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Global perspectives on nematode parasite control in ruminant livestock: the need to adopt alternatives to chemotherapy, with emphasis on biological control

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Abstract

Effective, sustainable control of nematode parasites of grazing livestock is becoming ever-more challenging and difficult. This is largely due to two contrasting issues. One is the rapid escalation of resistance to anthelmintic drugs, which is arguably the greatest problem now facing the small ruminant industries worldwide. Secondly, there is the increasing trend towards organic farming, in which there is prohibition of the prophylactic use of all chemical compounds. Livestock producers urgently need non-chemotherapeutic alternatives in parasite control. Researchers have responded to this challenge and a variety of quite different approaches have been the subject of intense investigation in many countries for several decades now. These vary in relation to their stage of development for on-farm use, their utility, and their applicability across the spectrum of grazing livestock enterprises throughout the world. One relatively recent innovation is the biological control approach to nematode parasites. This has now reached the stage of commercialization. This review focuses on these issues and provides an overview of the possible ways in which the biological control of nematode parasites could be employed in grazing ruminant livestock systems worldwide.

Keywords: nematode parasites, livestock, biological control, *Duddingtonia flagrans*

Introduction

Despite the remarkable achievements in the discovery and development of anthelmintic drugs, with ever-increasing levels of potency and ever-increasing spectra of activity, nematode parasitic disease remains one of the greatest limiting factors in successful, sustainable ruminant livestock production worldwide (Perry and Randolph, 1999). It is beyond the scope of this short review to give a comprehensive account of the multiplicity of reasons behind this, but the short answer is that parasites exhibit remarkable biological plasticity. This means essentially that parasites can evolve to counter any constraint, chemical or otherwise, that is used against them.

In a balanced ecological system, both host and parasite populations are firmly controlled by a complex array of interacting factors. However, the domestication of livestock has tipped the balance in favour of parasites. This is because domestication is almost always associated with restriction of livestock movement, increasing stocking rates, increasing the proportion of susceptible animals (young and breeding females) and increasing productivity demands. Although domestic livestock have been with us since pre-biblical times, I believe that the global threats imposed by nematode parasites on ruminant livestock production have never been so great as at the present time. This is due to two quite disparate factors: (i) the evolution of anthemintic resistance, and (ii) consumer demand and the organic farming movement. These will now be discussed in turn.

The evolution of anthelmintic resistance

For approximately the past half-century, we have lived in what can be considered the 'chemotherapeutic era' in

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relation to the control of diseases of man, his crops and his livestock. This era was heralded by the commercial availability of the so-called wonder-drugs. By virtue of their remarkable efficiency against target diseases or pest organisms, their broad-spectrum activity, their safety and their cheapness, these drugs fostered the notion that disease scourges could be kept permanently in check, if not eradicated, by the frequent use of drugs. Unfortunately, the development of resistance has proved to be an inevitable evolutionary consequence of the use of these compounds against bacteria, insects, fungi and now worm parasites (Fig. 1).

There is a depressing sense of *déjà vu* when one looks at the history of drug release and the development of resistance, which has occurred virtually in chronological sequence in all target pest organisms. The modern, broad-spectrum anthelmintics arrived in the marketplace considerably later than other broad-spectrum drugs, such as the antimicrobials, insecticides and fungicides. Therefore, we should have been forewarned that the development of resistance to these anthelmintics was almost certain to occur—and sooner rather than later!

