INTEGRATED CONTROL OF TICKS AND TSETSE

by

Stephen Torr¹, Mark Eisler², Paul Coleman³, John Morton¹
and Noreen Machila⁴

¹Natural Resources Institute, University of Greenwich, Central Avenue, Chatham Maritime, Kent ME4 4TB
²University of Glasgow Veterinary School, Bearsden Road, Glasgow G61 1QH
³London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT
⁴Centre for Tropical Veterinary Medicine, University of Edinburgh, Easter Bush, Roslin, Midlothian EH25 9RG

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INTEGRATED CONTROL OF TICKS AND TSETSE

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1 EXECUTIVE SUMMARY

1.1 Background

Livestock play a pivotal role in the livelihoods of communities in rural Africa and thus factors affecting the health and productivity of livestock are important constraints in the development and wellbeing of such communities. In sub-Saharan Africa, diseases transmitted by ticks and tsetse are important causes of mortality and morbidity in livestock; tsetse-borne trypanosomiasis has been estimated to cost Africa US$4.5 billion a year and East Coast Fever, transmitted by ticks, has been estimated at US$ 168 million.

Historically, research and control of tick- and tsetse-borne diseases were under the auspices of somewhat distinct groups with control of the various diseases and vectors often the responsibility of separate veterinary and entomology departments. Recently, however, control of tsetse- and tick-borne diseases is becoming increasingly integrated due to:-

- Privatisation and reduction of government veterinary and extension services, with animal health inputs devolving from the level of government agencies to that of individual farmers and livestock keepers.

- Increasing recognition of the need for integrated disease control rather than control of individual diseases; this applies to prevention, control, diagnosis and therapy wherein there are many potential synergies to be exploited through integration.

- Increasing awareness and availability of technologies that impinge on both types of disease, particularly pyrethroid insecticides that are effective against ticks and tsetse and, to some extent, genetically resistant cattle such as N’dama.

While it is apparent that integration is happening, there is scant information on the epidemiological, social and economic implications of this trend. And in particular, concern is attached to the impact that widespread use of pyrethroid-treated cattle may have on prevalence and severity of major tick-borne diseases, especially for poorer livestock-owning communities.
1.2 The problem

The review focuses on five major vector-borne diseases affecting livestock in sub-Saharan Africa:

- Theileriosis (East Coast Fever, Corridor disease) transmitted by *Rhipicephalus* spp. of tick;
- Babesiosis (redwater fever) transmitted by *Boophilus* spp. of tick;
- Anaplasmosis (gall sickness) transmitted by various species of tick (e.g. *Boophilus* spp.) and, mechanically, by biting flies such as *Stomoxys* spp.;
- Cowdriosis (heartwater) transmitted by *Amblyomma* spp. of tick.
- Trypanosomiasis (nagana in cattle, sleeping sickness in humans) transmitted by tsetse flies (*Glossina* spp).

The major biological, veterinary and epidemiological features of these diseases, and their current methods of treatment and control are briefly described. Since the mid-1980s, control of tsetse has become increasingly dependent on bait technologies, and particularly the treatment of cattle with pyrethroid formulations originally developed to control ticks. A review of the literature shows that there are examples from Burkina Faso, Kenya, Tanzania, Zimbabwe and Ethiopia where the treatment of cattle with pyrethroids to control tsetse has had an impact on vectors of TBDs. Effects include benefits, such as reductions in the numbers of ticks and TBD-related mortality, and potentially damaging costs such as a reduction in a population’s immunity to TBDs. However, while there is empirical evidence that using pyrethroid-treated cattle to control tsetse could exacerbate the incidence of TBDs, there is no unequivocal evidence that this has actually occurred.

1.3 The epidemiology of vector-borne diseases

For diseases such as those transmitted by ticks and tsetse, infection is required to produce disease, but not all infections give rise to clinical disease. TBDs and trypanosomiasis differ fundamentally in the balance between infection and disease. On the one hand, babesiosis, cowdriosis and anaplasmosis all display (i) an age dependent increase in the severity of disease and (ii) a reduced probability of disease following an initial infection. For trypanosomiasis on the other hand, host age has no effect on severity and infection does not, in general, confer any subsequent immunity. These simple differences are important not only for an infected individual, but also for the host population because they give rise to the condition of enzootic stability whereby clinical
disease is scarce despite a high rate of infection in the population. In essence, most young animals become infected with the pathogen, experience only mild disease and are immune thereafter. The relative likelihood of enzootic stability arising varies between diseases, being widespread and common for Anaplasma and Babesia bigemina and rare – if it exists at all – for Theileria. For Cowdria ruminatum, there is increasing evidence that enzootic stability occurs but uncertainties surround the roles of vertical transmission, maternal immunity and whether calves are subject to tick challenge. Evidence suggests that the use of pyrethroids is less likely to disturb enzootic stability of Anaplasma than Babesia spp. or Cowdria.

The relationship between force of infection and the level of clinical disease in a host population was modelled using simple analytical models. Changes in variables describing: (i) a pathogen’s overall virulence, (ii) the host’s period of reduced susceptibility (iii) period of immunity (iv) and inoculating dose resulted in changes in the ease with which enzootic stability was reached and overall levels of clinical disease. The variations were in line with documented differences between different TBDs and the results of the models reflected some of the known differences in general levels of disease and enzootic stability. These results suggest that such models could provide powerful tools to assess the impact of pyrethroid-treated cattle on TBDs. Several significant gaps in our basic understanding of the epidemiology of TBDs were identified, including the effects of: inoculum size and virulence, heterogeneities in vector competence, parasite transmission rates, carrier states and mechanical transmission. The likely impact of environmental, vectorial and socio-economic factors on the epidemiology of TBDs are discussed in relation to the analytical model, but it is recognised that there are significant gaps in our basic knowledge of interactions between pathogens, vectors and hosts.

