-off from ≥4 to ≥3 increased the sensitivity (correct identification of animals in need of treatment with an anthelmintic) of the test, while decreasing its specificity (incorrect identification of the proportion of those animals that would not require treatment, but would in fact be treated). 94%, 77% and 74% of the goats had

FAMACHA© scores of 1, 2 or 3 during the dry season, rainy season and end of the rainy season/start of the dry season, respectively, and were untreated as a source of *refugia*. 62%, 25% and 15% of the goats had FAMACHA© scores of 1 or 2 during the dry season, rainy season and end of the rainy season/start of the dry season, respectively, and would have been untreated using FAMACHA© scores ≥3 as an index. Therefore, during each sampling period, FAMACHA© scores of both ≥4 and ≥3 would have failed to provide a useful balance between predicting FECs ≥ or < threshold values for treatment, and ensuring that the majority of animals with FECs ≥ threshold values would be treated.

Complexity of FAMACHA© score phenotypes

The odds ratios for goat age, sex, BCS and FECs as predictors for a goat having a FAMACHA© score ≥3 or ≥4 during the dry season, the rainy season, or shortly after the rainy season are shown in (Figs. 2A and B). There was a positive association between low BCS (scores 1 or 2) and pallor of the conjunctival mucous membranes indicated by FAMACHA© scores of both ≥3 and ≥4; and with the exception of the dry season and FAMACHA© scores of ≥4 (as shown in Fig. 2B), there was a negative association between high body condition score ≥4 and pallor of the conjunctival mucous membranes. There was a positive association between older age and pallor of the conjunctival mucous membranes during each sampling period. There was a negative association between lower FECs (<250 epg) and FAMACHA© scores of both ≥3 and ≥4, with the exception of during the rainy season and FAMACHA© scores of ≥3 (as shown in Fig. 2A).

Appropriateness of decisions based on FAMACHA©, body condition scores and age as seasonal indices for targeted selective treatment of GI nematodes

When compared with FAMACHA© scores ≥4 alone during each sampling period, the combined indices of FAMACHA© score ≥4, BCS ≤2 and age ≥18 months would have missed fewer goats requiring treatment for FECs ≥250, ≥500 and ≥1,000 epg. During the dry season, this improvement in identifying those animals requiring treatment would have been at the cost of treating more animals unnecessarily. The two-way frequency tables used to calculate the percentages of goats that would have been untreated as a source of *refugia* during the dry season, rainy season and end of the rainy season/start of the dry season using these combined indices are shown in Supplementary Fig. 5B.

The sex and pregnancy or lactation status of goats that would have been missed when using the combined indices to predict FEC treatment thresholds is shown in Supplementary Fig. 5C. Female goats were recorded as being pregnant if reported so by the owner based on their appearance and behaviour. Goats were deduced to be in early lactation based on their pregnancy status during the previous sampling period, or the owners' report in the case of newly introduced animals. The pregnancy and lactation status of the remaining female goats is uncertain. The data show disproportionately (when compared to the overall population) high numbers of late-pregnant and early-lactating goats amongst the animals whose FECs were not predicted based on the combined indices.

Evaluation of anthelmintic efficacy

The reductions in FECs of individual goats are shown in Fig. 3. Day 14 egg counts of individual goats greater than zero are indicative of treatment failure. The treatment response was better, albeit imperfect, during the dry season than during the rainy season. During the rainy season, the FECs of the treated goats were similar to those of the untreated goats on the first and second visits (corresponding with the time of treatment and 14 days post treatment with 10 mg/kg albendazole), highlighting low, if any, drug efficacy.