Anthelmintic resistance is by far the greatest problem in the small ruminant (sheep and goat) industries throughout the world. There have been many recent reviews on the status of anthelmintic resistance (Waller, 1997a; Sangster, 1999), but such reviews become out-of-date very quickly as new reports appear regularly in the literature. However, as a generalization it can be said that the warmer and more humid the environment in which sheep and goats are raised, the greater is the resistance problem (Waller, 1997b). This in turn is linked

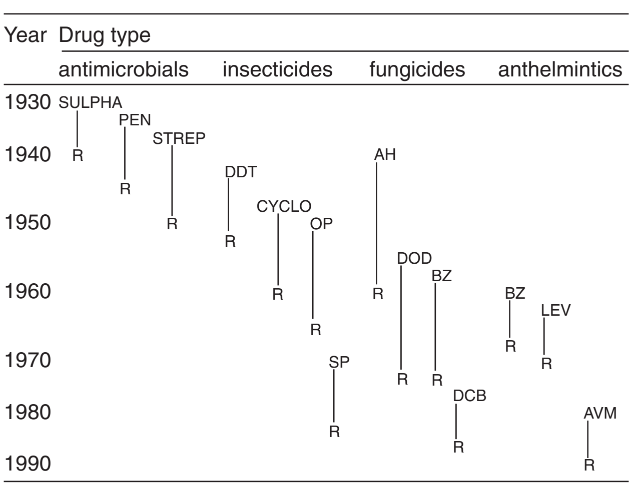

Fig. 1. Evolution of resistance. Year of commercial release of broad-spectrum drugs and the first appearance of resistance in target organisms. Antimicrobials: SULPHA, sulphonamides; PEN, penicillin; STREP, streptomycin. Insecticides: DDT, dicophane; CYCLO, cyclodienes; OP, organophosphates; SP, synthetic pyrethroids. Fungicides: AH, aromatic hydrocarbons; DOD, dodine; BZ, benzimidazoles; DCB, dicarboxamides. Anthelmintics: BZ, benzimidazoles; LEV, levamisole; AVM, avermectins. From Waller (1994), with permission.

to the importance of the highly pathogenic nematode parasite *Haemonchus contortus*.

Resistance in cattle nematodes appears to be spreading, but the reports are of localized cases. Most concern surrounds resistance to ivermectin, which has now been reported in *Cooperia* spp. in several countries in the southern hemisphere (for a review see Coles, 2002). The macrocyclic lactone anthelmintics are so widely used for parasite control in cattle that failure of treatment because of resistance would be a very serious matter.

Consumer demand and the organic farming movement

In recent years there has been increasing demand by consumers that agricultural products should be both 'clean' and 'green'. The impetus for 'clean' livestock products has followed the publicity surrounding the contamination of human food products with substances that have had tragic adverse embryogenic or teratogenic effects, and the development of super-resistant human microbial pathogens caused by gene transfer of resistance from organisms screened by the use of antibiotics (euphemistically termed 'growth promoters') in intensive livestock production systems. The threat of adverse effects on the environment of the use of any chemicals used in agricultural production has also driven this concern.

The term 'green' refers to livestock products that are produced by animals raised under outdoor conditions, in contrast to those produced in intensive, 'factory farming' operations. Ruminant livestock in Europe are now spending more time on pasture, for both economic and animal welfare reasons, and this entails greater exposure to pasture-borne parasites. This has been accompanied by a rapid increase in the popularity of organic farming. Countries in Europe lead the world in the move towards organically produced livestock products. For example, in Sweden there is an active government policy to foster organic farming and the country is aiming to have 20% of its agricultural commodities produced organically by 2005. Legislation now proclaims that, for organic farming, the prophylactic use of drugs, including of course anthelmintics, is prohibited. As a consequence, new and serious animal welfare issues are starting to emerge throughout Europe because of distress suffered by animals due to uncontrolled parasite infections.

These two quite contrasting issues—anthelmintic resistance and organic farming—have made the matter of maintaining effective parasite control a major concern for grazing livestock management enterprises throughout the world. Much work has been done in the investigation of alternative, non-chemotherapeutic parasite control options (for reviews see Barger, 1997; Gray, 1997; Waller, 1997c, 1999). This aspect will not be considered in detail here; this paper will rather focus on the potential of biological control.