It is recommended that the development of a comprehensive theoretical framework to investigate and evaluate the impact of various vector control strategies is undertaken. This framework should capitalise on existing models of the population biology of vector species which could feed into epidemiological and economic models, thereby allowing the relative effect of control interventions, such as insecticide treatment of cattle, on tick-borne diseases and trypanosomiasis to be evaluated. Such a framework must however differentiate between the epidemiologies of the different tick-borne diseases in different ecological settings.
1.4 **Conserving enzootic stability**

Conserving enzootic stability essentially depends on maintaining tick populations above a certain minimum threshold. This implies that tsetse control measures need to reduce their impact on tick populations. This problem does not arise when tsetse are controlled using methods such as: aerial spraying, ground spraying, artificial baits, or traditional methods of protecting cattle from flies since these have virtually no effect on tick populations. Even where cattle are treated with pyrethroids, there are opportunities to mitigate their effect on tick populations. These include: increasing the interval between applications, applying insecticides to a subset of a cattle population and/or avoiding the treatment of tick attachment sites. The costs and benefits of these strategies are considered using simulation models of tsetse populations and knowledge of the feeding behaviour of tsetse and ticks. Increasing the treatment interval to ~1 month probably reduces the impact on tick populations but intervals greater than this will compromise the efficacy of tsetse control. Selective application of insecticides to certain hosts and/or regions of hosts appear to be particularly beneficial; recent research suggests that this strategy may reduce insecticide costs by 95% and mitigate the impact on non-target species, including ticks, with little reduction in efficacy. It is recommended that a DFID-funded pilot study to develop this strategy is supported.

1.5 **Implications for farmers, communities and governments**

The broader implications of an integrated approach to tick and tsetse control are considered for farmers and society. In particular, the balance of private and public benefits of controlling tick- and tsetse-borne diseases are considered in the context of contemporary Africa, where government-funded provision of veterinary healthcare is in decline. In this context, the private use of drugs to control trypanosomiasis and TBDs has seen a large uptake whereas the use of artificial baits for tsetse control by individuals or communities has seen virtually no uptake in the absence of concerted support from governments and/or NGOs. Between these two extremes, lies the use of pyrethroid-treated cattle, which has seen some 'spontaneous' and sustained uptake by individuals and communities. It is suggested that these contrasting uptakes reflect, at least in part, differences in private and public benefits. On the one hand, use of drugs confers an entirely private benefit, which is immediately effective even when a single farmer treats a single cow. On the other hand, the benefits of artificial baits are largely public and only realised when large numbers of individuals work in a concerted manner over a large area for a relatively long period. Treatment of cattle with pyrethroids has a mix of private and
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public benefits, relating to tick and tsetse control respectively. Capitalising on the perceived private and visible benefits of pyrethroid-treated cattle will improve uptake of bait technologies for tsetse control and it is recommended that appropriate means of promoting these benefits to farmers and rural communities are developed.

NGOs play an increasingly important role in initiating and managing vector control strategies. Accordingly, they need to be provided with appropriate advice on integrated vector control and the possible dangers of exacerbating TBDs through tsetse control. And while the role of governments in animal health provision is declining, it is suggested that they still have an important guiding and legislative role to play, especially in relation to the prevention of drug and insecticide resistance and the conservation of enzootic stability.
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3 INTRODUCTION

Livestock play a pivotal role in the livelihoods of communities in rural Africa, providing important sources of nutrition, transport and fertilizer, as well as being significant financial and social assets for their owners. In sub-Saharan Africa, parasites transmitted by ticks and tsetse flies are a major cause of mortality and morbidity in livestock and consequently have a major impact on rural livelihoods.

In the past, research and control of tick- and tsetse-borne diseases were under the auspices of somewhat distinct groups (Muraguri et al., 1999). Indeed, even within each of these disease-vector complexes, control of the disease and that of the vector were often the respective responsibility of separate veterinary and entomology departments. Now however, there are increasing efforts to integrate control of tsetse and trypanosomiasis, as reviewed by Holmes (1999) and typified by the EU Concerted Action on Integrated Control of Pathogenic Trypanosomes and their Vectors (ICPTV). Similarly, there are also increasing efforts at integrated control of ticks and tick-borne diseases, as evidenced by the EU Concerted Action on Integrated Control of Ticks and Tick-borne Diseases (ICTTD)\(^1\). Even so, there has been little dialogue between workers concerned with the two groups of diseases.

To address this, the two EU Concerted Actions ICPTV and ICTTD-2 recently (April 2002) held a joint workshop at the Antwerp Institute of Tropical Medicine (ICPTV, 2002) on Integrated vector control including synergistic use of drugs and bait technologies for the control of trypanosomiasis and tick-borne diseases. This workshop brought together scientists and field workers from numerous African and European Institutions to discuss pertinent issues related to integration of the two areas.

The workshop highlighted how, in practice, control of tsetse- and tick-borne diseases are becoming increasingly integrated for three main reasons:

- Changes in international policy resulting in privatisation of, and reduction in government veterinary and extension services, with animal health inputs devolving from the level of government agencies to that of individual farmers and livestock keepers.