Discussion

Efficient peri-urban livestock production will become increasingly important in providing food and societal benefits to the world's burgeoning cities. In the current study, the activities of scoring conjunctival mucous membrane colour and weighing goats afforded a useful means of engagement with peri-urban livestock keepers, and an opportunity to evaluate the health and production of their goats. The average growth rate of the unimproved, indigenous goats, deduced from their bodyweights and ages when first recruited to the study, was approximately 25 g/day. By the very nature of unimproved goat breed production, there are few reliable published data describing weight gains. Nevertheless, 25 g/day represents just 10% of the potential that has been reported for genetically improved Boer goats kept on high planes of nutrition (Brand *et al*., 2017). Animals with low growth rates must digest and metabolise more nutrients than their more rapidly growing counterparts to produce the same yield of meat, because there is a fundamental requirement to meet maintenance nutritional requirements, before any nutrients can be used for growth. The economic impact of such inefficient production would not have been apparent to the goat keepers involved in the current study, because herbage was considered to be free. This may explain their lack of awareness of the concepts of production limiting disease management, but is unhelpful in the context of regional, national or global food security. Poorer growth rates such as those of the peri-urban goats in the present study also result in higher greenhouse gas production (Ortiz-Gonzalo *et al*. 2017), arising from the level of forestomach microbial digestion per unit of food produced and poor carbon sequestration. The growth rates of the animals in the current study would have been limited by the availability of nutrients from herbage growing along roadsides and along the margins of cultivated ground, and sometimes supplemented by household by-products. Nevertheless, the very poor deduced growth rates and high variability between of some of the animals, shows the potential for improved production efficiency. This study identified immediate opportunities for improved health and nutritional management (for example, to address the causes of conjunctival mucous membrane pallor), and potential for genetic selection and improvement of the indigenous goats, as pragmatic components of poverty alleviation and better human wellbeing.

None of the peri-urban goat keepers indicated an awareness of the threat of GI nematode parasitism, or had knowingly administered anthelmintic drugs to their animals. Similar findings were reported in a study of rural calf owners, also in southern Malawi (Leahy *et al*., 2017). There are no reports in the scientific literature of GI nematode parasitism of goats in Malawi, despite these parasites being ubiquitous and their known impact in goats kept in similar low-input systems in other South African Development Community regions (Zvinorova *et al*., 2016). The mean FECs of all of the goats sampled during the first visit of the dry season, the rainy season and shortly after the rainy season indicate low to moderate GI nematode burdens. Disappointingly, some of our L_3

coprocultures failed, attributed to poor sensitivity (Pit *et al*., 1999) arising from recognised practical challenges of desiccation and fungal overgrowth while working in field conditions in a subtropical environment. While caution is needed in the interpretation of our results, they confirm a predominance of *Haemonchus*. The seasonality of the FECs, being highest during the rainy season and lowest during the dry season, is consistent with the pattern of haemonchosis seen in goats in seasonal tropical locations with distinct wet and dry seasons and seasonally high temperatures (Santos *et al*., 2012). In these climatic conditions, *H. contortus* larval development occurs only during the warm and wet periods (Dinnik and Dinnik, 1958) and larval survival is short while conditions are hot and dry (Dinnik and Dinnik, 1961).

The management of the goats in the present study essentially involved extensive grazing and browsing of natural herbage while tethered during the daytime; and housing at night. Relative to intensive pastoral grazing management, these conditions would not be conducive towards high levels of GI nematode infective larval contamination or host challenge. Accordingly, the mean FECs were consistent with chronic haemonchosis in small ruminants kept under extensive grazing situations in subtropical African environments, where animals are often seasonally malnourished (Allonby and Urquhart, 1975). The mean FECs were lower than the arbitrary value of 2,000 to 3,000 epg that is associated with acute haemonchosis occurring in subtropical regions (Besier *et al*., 2016b); albeit 9% of goats sampled during the first visit of the rainy season had FECs greater than this clinical disease threshold. These results highlight the need for GI nematode control strategies to minimise production losses due to both chronic and acute haemonchosis in peri-urban goats.