Biological control of nematode parasites

Currently, work on the biological control of nematode parasites of livestock is almost exclusively associated with the nematode-destroying microfungus *Duddingtonia flagrans*. This is because this organism has three very important attributes: the ability to survive passage through the gut of livestock, a propensity to grow rapidly in freshly deposited dung, and a voracious nematophagous capacity (for a review see Larsen, 1999). Control is effected by the fungus capturing the infective larval stages of nematodes before they migrate from dung to pasture to complete their life cycle after ingestion by grazing animals. Field evaluation of this concept for a range of livestock species (sheep, goats, cattle, horses, pigs), in a variety of geoclimatic regions, has been under way for the past decade (for reviews see FAO, 1998, 2002; Larsen, 1999). At the same time, a number of potential stumbling blocks on the path towards product registration have largely been overcome. These are:

- the scaling-up of production of *D. flagrans* to produce large quantities of spore material (Gillespie, 2002);
- proving that deployment of *D. flagrans* is environmentally benign (Yeates *et al.*, 1997, 2002, 2003; Faedo *et al.*, 2002; Knox *et al.*, 2002); and
- establishing that *D. flagrans* is ubiquitous and that very close genetic similarity exists between isolates from widely separated localities (Faedo, 2001; Skipp *et al.*, 2002), suggesting a clonal population worldwide.

The near-commercialization of this non-chemical approach to nematode parasite control is attracting increasing interest across a wide spectrum of individuals, including researchers, administrators, entrepreneurs, extension workers and farmers. This interest is driven by anthelmintic resistance and the organic farming agenda.

However, it is very important to understand that biological control cannot be considered a replacement for anthelmintics. It has no chemotherapeutic effect, and damaging, or potentially damaging, worm infections inside the animal will therefore not be affected. The purpose of using *D. flagrans* is to achieve prophylactic worm control, whereby future free-living parasite populations on pasture are reduced. Thus, I believe that biological control should be used in combination with other effective parasite control procedures, including the timely and selective use of anthelmintics. To achieve good levels of worm control in purely organic livestock farming enterprises will require very high standards of livestock management, as biological control on its own certainly cannot be expected to achieve this result.

The following is my attempt to identify those situations in which biological control may be appropriate for the ruminant livestock industries found throughout the world. As a very broad generalization, the conditions under which livestock are maintained fall into various categories, and these will be discussed in turn.

Extensive, nomadic livestock industries

The vast tracts of marginal agricultural land, ranging from rugged mountainous country and deserts to natural grasslands, which encompass Asia, the former USSR and the Sahel region of Africa, account for more than 700 million small ruminants (FAO, 2000). Production systems are largely based on traditional transhumance activities and the shepherding of small flocks, which graze on different pastures in the different seasons. Nematode parasitism is regarded as the cause of important losses in production in these regions (FAO, 1992), but this is exacerbated by severe and often lengthy seasonal nutritional shortages. Anthelmintic treatment tends to be *ad hoc* and haphazard, but is generally infrequent, so the extent of selection for anthelmintic resistance may be considered to be low. There are probably very few instances where an opportunity for alternative parasite practices would arise, and there is even less likelihood of their adoption.

Broad-acre, permanent grazing livestock industries

Typical of this form of husbandry are the ruminant livestock industries of Australasia, southern Latin America and southern Africa. Here livestock are grazed all year round on permanent pasture. Improvements in pasture production by the introduction of superior plant cultivars and the application of fertilizer has led to expansion, particularly in sheep numbers. This has been accompanied by an increasing risk of nematode parasitic disease, but has coincided with the revolution in control by the use of chemotherapy. This in turn has meant that livestock producers rely almost exclusively on the use of anthelmintics to control parasites in their flocks. As a result, some of the greatest problems of anthelmintic resistance are found in these regions of the world (van Wyk *et al.*, 1997; Waller 1997a; Sangster, 1999).