\(^1\) The 2\(^{nd}\) phase of ICTTD was renamed International Consortium on Ticks and Tick-Borne Diseases (ICTTD-2)
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- Increasing recognition of the need for integrated disease control rather than control of individual diseases; this applies to prevention, control, diagnosis and therapy wherein there are many potential synergies to be exploited through integration.

- Increasing awareness and availability of technologies that impinge on both types of disease, particularly pyrethroid insecticides that are effective against ticks and tsetse and, to some extent, genetically resistant cattle such as N’dama.

The last point is particularly germane to the poorest livestock owning communities within this region. On the one hand, these communities generally own indigenous breeds of cattle, which can develop a natural immunity to tick-borne diseases. On the other, the most practicable and cost-effective means of controlling tsetse for such communities is the use of insecticide-treated cattle. Consequently, attempts by such communities to control tsetse could potentially result in the loss of the widespread natural phenomenon known as enzootic stability (see section 6.1.1) in which tick-borne diseases are controlled by natural immunity, and hence significantly increase morbidity and mortality. The potential catastrophe caused by destabilising tick-borne disease control is exemplified by the case of Zimbabwe where rural cattle were routinely treated with insecticide to control tick-borne diseases. Civil war in the 1970s disrupted the dipping regime and over one million rural cattle died as a result of tick-borne diseases.

While it is apparent that integration is happening, the Concerted Action workshop revealed that there is scant information on the epidemiological implications of control of each type of disease and vector on the other, and therefore much to be done before recommendations could be made for optimising fully integrated control strategies. In particular, the likely impact of widespread use of pyrethroid-treated cattle on the incidence of tick-borne disease was unknown. This appeared to be for a number of related reasons:

- Uncertainty about the degree to which enzootic stability contributes to the status quo of each of the major tick-borne diseases, and therefore the potential for a worsening disease situation if it were to be destabilised.

- The extent to which pyrethroid treatment of cattle is likely to be taken up by cattle keepers in the various agro-ecological zones and production systems in Africa.

- The intensity and modality of use of the technology by those taking it up.

This report reviews current knowledge relating to the potential conflicts and synergies between tick- and tsetse-borne diseases to answer the following questions.
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1. Are there integrated, cost-effective control packages that are acceptable to poor livestock owners?
2. What impact will these packages have on tick-borne diseases?
3. Are there adverse environmental, social and/or economic impacts, and can these be mitigated?

The report also considers the outstanding scientific, social, economic and policy issues relating to these questions. In particular, we use empirical and theoretical evidence to identify circumstances under which tsetse control can potentially improve or exacerbate the incidence of tick-borne diseases. Following on from this, we then recommend various technical, social, economic, research and policy interventions that should contribute to the development of a cost-effective and sustainable integrated approach to controlling vector-borne diseases of livestock in Africa.
THE DISEASES AND VECTORS

4.1 Tick-borne diseases

Tick-borne diseases affect 80% of the world’s cattle population, with an estimated global annual cost of US$ 14 -19 billion (Young et al., 1988). In Africa, three tick genera are particularly important vectors:

*Rhipicephalus* spp., which transmit the protozoan *Theileria parva*, the causative agent of East Coast Fever (ECF) in East, Central and Southern Africa.

*Boophilus* spp., which transmit protozoa (*Babesia* spp) and rickettsia (*Anaplasma* spp.) which cause babesiosis and anaplasmosis respectively and;

*Amblyomma* spp., which transmit rickettsia (*Cowdria ruminantium*), the causative agent of heartwater, and protozoa (*Theileria mutans*). *Amblyomma* spp. are also implicated as an important factor in the epidemiology of bovine dermatophilosis, particularly in West Africa. The major tick-borne diseases of cattle in sub-Saharan Africa are shown in Table 1.

An important feature of the biology of ticks is their high potential reproductive rate, which distinguishes them from the other groups of vectors considered in this report, the tsetse flies. A single engorged female tick lays many thousands of eggs, which has major implications for the control of these vectors. This is discussed further in section 6.1.6. Another minor point is that the sexual stages of the protozoan haemoparasites discussed here occur in the tick, which therefore is arguably the definitive host, rather than the vertebrate.

There are no reliable recent estimates of the continental impact of these diseases. However, Minjauw and McLeod (2001) estimated that the national annual losses for several sub-Saharan countries ranged between US$0.5 million for Malawi to US$32 million for South Africa.

4.1.1 Theileriosis

The theilerioses are a complex of diseases caused by tick-borne apicomplexan parasites of the genus *Theileria*. Theileriosis of cattle in Africa has been considered to have more impact on the development of the beef and dairy industries, and on veterinary infrastructure legislation and policies and on veterinary research in Africa than any other
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livestock disease complex (McCosker, 1991). While this view probably overlooks the rather wider distribution of tsetse and bovine trypanosomiasis, it nevertheless underlines the importance of theileriosis on the continent.

4.1.1.1 East Coast fever

Most important of these in sub-Saharan Africa is East Coast fever (ECF), which together with the closely related syndromes known as corridor disease and January disease is caused by infection with *Theileria parva* transmitted by three-host hard ticks of the genus *Rhipicephalus*, notably *R. appendiculatus*, the brown ear tick (Lounsbury, 1904). The natural host of *T. parva* is the Cape buffalo (*Syncerus caffer*). Domestic cattle become readily infected by inoculation of sporozoite stages of *T. parva* in the saliva of attaching infected ticks. The sporozoites invade bovine leucocytes to form multinucleate intracellular macroschizont stages, the cause of an acute lymphoproliferative-degenerative disease that results in significant morbidity and mortality in cattle. Macroschizonts later undergo merogony to produce intracellular microschizonts, which are released from host leucocytes into the bloodstream where they invade erythrocytes to become piroplasms. Engorging ticks are infected by ingestion of these parasitosed host erythrocytes (Cowdry and Danks, 1933).