In our hands, FAMACHA© may have been imprecise in determining a score of 3 beyond an accuracy of +/-1, but the reliability was improved by scoring animals immediately following their restraint to allow for effects of stress on conjunctival mucosa colour. Furthermore, the evaluation of reliability of the inter-observer results was influenced by the low numbers of goats with a FAMACHA© score of 4 and 5. Nevertheless, FAMACHA© scoring proved to be a simple and practical means to engage with peri-urban goat keepers in addressing the aforementioned challenges, due to its immediate visual impact providing an index of the health of their animals and raising awareness of challenges such as GI nematodes. Overall, and during each of the three sampling periods, neither FAMACHA© score treatment thresholds of ≥4, nor of ≥3, afforded a satisfactory level of sensitivity in identifying those animals requiring treatment for FECs ≥250, ≥500 and ≥1,000 epg. These FECs were chosen as arbitrary thresholds that might be representative of co-infecting GI nematode burdens causing production loss, or contributing to infective larval challenge under different seasonal environmental conditions. The indices used to decide on the need to manage *refugia* populations and reduce the selection pressure for anthelmintic resistance will depend upon: the predominant GI nematode species; host burdens; predicted levels of infective L_3 challenge; seasonal effects on free living stage development and survival; anthelmintic efficacy; and the fitness (Leathwick, 2013) of resistance mutations.

H. contortus burdens of more than 500 adult worms can rapidly cause anaemia and death (Emery *et al*., 2016). Accounting for the daily egg production of about 4,000 eggs per day, and likely weight of faeces voided by infected goats, the FEC threshold of ≥1000 epg used in this study crudely represents burdens of about 500 adult worms. However, owing to the blood feeding behaviour of *H. contortus*, production loss may occur with FECs ≥250 epg. Furthermore, the parasite's high fecundity, seasonally rapid development of infective L_3 in hot and humid environments, and high establishment rates in single species infections (Dineen *et al*., 1965), results in its ability to cause severe disease and death rapidly. This is particularly important for individually owned animals, as opposed to the larger co-managed groups of small ruminants for which targeted selective treatment regimes for haemonchosis have been developed (Malan *et al*., 2001; Vatta *et al*., 2001; Van Wyk and Bath, 2002), and where overall productivity of the group is more important than that of individuals. Accurate identification of close to all of the goats that would require treatment (high test sensitivity) at seasonally different FEC thresholds is, therefore, a higher priority in the development of targeted selective treatment of GI nematodes in peri-urban goats than in larger groups of co-managed small ruminants. A similar priority was reported for the targeted selective treatment of haemonchosis in managed Canadian sheep flocks (Westers *et al*., 2016).

In the face of anthelmintic resistance, treatments which achieve high efficacy require lower levels of *refugia* to dilute anthelmintic resistant survivors than those that do not (Leathwick, 2014). This argument is used in New Zealand to justify the use of more effective drug combinations in the targeted selective treatment of *Trichostrongylus colubriformis* and *Teladorsagia circumcincta* GI nematodes (Leathwick *et al*., 2012). In the current study, the efficacy of treatment with 10 mg/kg albendazole was incomplete during the dry season and poor during the rainy season. Besides genetic resistance, low anthelmintic efficacy may be due to poor drug bioavailability, for example due to the use of poor-quality products (Van Wyk *et al*., 1997), or due to enhanced drug metabolism in goats (Lespine *et al*., 2012). These risks were reduced by sourcing a branded benzimidazole product, correct storage and accurate administration of twice the recommended sheep dose rate, after weighing and using a syringe. It was not possible to attribute drug inefficacy wholly to benzimidazole anthelmintic resistance; nevertheless, these results provide a compelling case for the use of more effective, albeit more expensive, drug combinations in the anthelmintic treatment of peri-urban goats.