In broad-acre, permanent grazing regions of the world, there are seasonal peaks in the availability of infective nematode larvae on pasture. Most of these peaks are invariably derived from relatively short periods of time rather than from the progressive accumulation of prior contamination by animals grazing on the pastures. In regions that receive predominantly winter rainfall, the seasonal peak in the availability of infective larvae is generally in spring, and is derived largely from contamination during the previous late summer/autumn. For regions that receive summer rainfall, the larval peak occurs in late summer/autumn, derived from spring/early summer contamination. In

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regions that receive rainfall more or less evenly throughout the year, larval numbers on pasture tend not to oscillate from very high to very low levels, but are of more even amplitude throughout the year, the overall magnitude of infectivity being determined by the amount of rainfall.

Opportunities for the use of biological control

Because of the numerical and economic importance of the sheep industries in these regions of the world, the following broad recommendations apply to this industry, but are equally applicable to goats run under similar conditions. The obvious time to deploy biological control is at critical times when numbers of larvae on pasture are low, but when faecal contamination during relatively short periods subsequently results in the seasonal peaks of infective larvae on pasture. These times are discussed below.

Sheep flocks: ewes

The times suitable for deployment of biological control are late summer and/or autumn in winter rainfall regions; spring and/or early summer in summer rainfall regions; and between lambing and weaning in regions with uniformly distributed rainfall.

These times generally coincide with lambing, and thus the periparturient ewe would invariably be excreting a relatively large number of nematode eggs. As the timing of lambing varies in these regions, it would be a good policy to make the deployment of biological control measures at the time of lambing a blanket recommendation. As the periparturient ewe is under considerable stress, a sound recommendation would be to treat all ewes prior to lambing with an effective anthelmintic, particularly if they have been grazing previously on contaminated pastures. Invariably, they would have resident worm populations, particularly of inhibited larvae, and the peri-parturient relaxation of resistance results in resumption of worm development, high faecal egg counts and (depending on the magnitude of infection) effects on milk production and mortality. Unless the lambing ewes are placed on genuinely parasite-free pasture, they will rapidly re-acquire infections. However, positive faecal egg counts will not occur until at least 3 weeks after an effective anthelmintic treatment. This is the time to commence deployment of biological control.

As the objective of deployment of biological control in all of the three instances outlined above is to reduce the number of infective larvae on pasture at a time when pasture growth is at its maximum and when weaning generally occurs, it would provide the opportunity to keep the young weaned lambs on the lambing pasture. However, although this advice is theoretically sound, there is justifiable concern that it simply is not good management practice to leave weaners on the lambing pastures. Extensive work in Australia has shown that, irrespective of the level of parasite control that is practiced (anthelmintic treatment being implied) in lambing flocks under conditions of permanent grazing, the most important strategy is to move lambs off the pastures where they were raised with their dams at weaning, when they are approximately 3 months of age (Waller *et al.*, 1987a, b). Under these circumstances, the strategy of using biological control discussed in the next section could be implemented.

Sheep flocks: weaner lambs

Young, recently weaned sheep are highly susceptible to parasite infection. The objective is therefore to graze these animals on pastures of low infectivity. Unless weaning is accompanied by treatment with a highly effective anthelmintic and the animals are then moved to helminthologically clean pastures, weaner sheep are highly likely to contaminate their pastures. Providing biological control for a relatively short period of time (2–3 months) immediately after weaning will help ensure that pastures remain only lightly infected. Provided that nutrition is not limiting, these animals will grow well and gradually acquire natural immunity to parasite infection on the same pastures during the following months. However, the likelihood of farmers adopting biological control at this time will depend on the mode of delivery. A fungal bolus rather than a feed supplement would be more commercially attractive. This is simply because if good-quality pasture is available it is unlikely that weaners will be attracted to supplementary feeding, unless they have been trained previously (before weaning). More to the point is that most sheep farmers would be reluctant to provide a costly feed supplement when they had good-quality pastures available for their weaners.