*Theileria parva* was first described in Southern Rhodesia by Robert Koch (1889), who correctly identified small piroplasms as being the cause of a newly described disease of cattle that had previously been confused with redwater (babesiosis). Koch (1903; 1905; 1906) went on to describe the distinctive schizont stage of the parasite in lymphoid cells. In spite of concerted attempts to contain it, the outbreak extended throughout the Southern Africa region and was responsible for deaths of around 400,000 cattle in the region until it was finally brought under a measure of control in 1910. Bruce *et al.* (1910) first described the enzootic form of theileriosis in Uganda as a disease of calves known locally as Amakebe and which had long been recognised by local people (Mettam and Carmichael, 1936). The African buffalo (*Syncerus caffer*) represents an important natural host and reservoir of *T. parva* infection, and its distribution has significant implications for the epidemiology of the disease. The form of the disease that became known as Corridor Disease because of its association with buffalo migrating through a game “corridor” between the Umfolozi and Hluhluwe Game Reserves in Zululand was distinguished from ECF by its very high mortality, the low numbers of piroplasms and frequent absence of schizonts, and lack of onward transmission from infected cattle if they were removed from
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contact with buffalo (Neitz, 1955). The epidemiology of theileriosis caused by *T. parva* is discussed in detail in section 6.

Theileriosis caused by *T. parva* currently affects cattle in Burundi, Kenya, Malawi, Mozambique, Rwanda, Sudan, Tanzania, Uganda, Zaire, Zambia and Zimbabwe. The total regional loss in 1989 was estimated by Mukhebi *et al.* (1992) at US$168 million, including estimated mortality of 1.1 million cattle. TickCost (1999), a combined ILRI/ACIAR (ACIAR, 1999) research project estimated that in Kenya alone, actual losses attributable to East Coast fever amount to $US 95 million. The distribution of the disease and its vectors in sub-Saharan Africa was recently described by Minjauw (2001b).

4.1.1.2 *Tropical theileriosis*

*Tropical theileriosis* caused by *T. annulata*, although of limited distribution in sub-Saharan Africa where it may have a small overlap with *T. parva* in southern Sudan, has a far more extensive distribution in tropical and sub-tropical regions globally, including much of North Africa (Norval *et al.*, 1992). As many as 200 million cattle are considered at risk worldwide (Purnell, 1978). In contrast to *T. parva* infection, the pathogenesis of the disease is dominated more by the haematological effects of the intra-erythrocytic piroplasm stages than the effects of the schizonts on the lymphoid system (Sergeant *et al.*, 1924; Neitz, 1957; Barnet, 1968; Eisler, 1988). The range of this disease is not known to overlap with that of tsetse-transmitted trypanosomiasis (with the possible exception of southern Sudan) and it will not be considered further here.

4.1.1.3 *Theileria mutans* infection

Finally, *T. mutans* a parasite of cattle and Cape buffalo is very widespread in sub-Saharan Africa, where the distribution follows that of its tick vectors (Walker and Olwage, 1987), at least five species of African *Amblyomma* ticks (Norval *et al.*, 1992). Compared to *T. parva* or *T. annulata*, *T. mutans* is generally regarded as only mildly pathogenic to cattle, although there are records of *T. mutans* being pathogenic and even fatal in East Africa, and anaemia can become severe in cases of pathogenic strains (Brown *et al.*, 1990). *Theileria mutans* can be responsible for productivity losses in cattle, especially when present as a concurrent infection with other tick-borne parasites or stress caused by poor nutrition or other infections. *Theileria mutans* pathogenicity has been was demonstrated in Kenya, where calf herds were monitored from birth onwards; *T. mutans* was found to be a frequent cause of severe anaemia, occasionally causing mortality, and the development of calves may be severely retarded (Grootenhuis and Young, 1981; Moll *et al.*
However the precise prevalence of pathogenic *T. mutans* is unknown, due in part to the lack of specific and simple epidemiological tools (Skilton, *pers comm*).

### 4.1.2 Babesiosis

In the late 19th century Smith and Kilbourne (1893) demonstrated Texas fever, an important disease of cattle in the Southern United states to be transmitted by ticks. This was the first demonstration of a vector-borne disease and predated Ross's (1897) discovery of the transmission of malaria by mosquitoes and Bruce's (1895) discovery of the trypanosome cause of tsetse-fly disease of cattle. The *Babesia*, first identified by Babes (1888) in association with haemoglobinuria in cattle in South Africa, are intraerythrocytic, apicomplexan protozoan parasites widespread in both tropical and temperate regions and affect all livestock species. In cattle they are responsible for fever, haemolysis, haemoglobinuria or “redwater“ - a common name for the condition, anaemia, circulatory disorders and occasionally neurological signs (Ristic, 1981b). Transmitted by several ticks of the genus *Boophilus*, including the widespread *B. decoloratus* (the blue tick), the large *Babesia, B. bigemina*, is more widespread in Africa than the smaller but more pathogenic *B. bovis*, which is transmitted by *Boophilus microplus* (the cattle tick) and the *B. annulatus* (the Texas fever tick) but not *B. decoloratus*. Infection with *B. bovis* generally causes a more acute and severe disease than infection with *B. bigemina*. Transovarial transmission from one generation of ticks to the next is important, particularly as these vector species are one host ticks. A single engorged female tick may give rise to many thousands of infected eggs, and the parasite may be maintained in the tick population in the absence of a suitable bovine host.