The proportion of animals that can be left untreated to generate *refugia* will be influenced by the levels of infective larval challenge (Dobson *et al*., 2011). When there are very few infective L_3 to act as natural *refugia*, as during the dry season in the current study, then leaving a smaller proportion of animals untreated will have a larger effect, and conversely during the rainy season, a larger proportion of untreated animals will be required. Modeling studies of the proportions of untreated small ruminants required to generate sufficient *refugia* to slow the onset of anthelmintic resistance under Australian and New Zealand management conditions are all based on groups of grazing animals kept at pasture (Dobson *et al*., 2011; Leathwick 2013; Cornelius *et al*., 2016). A Kenyan study reported that leaving 77% to 89% of pastorally managed goats untreated would likely contribute sufficiently to the *refugia* of unselected parasites to decrease the risk of anthelmintic resistance (Ejlertsen *et al*., 2006). However, the exact figures on the relationship between the proportion of *refugia* and rate of development of resistance are not known. Furthermore, in these scenarios, the GI nematode epidemiology would have differed considerably from that of the tethered peri-urban goats kept in southern Malawi. Further studies based on empirical data are, therefore, required to determine the proportions of peri-urban goats that would be left untreated using different indices to predict the need for treatment. It is then necessary to determine if these proportions would be sufficient to delay the onset of anthelmintic resistance.

Appropriate *refugia* based strategies for the targeted treatment of haemonchosis require solutions that are customised for region and enterprise (Emery *et al*., 2016). Previous studies of FAMACHA© scoring *refugia* management strategies in small ruminants have all pertained to pastorally managed groups of animals kept on smallholdings and larger commercial farms. The current study is the first to investigate the role of targeted selective treatment of individually managed, usually tethered and browsing peri-urban goats. A very high sensitivity is required of the predictive index in this context, to avoid missing treatment of individual animals that are at risk of acute haemonchosis. Various explanations were considered as to why FAMACHA© scores alone lacked sensitivity to detect goats requiring treatment, but these were not quantified in this study. The goats may have been co-infected with non-haematophagous GI nematodes, for example *Oesophagostomum* spp. which are commonly identified at slaughter slabs in the study sites. Alternatively, the goats may have been anaemic for other reasons, such as: the additive effect of poor protein nutrition on older pregnant and lactating does (Strain and Stear, 2001); concurrent haematophagous parasitic infestations, for example ticks, liver flukes, or fleas (Ejlertsen *et al*., 2006); and haemoprotozoan parasites such as *Babesia* spp. or *Theileria* spp*.,* that are considered to be common in the study regions. Burdens of *Ctenocephalides felis felis* fleas were noted on many of the study goats and confirmed according to published morphological keys.

Examination of the complexity of the FAMACHA© score phenotypes showed variable associations with FEC, age and BCS. Our results showed reasonable agreement in FAMACHA© and body condition scoring between observers, while the age of goats ≥18 months can be determined simply and with reasonable accuracy by examination of the stage of eruption of the central incisor teeth (Holst and Denney, 1980). Therefore, we decided to investigate the value of combined FAMACHA© score ≥4, BCS ≤2 and age ≥18 months as a practical combination of indices in predicting FECs of individual goats during each of the three study periods. These combined indices increased the sensitivity of the method to identify goats requiring treatment for each of the FEC thresholds during each sampling period when compared with FAMACHA© scores ≥4 alone, albeit at the expense of leaving fewer animals untreated as a source of *refugia*. Extending decisions to treat animals to include late-pregnant and early-lactating does, would have further increased the sensitivity to acceptable levels. This conflicts with the situation in Canadian sheep flocks, where additional indices did not improve the sensitivity of FAMACHA© scores ≥ 3 (Westers *et al*., 2016); highlighting the need for caution in extrapolating results of studies based on commercial pastoral sheep production where *H. contortus* is the predominant cause of anaemia to peri-urban goat production, where there are multiple potential causes of pallor of conjunctival mucous membranes (Ejlertsen *et al*., 2006).

When our data were modelled to show the potential value of FAMACHA© score in a decision support tool for animal health management, age, sex, BCS and FEC only accounted for some of the variability. Evaluation of conjunctival mucous membrane colour, BCS and incisor tooth dentition was straightforward, and provided an additional opportunity to evaluate the general health of the goats. This is important in the development of evidence-based planned animal health management to improve production efficiency. A similar principle has been reported in South Africa, referred to as a 'five point plan' (Bath and Van Wyk, 2009).