Cattle

As a generalization, it can be said that very little, if not zero, parasite control is practiced for adult beef cattle in these regions. The only class of animals that receive attention in this respect are weaned animals up to approximately 18 months of age. For this class of animals, considerable anthelmintic medication can be given, either in the form of sustained-release boluses (blanket anthelmintic cover for up to 4 months) or frequent anthelmintic treatment (usually injections). This is particularly so in the humid regions of southern Latin America and applies to a lesser extent in Australasia. It is in cattle managed under these latter circumstances that reports of anthelmintic resistance in cattle nematodes have emerged (Vermunt *et al.*, 1995, Echevarria and Pinheiro, 2001; Fiel *et al.*, 2001).

For the dairy industry, there is still debate about whether anthelmintic treatment improves productivity in adult cows (Elbers and Schukken, 1995; Reinemeyer, 1995). However, to achieve improved productivity

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requires that the animals need to be maintained essentially worm-free. Irrespective of whether the productivity benefit is achievable, it is unrealistic and arguably counterproductive in the long term. Essentially, this type of management will prevent the animals mounting and maintaining an immune response to parasites, through the acquisition of modest numbers of infective larvae. Biological control would not claim to emulate such conditions, so the only justification for using biological control in dairy cows would be to render the pastures that they graze (and contaminate) of very low (zero) infectivity. However, the fact that adult dairy cows are large and produce voluminous quantities of faeces with invariably negligible nematode egg counts would mean that the benefit–cost relationship of using biological control in dairy cows is highly questionable. Additionally, it has been shown that pastures previously grazed by adult cows that have received no previous worm treatment are of very low infectivity, and are thus suitable for grazing by young stock (Dimander *et al.*, 2003). Factors to bear in mind when considering the use of biological control in young dairy cattle are similar to those described above for beef cattle.

Possible means of deployment of biological control

Sheep and goats

The suggested target groups of animals are lactating ewes and/or weaned lambs. The recommendation is for the deployment of the biological control agent for a limited time, with a maximum of 3 months in any circumstance. Also, the times suggested for the use of biological control often coincide with those of the short-term targeted supplementary feeding that is accepted management practice in these classes of sheep on many farms found in these regions. The recommendation would be to co-administer spores of *D. flagrans* with the feed supplement. However, because of the extensive nature of sheep production in these regions, strict adherence to daily supplementary feeding is often neither possible nor practical. It must be recognized that feeding less often than each day will result in uneven shedding of fungal spores in the dung of animals, thus allowing the opportunity for some nematode eggs to develop to infective larvae in a faecal environment with suboptimal concentrations of *D. flagrans*. Also, as previously mentioned, the concept of inclusion of a biological control agent with supplementary feed (grains or commercial pellets) will have little appeal to farmers at times when good-quality pasture is available, such as at weaning.

An additional bonus can be obtained when biological control is used in circumstances where farmers face problems with anthelmintic resistance. As mentioned previously, biological control should be used prophylactically, on the basis of the epidemiology of parasite infections, and in most circumstances after anthelmintic treatment. Used in this way, biological control would attack the free-living stages derived from worms that had survived drenching, as well as the progeny of parasites acquired by subsequent larval pick-up from pasture.

Clearly, much greater opportunities for biological control would exist in these regions if effective methods of depot delivery of *D. flagrans* were available, such as the use of supplementary feed blocks or controlled-release devices. Although work has been conducted on such systems of sheep management in broad-acre permanent grazing, no fungal block (Waller *et al.*, 2001a) or fungal controlled-release device (Waller *et al.*, 2001b) has been developed which provides effective parasite control for the minimum required time of 2 months.