The distribution of the disease and its vectors in sub-Saharan Africa was recently described by Minjauw (2001a). The economic effects of babesiosis are considered together with those of anaplasmosis, below. The epidemiology of babesiosis is discussed in detail in section 6.

### 4.1.3 Anaplasmosis

Anaplasmosis is a disease of cattle characterised by pyrexia, progressive anaemia and icterus. *Anaplasma marginale*, a rickettsia is the cause of most clinical disease (Theiler, 1910), while the closely related *A. centrale* causes only mild effects (Potgieter and Stoltz, 1994). As with babesiosis, the severity and form of the disease varies with age, being subclinical in calves and very severe or fatal in older adults. *Anaplasma* are transmitted
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primarily by *Boophilus decoloratus*, *B. annulatus* and *B. microplus*, but some *Rhipicephalus* ticks are also implicated in transmission. Although *Boophilus* spp. are one-host ticks, transovarial transmission is now considered to be unimportant for transmission of *Anaplasma*, and transmission by these ticks is now thought to be intrastadial by wandering males moving amongst bovine hosts.

In addition, *Anaplasma* is readily transmitted by mechanical transmission, in which biting flies are considered to be important, particularly where tick numbers are low. Finally, iatrogenic transmission by veterinary procedures such as multiple inoculation using the same hypodermic needles and by surgical instruments is also possible.

As with other tick-borne diseases, the presence of a carrier state is considered to be important in the epidemiology of anaplasmosis. Recovered cattle may remain subclinically infected in a state of premunition, but remain infectious for potential vectors. Furthermore, recrudescence of clinical disease may occur in these animals as a result of stress (Richey, 1992) or intercurrent infection such as theileriosis (Ilemobade., 1981) or trypanosomiasis (Fox et al., 1994). The epidemiology of anaplasmosis is discussed in detail in section 6.

Like babesiosis, anaplasmosis occurs over large regions of the globe, in tropical, subtropical and some temperate areas. The distribution of the disease and its vectors in sub-Saharan Africa was recently described by Minjauw (2001a). The presence of the disease in many developed countries such as the United States and Australia has lead to the availability of copious detailed information being available on the Internet (e.g. The State of Queensland, 2002).

Mixed infections of *Babesia* spp. and *Anaplasma marginale* are common, and because they share vector ticks, the diseases are often considered together. It has been estimated that 70% of cattle in Kenya are found in areas where anaplasmosis and babesiosis are enzootic, and that disease incidence is 5% in adult cattle (TickCost, 1999). The same report estimated that in Kenya, annual losses due to babesiosis and anaplasmosis combined are $US 6.9 million. Annual mortalities were estimated to be 5,798 in small-scale, mixed farming systems, 3,578 in large-scale, pastoral systems, 1,974 in large-scale dairy systems and 9,870 on small-scale commercial dairies. However, no account was taken of production losses due to subclinical or chronic infections or of the cost of treatment of clinical cases. In the case of anaplasmosis particularly, this is a substantial oversight, because chronic infection, causing anaemia, poor production and weight loss is known to be common, and recovery from acute attacks is usually protracted. The real cost of the disease is likely to be higher.
4.1.4 Heartwater

Cowdriosis, or heartwater, is caused by *Cowdria ruminantium*, a rickettsia (Cowdry, 1925) that is transmitted by at least 5 species of ticks of the genus *Amblyomma*, most commonly by *A. variegatum*. *Amblyomma hebraeum* is also of particular importance in southern Africa, where the disease was first recognised as long ago as 1858 (Henning, 1956). The disease in cattle is described in detail by Uilenberg (1981). Typical clinical effects of heartwater include pyrexia, diarrhoea, incoordination or convulsions, hydropericardium, hydrothorax, oedema of lungs and brain (Bezuidenhout *et al.*, 1994). The disease is seen primarily in exotic cattle, since it appears that indigenous cattle have acquired considerable resistance through natural selection (Uilenberg, 1981).

Calves, in particular, have a natural resistance to the disease in the first few weeks of life, which is independent of the immune status of the dam (Neitz & Alexander, 1941; Alexander, Neitz & Adellar, 1946; Du Plessis & Malan, 1987, 1988), although passive transfer of factors in colostrum is also known to be important in endemic areas (Deem *et al.*, 1996a). Whether or not calves are subject to tick challenge during this early protective period appears to be controversial (Du Plessis *et al.*, 1992; Norval *et al.*, 1995; O’Callaghan *et al.*, 1998), but there is also evidence of vertical transmission on *Cowdria ruminantium* (Deem *et al.* 1996b), which could also have an important bearing on the epidemiology (see section 6.1.4).