Peri-urban goat production in seasonally resource-poor or -abundant environments has been neglected in terms of agricultural extension aimed at providing smallholders with innovative methods to improve food production efficiency and economic returns. This study highlights inefficiencies in peri-urban goat production and shows the contributory role of animal health challenges, including haemonchosis. Our results show the value of combining evaluation of conjunctival mucous membrane colour, BCS and incisor tooth dentition, both to increase awareness of the importance of disease management in reducing production loss, and in the targeted selective treatment of haemonchosis.

There is a responsibility to ensure that any control measures arising from increased awareness of the importance of GI nematodes are rational and do not present a high risk of selection for anthelmintic resistance (Kaplan and Vidyashankar, 2012). Use of combined evaluation of conjunctival mucous membrane colour, BCS and incisor tooth dentition as simple indices for targeted selective treatment that can be measured by livestock keepers or animal health workers, may afford a more sustainable approach for the control of GI nematodes in peri-urban goats than the current widespread practice of mass drug administration. This may be particularly important during the dry season when grazing or browsing management may not be conducive to there being significant populations of free-living stages in *refugia*. Our results demonstrate what can be achieved using rudimentary facilities and basic clinical methods for quantitative data collection. They also highlight opportunities to use next generation post genomic methods to explore and refine the outcomes, for example to determine causes of drug inefficacy, or to determine the proportions of goats that need to be untreated under different situations to provide an adequate source of *refugia* for anthelmintic resistance mitigation. Community-led approaches (Walker *et al*., 2015) are now needed to influence the uptake and effectiveness of targeted selective treatment regimes against GI nematodes that can be implemented effectively by resource-poor farmers.

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Table

A

August 2017 (dry season).

	FAMACHA© ≥ 4		FAMACHA© ≥ 3	
	% correct	% missed	% correct	% missed
≥ 250 epg	80.7	14.6	61.5	8.1
≥ 500 epg	90.8	3.6	63.0	1.5
≥ 1000 epg	92.7	1.3	61.5	0.9

January 2018 (rainy season).

	FAMACHA© ≥ 4		FAMACHA© ≥ 3	
	% correct	% missed	% correct	% missed
≥ 250 epg	53.5	41.1	56.3	13.6
≥ 500 epg	60.2	30.5	49.6	9.6
≥ 1000 epg	66.5	18.9	40.9	5.5

May 2018 (end of rainy season).

	FAMACHA© ≥ 4		FAMACHA© ≥ 3	
	% correct	% missed	% correct	% missed
≥ 250 epg	63.8	20.3	34.8	5.2
≥ 500 epg	69.5	10.6	28.1	1.7
≥ 1000 epg	73.3	3.8	20.1	0.7

B

August 2017 (dry season).

Treat: FAMACHA© 4 and 5 + BCS 1 and 2 + age <18 months

	% correct	% missed
≥ 250 epg	39.6	5.6
≥ 500 epg	36.8	1.1
≥ 1000 epg	35.8	0.2

January 2018 (rainy season).

Treat: FAMACHA© 4 and 5 + BCS 1 and 2 + age <18 months

	% correct	% missed
≥ 250 epg	50.4	22.6
≥ 500 epg	46.5	17.3
≥ 1000 epg	42.1	11

May 2018 (end of rainy season).

Treat: FAMACHA© 4 and 5 + BCS 1 and 2 + age <18 months

	% correct	% missed
≥ 250 epg	42.1	7.8
≥ 500 epg	33.6	4
≥ 1000 epg	29.8	0.9

Table 1: A. Summary of values of FAMACHA© scores of ≥4 or ≥3 to predict FECs ≥250, ≥500 and ≥1,000 epg. '% correct' refers to correct prediction of FECs ≥ or < threshold values for treatment as a percentage of the total number of goats. '% missed' refers to failure to predict FECs ≥ threshold values for treatment as a percentage of the total number of goats. B. Summary of values of FAMACHA© scores of ≥4, plus BCS scores ≤2, plus age ≤ 18 months to predict FECs ≥250, ≥500 and ≥1,000 epg.