In accordance with general recommendations for biological control, it should be used in conjunction with other forms of parasite control, with the aim of maintaining effective parasite control for the foreseeable future. Other such adjuncts that are applicable to sheep production in the broad-acre, permanent pasture regions of the world include:

- alternative grazing strategies with other species or classes of stock (Barger, 1996);
- exploiting aftermath grazing where applicable (Barger, 1996);
- the use of specific aids, such as the FAMACHA system (Malan and van Wyk, 1992; van Wyk and Bath, 2002); and
- long-term selection, both within and between breeds, for innate resistance to parasites (Woolaston and Baker, 1996; McEwan *et al.*, 1997).

Cattle

Substituting biological control for blanket anthelmintic treatment is an obvious possibility, although this, to my knowledge, has not been trialed. One obvious proviso is that in situations where managers have found it necessary to treat intensively with anthelmintics to prevent parasite-induced losses, and where anthelmintic resistance has emerged, biological control alone will almost certainly not work. Substantial changes in management, including other adjuncts to control parasites, will need to be made.

The use of a fungal controlled-release device for use in young cattle is certain to have considerable appeal in cattle-raising enterprises in these regions.

Intensive livestock industries

For the purposes of this review, I consider that these relate to essentially two geographically, financially and culturally distinct regions of the world. The first of these is represented by the livestock industries of the humid tropics and subtropics, which are typified by smallholder farmers. The second is represented by the grazing ruminant industries of Western Europe (although certain sectors of the sheep industries in France and the UK would be more akin to the broad-acre production systems outlined above). These two groups of industries share similar characteristics insofar as there are many fewer animals per owner than in the broad-acre permanent grazing regions, much greater contact occurs between the owner and his stock, and the housing of stock is a feature.

Possible means of deployment of biological control

The contrast in intensive livestock management systems is not between the animal species (sheep and cattle) but between geographic regions.

Tropical and subtropical regions

From the outset, it is important to recognize that in extreme situations of subsistence farming, which are an unfortunate feature in these regions of the world, many technological developments are either unaffordable or inappropriate. For example, anthelmintics of reputable brands may be too expensive, or locally manufactured products of such inferior quality, that they are not used by the stock-owner. As a consequence, massive mortalities of young stock caused by internal parasites are still, tragically, a commonplace phenomenon, particularly in countries of Africa and Asia. At the other extreme, where anthelmintics have been used intensively, high levels of multiple resistance have developed to such an extent that total chemotherapeutic failure in the control of worm parasites of small ruminants is now a reality (Waller, 1997a). Between these two extremes, farmers face a continual battle in their attempts to prevent mortality, contain clinical disease and reduce production loss due to worms as much as possible. This almost always requires the frequent use of anthelmintics and, as a consequence, there is inexorable movement down the path to total anthelmintic failure.

The major environmental variable that controls the severity of nematode parasites in the tropics and subtropics is rainfall, as it is almost always warm enough to facilitate the rapid development of the free-living stages on pasture. In addition, the most pathogenic nematode parasite of small ruminants, *Haemonchus contortus*, is endemic throughout the whole region. Thus, in situations where it is wet practically throughout the year, clinical outbreaks and mortality due to haemonchosis in sheep and goats of all ages can occur at any time. In areas with distinct rainy (wet) and dry seasons, discontinuities in the pattern of larval availability on the pasture can occur.

Because of the invariable development of high levels of multiple anthelmintic resistance in those countries in the tropics and subtropics where farmers can afford to drench, it is critical to understand that no alternative parasite control method on its own can be an effective, practical alternative, even in the short term. The message that must be heeded by owners of small stock is that a combination of control methods must be adopted—one of which may be biological control.