Heartwater, considered to be the most important tick-borne disease in southern Africa, and second in importance only to East Coast fever in east Africa (Uilenberg, 1983; Howell *et al.*, 1981) is responsible for loss of production and the annual mortality rate due to heartwater in enzootic areas in South Africa was estimated to be 1.3% (du Plessis *et al.*, 1994). A recent estimate of the cost of heartwater in the SADC Region alone was $US 37-47 million (Minjauw *et al.*, 2000). TickCost (1999), estimated that in Kenya, heartwater is responsible for annual losses of $US 13.3 million, through annual mortalities of around 50,000 animals in small scale mixed (14,000), large scale pastoral (9,000), large scale dairy (5,000) and small scale dairy (23,000 ) systems respectively. The distribution of the disease and its vectors in sub-Saharan Africa was recently described by Minjauw (2001c).
<table>
<thead>
<tr>
<th>Disease</th>
<th>Organism</th>
<th>Vectors</th>
<th>Hosts</th>
<th>Transmission</th>
<th>Tick Predilection site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaplasmosis</td>
<td><em>Anaplasma marginale</em></td>
<td>Many tick species</td>
<td>2 or 3</td>
<td>Intrastadial and transstadial</td>
<td>Perianal, but also elsewhere</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Biting flies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Babesiosis</td>
<td><em>Babesia bigemina</em></td>
<td><em>Boophilus decoloratus</em></td>
<td>1</td>
<td>Transovarian (nymphal/adult</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>transmission)</td>
<td></td>
</tr>
<tr>
<td>Babesiosis</td>
<td><em>Babesia bovis</em></td>
<td><em>Boophilus microplus</em></td>
<td>1</td>
<td>Transovarian (larval transmission)</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B. annulatus</td>
<td></td>
<td>adult must feed to pass on to</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>next generation</td>
<td></td>
</tr>
<tr>
<td>Cowdriosis (Heartwater)</td>
<td><em>Cowdria ruminantium</em></td>
<td><em>Amblyomma variegatum</em></td>
<td>2 or 3</td>
<td>Transstadial</td>
<td>Adults: Ventral surfaces of torso, axillae,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. hebraeum</td>
<td></td>
<td></td>
<td>scrotum, udder, perineum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. gemma</td>
<td></td>
<td></td>
<td>Nymphs: hooves and legs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Larvae: widespread</td>
</tr>
<tr>
<td>East Coast fever</td>
<td><em>Theileria parva</em></td>
<td><em>Rhipicephalus appendiculatus</em></td>
<td>2 or 3</td>
<td>Transstadial</td>
<td>Adults: ears &amp; perineum</td>
</tr>
<tr>
<td>Corridor Disease</td>
<td></td>
<td>R. duttoni</td>
<td></td>
<td></td>
<td>Immatures: head, ear, dewlap, legs, body</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R. zambeziensis</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Intrastadial:** Parasite is transmitted within a stage when tick moves between hosts.

**Transovarian:** Parasite is transmitted through the eggs of the infected vector to its progeny.

**Transstadial:** Parasite is retained through the moult of its vector i.e. transferred from larva to nymph and/or nymph to adult tick.
4.2 Tsetse-borne trypanosomiasis

Tsetse flies (Glossina spp.) transmit various species of Trypanosoma, which cause trypanosomiasis in humans (sleeping sickness) and livestock (nagana). The livelihoods of some 260 million people living in sub-Saharan Africa are affected by this disease complex and it has been estimated that the 40 million annual cases of animal trypanosomiasis costs Africa US$ 4.5 billion per year (Budd, 1999).

4.2.1 The tsetse fly

Tsetse mate just once and every 7 - 9 days thereafter, the female produces a single egg, which develops into a larva within the uterus of the fly. After ~9 days the mother deposits the larva which burrows into the ground where it pupates. After a further 30 days, an adult fly emerges which then matures, mates and deposits its first larva some 12-14 days after emergence. Thus >50 days elapse between the emergence of one fly and the subsequent emergence of the first of its progeny. This life cycle, with a slow reproductive rate and substantial parental investment in the care of young, is a relatively unusual example of an insect with a K-type life history. This slow rate of reproduction means that tsetse populations can be eradicated by killing just 2-3% of the female population per day.

All the energetic and growth requirements for this life cycle are provided exclusively by blood taken from vertebrate hosts, with both sexes of tsetse feeding at ~3-day intervals. Tsetse use a variety of olfactory and visual cues to locate their hosts, and this process means that tsetse range widely through the bush, moving up to a kilometre a day. To reproduce itself, each female must on average produce two larvae which means it must live at least 24 days, in which time it will take at least nine bloodmeals. The longevity, high mobility, and frequency of bloodmeals all contribute towards making tsetse an inherently efficient vector.

The 30 species of tsetse are divided into three groups with contrasting ecological and behavioural characteristics.

First, the Morsitans group of tsetse is found mainly in savanna woodlands across sub-Saharan Africa. These species are highly mobile and use a combination of visual and olfactory stimuli to locate their hosts. The group includes the more important vectors of animal trypanosomiasis such as G. pallidipes, G. morsitans spp. and G. austeni.
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Second, the Palpalis group comprises species found mainly in riverine woodland of west and central Africa. Species from this group are generally less mobile, being confined to their riverine habitats, and use visual cues, rather than olfactory ones, to locate their hosts. The group includes important vectors of human sleeping sickness such as G. fuscipes and G. palpalis spp.

Third, the Fusca group comprises species typically found in humid forests. Species from this group are generally considered to be less important as a vector, largely because their natural habitat is less used by livestock and people. Nonetheless, some species (e.g. G. brevipalpis, G. longipennis) have been implicated as significant vectors of animal trypanosomiasis.