Figures and legends

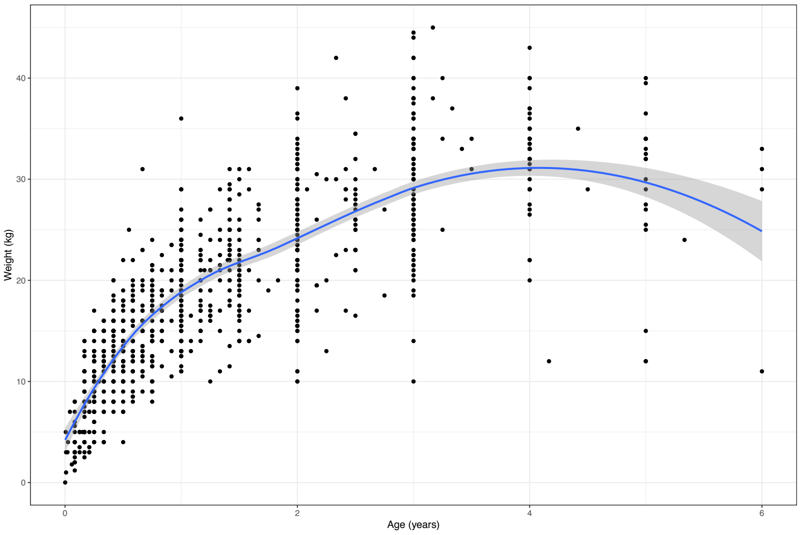

Fig. 1. Body weight and reported age of each of 999 goats at the time of recruitment and 95% confidence intervals for the best fit prediction.

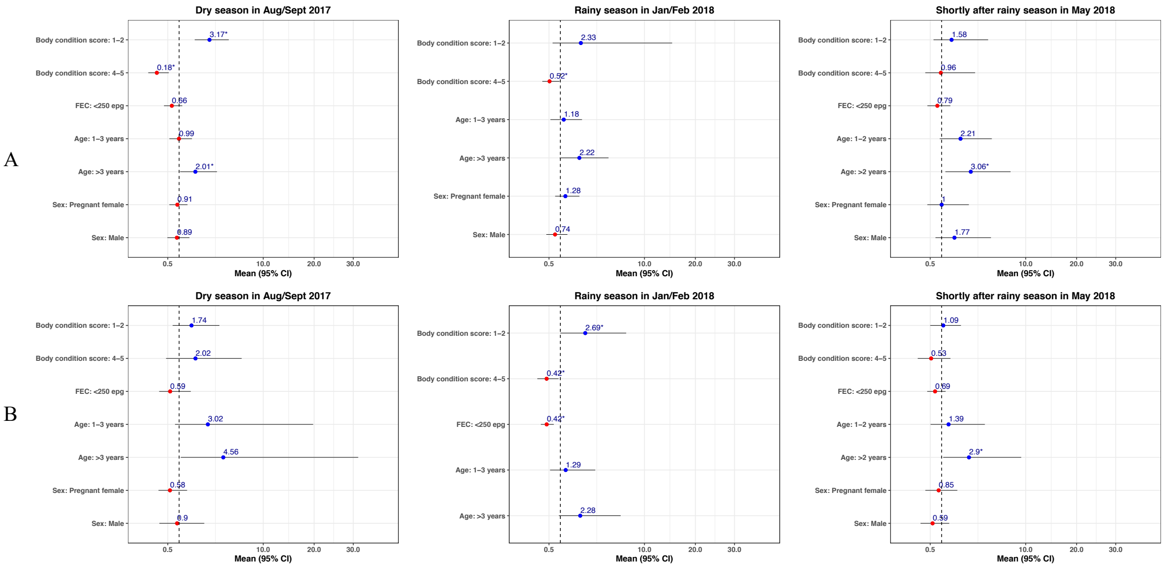

Fig. 2. Models investigating factors predicting a FAMACHA© scores of ≥3 (A) or ≥4 (B). (Goats <6 months-old are excluded). The dots are mean odds ratio values and the solid lines are 95% confidence intervals. Where these lines do not overlap the vertical dotted line, the odds ratios of those explanatory variables predicting a FAMACHA© score of ≥3 (A) or ≥4 (B) are significant. Red dots represent negative effects of explanatory variables predicting a FAMACHA© score and blue dots represent a positive effect. * donates statistical significance according to our methods. This shows the multifactorial complexity of the FAMACHA© score phenotype.