The almost universal practice of night housing of small ruminants in the tropics and subtropics means that the opportunity of using a biological control agent, incorporated in a feed supplement, is a practical possibility. An additional option is the incorporation of *D. flagrans* spores in feed blocks used for immediate and rapid consumption. Both these methods of deployment have been tested with success in the control of nematodes of sheep and goats in Malaysia (Chandrawathani *et al.*, 2002). But the potential for unnecessary problems in the making and use of fungal blocks (e.g. the short duration of spore viability, palatability, etc.) suggests to me that the additional complication of formulating blocks—rather than simply offering the fungal material as a daily feed supplement—is unwarranted. As mentioned above, such deployment of biological control must be accompanied by other parasite control measures. By far the most effective, sustainable, consumer- and user-friendly of these is short-term rotational grazing. This has been shown to be spectacularly successful in the humid tropics (Barger *et al.*, 1994; Sani and Chandrawathani, 1996). The combination of biological control with rotational grazing is currently being trialed in Malaysia and results to hand have proved to be very encouraging (personal communication, P. Chandrawathani). Other strategies that need to be incorporated include:

- use of an appropriate, effective anthelmintic (if available) prior to the introduction of animals into the rapid rotational grazing scheme;
- selection or purchase of breeds with high levels of natural resistance to parasites (Gray, 1995; Baker, 1996);
- improving nutrition, e.g. adopting low-cost, farm-manufactured urea–molasses technology (Knox and Zahari, 1997);
- use of medicated urea–molasses blocks on a selective, strategic basis—use of anthelmintics in this way (commonly the benzimidazoles) generally shows that drug efficacy is restored (Knox, 1996); and
- use of FAMACHA© (Malan and van Wyk, 1992; van Wyk and Bath, 2002).

Another possibility for the use of biological control which has very limited, but locally very important, applicability is in the control of *Strongyloides papillosus*, a parasite responsible for the sudden death syndrome reported in intensively reared young calves on the southern subtropical islands of Japan (Taira and Ura, 1991). This parasite is ubiquitous in young ruminants, but of particular importance in the tropics and subtropics. It is unique in having the ability to reproduce in the free-living environment as well as in the parasitic stage within the host. Because *S. papillosus* can replicate in the bedding, numbers of infective larvae increase exponentially and young animals that are kept in pens can be exposed to massive larval challenge by percutaneous infection within 5–7 days. The outcome of this may be the sudden death syndrome referred to above. A study in Malaysia (Chandrawathani *et al.*, 1998) showed that the nematophagous fungus *Arthrobotrys oligospora* was capable of greatly diminishing the numbers of *S. papillosus* in ideal culture conditions. The pens used in these intensive rearing units are small, which suggests that fungal material could simply be applied directly to the bedding. This opens up the possibility of using *A. oligospora*, or any other readily available, easily cultivated, voracious nematophagous fungus, to control this important parasite, as the need to feed animals with fungal material does not apply.

Temperate regions

Except for the UK and France, the small ruminant industries of Europe are numerically insignificant by world standards. However, they provide products for the protected local or niche markets and consequently the value of individual animals is high. In addition, lucrative premiums for organically produced livestock products are also largely responsible for the surge in popularity of organic farming in Western Europe.

Typically, European ruminant livestock are raised on farms that have a variety of agricultural enterprises. This high degree of diversification potentially allows efficient worm control practices whereby maximum benefit can be achieved by movement of animals to 'low-worm' pastures produced by a variety of means. In addition, housing the animals, which is seasonal (winter) in Europe but a daily occurrence in the tropics, offers a great opportunity to manage parasite populations in grazing livestock.

Clearly, if animals are genuinely worm-free at the time of pasture turn-out in spring (this is still possible in Europe with the prior use of macrocyclic lactone anthelmintics) and the pastures are new leys, there is a genuine 'clean animals onto clean pasture' situation. In these circumstances, no other worm control measure is necessary.

However, in practice this ideal state of affairs occurs very infrequently. Thus, there is a great opportunity for biological control for livestock in the intensive livestock industries of the temperate regions. The simplest method, and the easiest to implement at present, is daily supplementary feeding. The obvious time to employ this is at pasture turn-out in spring. The assumption is that either (i) the pasture has some level of infectivity of larvae that are derived from livestock grazing (and thus contamination) the previous year and have survived the winter, or (ii) the animals have residual infections (predominantly arrested populations) that have remained *in situ* during the housing period.