4.2.2 Pathogenic trypanosomes of cattle

In sub-Saharan Africa there are three main species of tsetse-transmitted trypanosome pathogenic to cattle, Trypanosoma brucei, Trypanosoma congolense, and Trypanosoma vivax. These species have been further sub-divided by epidemiological biochemical and molecular techniques into a number of types and subspecies, notably the Forest, Kilifi, Savanna and Tsavo types of T. congolense, and the three subspecies of T. brucei: T. brucei brucei, T. brucei rhodesiense and T. brucei gambiense. While the practical significance of the different types of T. congolense for disease control is not well understood, the importance of the subspecies of T. brucei is well known; T. brucei rhodesiense and T. brucei gambiense (but not T. brucei brucei) are infective for man and are the causal agents of human sleeping sickness. Hence, while T. brucei infections in cattle are often considered to be less pathogenic for cattle than T. congolense or T. vivax, in some areas they are of equal if not greater importance in that cattle may form an important reservoir of the rhodesiense form of the human disease (Hide et al., 1996; Fèvre et al., 2001; Welburn et al., 2001). However, the commonly used field techniques used in disease control are unable to distinguish between these subspecies in infections of domestic animals. In fact, in most common disease control situations, diagnosis is presumptive, and based on clinical signs, or at best based on microscopic techniques that have only limited ability to distinguish between the parasites even at species level.

The main clinical signs of trypanosome infection in cattle are anaemia, weakness, weight loss or reduced growth rate, enlargement of lymph nodes, reduced milk yield, abortion, and in severe and advanced cases cachexia and death (Fiennes, 1970; Morrison et al., 1981; Stephen, 1986; DFID Project R7597, unpublished data). In addition to overt clinical
disease in cattle there are losses due to depressed productivity and immunosuppression leading to increased susceptibility to other diseases.

One important biological feature of pathogenic trypanosomes is their ability to vary the structure of their external surface coating of so called variable surface glycoprotein (VSG). This process is known as antigenic variation, and results in the ability of the parasite to evade the immune response of the mammalian host most effectively (Vickerman, 1978; Cross, 1978). The number of variant antigenic types (VATs) of a single strain of trypanosomes is controlled genetically by complex gene switching processes that result in a vast “repertoire”. No sooner than the host develops an antibody response to one type, than the parasite switches to another, thereby evading immune destruction. Moreover, there are usually several species, subspecies or types, and strains circulating in any given area, all of which may have distinct antigenic repertoires. Hence cattle do not normally develop immunity to trypanosomiasis and can undergo repeated infection throughout their lifetimes. The complexity of this immune evasion mechanism is also the reason why hitherto it has not been possible to develop a vaccine. This is in striking contrast to the situation with tick-borne diseases, to which solid immunity may develop if animals survive infection, and for which vaccines have been developed.

Finally, it should be remembered trypanosomiasis risk results in exclusion of cattle from vast areas of Africa that would be otherwise suitable for their use.

4.3 Integrating Control

Most of the 11 million square kilometres of Africa affected by tsetse are also affected by at least one of the tick-borne diseases. Consequently, livestock owners are generally faced with the need to control at least two diseases simultaneously. For tick-borne diseases, various effective control methods exist including:- the treatment of cattle with acaricides, cattle vaccination, clinical treatment of cases with appropriate drugs and regulation of livestock movement and grazing patterns. For trypanosomiasis, however, there are fewer options. In particular, there are no vaccines and the emergence of drug-resistant strains of trypanosome hampers the use of the few effective drugs that are available. But perhaps the greatest contrast lies in the natural immunological response of cattle to the two disease complexes. On the one hand, cattle infected with tick-borne parasites can, in certain circumstances, suffer relatively mild symptoms of disease and then develop an often-lifelong immunity. This phenomenon is particularly prevalent in indigenous breeds of cattle exposed to tick-borne diseases at a young age, where the
probability of developing severe clinical disease is lower than in older animals, and by exploiting this, traditional livestock keepers have successfully maintained cattle in tick-infested areas. For trypanosomiasis on the other hand, most\textsuperscript{2} cattle infected with tsetse-borne parasites eventually develop the disease and die. Consequently, cattle cannot generally be maintained successfully in tsetse-infested areas without the use of trypanocidal drugs and/or tsetse control.

Hitherto, this contrast has not presented a problem. However, in the 1980s several novel methods of controlling tsetse were developed. One such method involved treating cattle with an insecticide, which kills not only tsetse, as intended, but also ticks. This impact on ticks could reduce tick-borne disease but could also disrupt the natural acquisition of resistance, thereby leaving older animals susceptible to tick-borne infections resulting in greater levels of clinical disease.

\textsuperscript{2} With the notable exception of trypanotolerant breeds of cattle such as N’dama.
5 PAST AND PRESENT TICK AND TSETSE CONTROL IN AFRICA

5.1 Tick and TBD Control

The control of TBDs in Africa has, in those areas where it occurs, been largely driven by the need to control theileriosis caused by *T. parva* infection, most feared of all the African tick-borne diseases. Tick-borne disease control relies on three main components, namely tick control, immunisation, and chemotherapy. In addition, exploitation of the phenomenon of enzootic stability (see section 6), together with the reduced genetic susceptibility of certain breeds of cattle to tick infestation is increasingly being recognised as a potential strategy for exploitation in this respect.

5.1.1 Use of acaricides

In much of east and southern Africa intensive compulsory use of acaricide by dipping, supported by legislation on cattle movement did much to keep East Coast fever at an acceptable level during the colonial period. So called short-interval dipping at frequencies sometimes as great as three times per week was necessary to prevent cattle from becoming infected with *T. parva*. Hopes that the important vector ticks might be eradicated, as was the case for *Boophilus annulatus*, vector of Texas fever in the Southern United States (Kutler, 1988), were not sustainable in Australia (Kutler, 1988) or southern Africa (Norval 1982, 1983). Moreover, more recently rising costs of acaricide, declining budgets for veterinary disease control and development of acaricide resistant ticks has led to widespread abandonment of this practice (Norval 1982, 1983; Latif and Pegram, 1992).