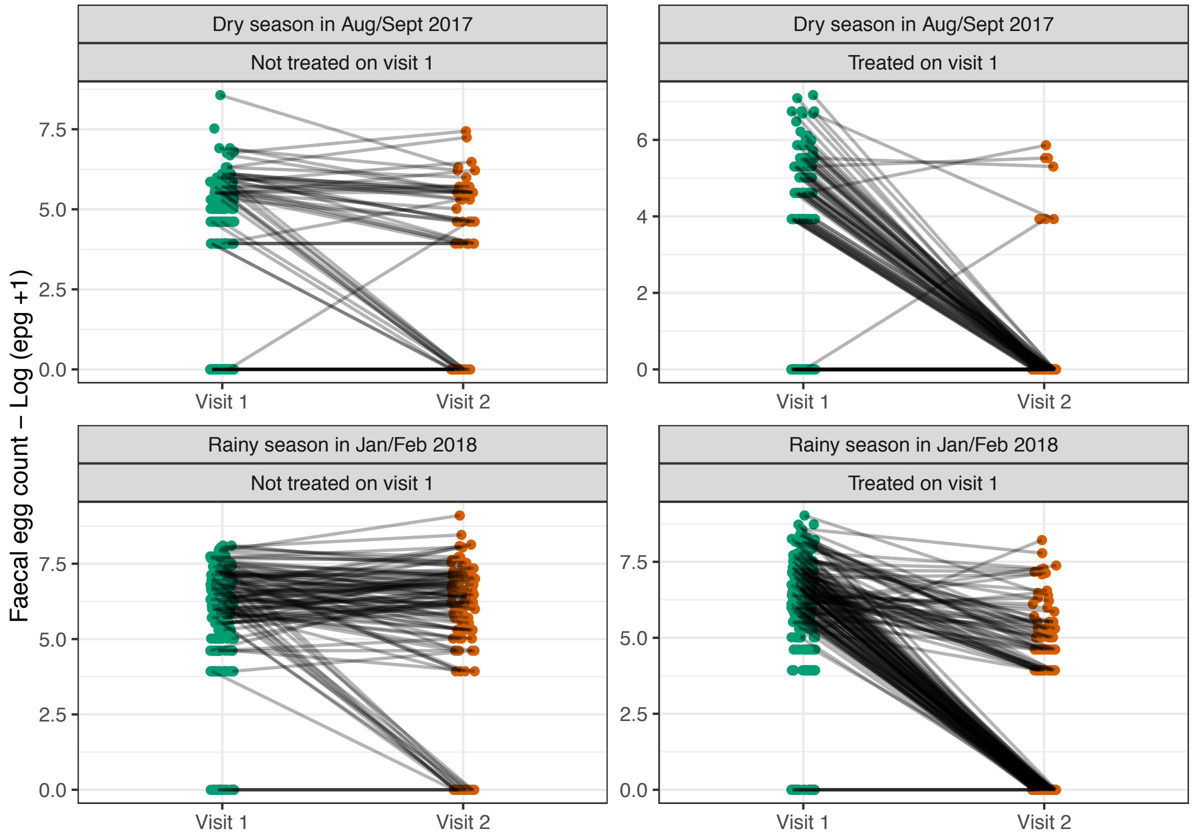

Fig. 3. Log faecal egg count +1 (epg) on the first visit and second visit 14 days later during the dry season and rainy seasons. The individual animal FECs are shown for untreated goats and for goats that were treated with 10 mg/kg albendazole at the time of the first visit.

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