In sheep enterprises in western Europe, lambing occurs most commonly within a period of 1–2 weeks before turn-out. Ewes with young lambs at foot are allowed access to high-quality pasture, but if they are not treated with anthelmintic, or if they graze on pastures used by sheep the previous year, they will become infected with parasites. Inevitably they will excrete high numbers of nematode eggs during the period between lambing and weaning (the post-partum rise). It is this contamination that gives rise to the peak of infective larval numbers later in the season. This can be catastrophic to the growth of young lambs if they remain on, or are reintroduced to, this pasture after midsummer. In a farm trial in which a biological control agent was applied as a daily fungal supplement to drenched ewes for just 6 weeks after turnout onto contaminated pastures, there was superior weight gain and earlier turn-off (marketing), and fewer lambs that had to be carried over the following winter due to parasite-induced loss of productivity, compared with a flock that was managed traditionally (Waller *et al.*, 2002).

Similar studies with young, first-year grazing cattle in northern Europe have also met with success. Feeding a biological control agent as a daily supplement for 2–3 months after turnout reduced larval counts on the herbage towards the end of the season, thereby limiting the risk of parasitic gastroenteritis, and there was improved weight gain compared with calves not receiving the fungal supplement (Denmark: Larsen *et al.*, 1995; Nansen *et al.*, 1995; Lithuania: Šarkūknas *et al.*, 2000; Sweden: Dimander *et al.*, 2002). The arguments, as I see them, for the use of biological control in adult cattle are covered above in the section entitled 'Broad-acre, permanent grazing livestock industries'. I believe that there would be little merit, economically or from the standpoint of parasite control, of using biological control in adult cattle, whether beef or dairy.

Conclusions

Results are now steadily accumulating to show parasitological benefits and—more importantly from the standpoint of farmers—improvements in animal performance by the strategic use of biological control against nematode parasites of livestock. Work has moved from the concept phase and there are now companies actively involved in this technology. It appears that the hurdle of producing commercial quantities of *D. flagrans* spores has been overcome. Further practical field trials yielding positive results are required immediately if biological control products are to be registered and farmers are to become interested in using this technology.

All trials so far conducted in widely dispersed localities to assess the possible adverse impact (on beneficial soil nematodes) of using biological control show that this technology is environmentally benign (Yeates *et al.*, 1997, 2002a, b; Faedo *et al.*, 2002; Knox *et al.*, 2002). Further work has shown that dose rates of fungal spores can be reduced substantially from those selected in the initial trials, in both sheep (Waller *et al.*, 2001a; Chandrawathani *et al.*, 2002) and cattle (Dimander *et al.*, 2003). This is a very important economic issue because it will reduce the cost of production and the saving will ultimately be passed on to the consumers—that is, the livestock owners who will use the technology. This review has focused on ruminant livestock, but there is ample evidence to show that the same biological control technology has a place in grazing pig production, and most particularly for the control of nematode parasites of horses.

It is my view that it is in Western Europe where the greatest initial opportunities for a commercial biological control product will occur. This is because of the high value of individual animals, the impetus towards organic farming, the small number of animals per operator, and the relatively easy management of ruminants in this region. However, the threat of unmanageable anthelmintic resistance is a goad to stimulate the search for viable alternatives in the control of parasites of small ruminants in the intensive livestock systems of the tropics and subtropics. The likely consumer resistance to paying for this new technology may be overcome, as there are examples (e.g. Malaysia) of governments financially underwriting the costs of establishing and supporting local livestock industries. The threats posed by the problem of anthelmintic resistance also apply, of course, to the sheep industries in the broad-acre, permanent grazing regions. It may be the sheer weight of animal numbers (sheep) in this region that will provide the commercial drive to produce the first glittering prize of a marketable biological control product for nematode parasites of livestock.

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