The problem of development of acaricide-resistant ticks has led to use of a succession of classes of compounds for the control of ticks. Initially arsenical products were used, which was followed by the development and widespread use of various compounds including DDT, BHC, toxaphene, dieldrin, organophosphates and carbamates. Many of these classes of compound suffered from significant problems with toxicity to both the cattle and the dip operators, as well as resistance development (McIntyre and Ristic, 1981). These were later widely replaced by the use of amitraz, which being a different class of compound, was effective against ticks resistant to organophosphates. Again, the spectre of resistance loomed, but many policymakers, (e.g. the Government of Kenya) decided to withhold the availability of the next generation of acaricides, the synthetic
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pyrethroids, until amitraz resistance became a significant problem. This policy may in part be based on the observation that following the introduction of a new acaricide, resistance is frequently observed after a period of approximately 10 years (Geerts and Holmes, 1997). In some areas, however, these compounds are nevertheless available as pour-on formulations marketed for the control of tsetse.

It is increasingly believed in many parts of Africa that intensive dipping is not cost effective, especially with regard to the widespread tick *Boophilus decoloratus* (Kaiser et al., 1982; Pegram et al., 1986). Once thought of as an important pest in its own right, by analogy to the related *Boophilus microplus*, itself a cause of large production losses and even death in susceptible cattle, *B. decoloratus* may only cause light infestations in undipped indigenous cattle (Norval et al., 1992). Given that it transmits *Babesia bigemina* for which enzootic stability is common (see section 6), and competes with and excludes from large areas of Africa *B. microplus*, which also transmits the more pathogenic *Babesia bovis*, good arguments can be made against controlling it by dipping. In areas where ECF is a problem it may even be possible to revert to use of some of the older acaricides to which the one-host *Boophilus* has become resistant, since the three host *Rhipicephalus* vectors of ECF take longer to become resistant (Norval et al., 1992).

De Castro et al., (1997) compared the use of intensive acaricidal treatment with less intensive “strategic” treatment and no treatment of traditionally managed Sanga cattle in Zambia, and found that strategic rather than intensive treatment gave the best economic returns. None of these regimens, mainly intended to control *Amblyomma variegatum* using hand spraying rather than dipping, was able to control *Amblyomma variegatum* when it was introduced into the area. However, following the introduction of ECF, it was found that a combination of immunisation by the infection and treatment method (see section 5.1.3.1 below) with strategic dipping continued to give the most cost-effective disease control (Minjauw et al., 1999).

The present predicament of resource-poor cattle owners in Africa is that most dips are non-functional and acaricide is too expensive for routine strategic use. In the post-privatisation era, the high cost of dip maintenance falls upon the end user, with attendant public good and attendant free-rider problems as discussed in section 8.3. Briefly, there is little incentive for individuals to contribute to the maintenance of dips and spray races, and a number of other technologies have come to the fore. Methods more readily used by individual small-scale cattle owners as pure “private goods” include hand spraying, hand dressing i.e. manual application of acaricide solutions, pour-on preparations and
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hand picking or manual removal of ticks. Of these, the pour-on preparations are frequently based on the synthetic pyrethroids deltamethrin and alphacypermethrin, and under appropriate circumstances give opportunity for integrated tsetse and tick control, as discussed in sections 5.2.1.2 and 7.

5.1.2 Chemotherapy

Early attempts at chemotherapy of East Coast fever centred on the use of the tetracyclenes (Neitz, 1953; Brocklesby and Bailey, 1962). These have a suppressive effect on the early stages of *Theileria* in cattle, which has been found useful in the infection-treatment method of immunisation (see below), but is only of limited value in the treatment of clinical cases.

Chemotherapy of *T. parva* infection is has recently improved with the introduction of the drugs parvaquone (Clexon™) (McHardy *et al.*, 1983; Dolan *et al.*, 1984a), buparvaquone (Butalex™) (McHardy *et al.*, 1985) and halfuginone (Terit™) (Schein and Voight, 1979; 1981; Dolan, 1986). However, treatments are expensive, at up to US$ 40 per adult animal, and unless given relatively early in the course of the disease may be ineffective (Norval *et al.*, 1992). Resource-poor farmers may be reluctant to make the investment in a course of treatment for a number of reasons, including availability of cash, uncertainty of the diagnosis, and the risk that investing in treatment will add significantly to the losses if it is unsuccessful.

5.1.3 Vaccination

5.1.3.1 *Theileria parva*

As long ago as 1910 it was recognised that cattle that survive infection with *T. parva* become immune to the disease (Anon, 1910), and this has subsequently been formally demonstrated in the laboratory (Burrige *et al.*, 1972). In spite of major investment in the development of a molecular vaccine for *T. parva*, slow pace and past unrealistic timescales have led to a lack of credibility in this area (CGIAR, 1999). However, a renewed and concerted research effort in this area funded by DFID has improved the likelihood of a molecular vaccine in the near to medium term future. Meanwhile, the more cumbersome infection and treatment method of immunisation developed in the early 1960s (Brocklesby and Bailey, 1962; Radley, 1981) continues to be used in quite effectively in several countries, notably Kenya, Malawi, Uganda, Tanzania, Zambia and Zimbabwe (Minjauw and McLeod, 2001). Its widespread application is hampered
however by the need for effective cold-chain facilities to transport live parasite sporozoite stages. In addition, there are occasional difficulties arising from either failure to achieve immunisation, usually due to cold-chain breakdown and sporozoite inactivation, or severe, possibly fatal, clinical reactions due to inadequate doses or quality of the tetracycline used to attenuate the pathogenic effects of administration of live parasites (Minjauw and McLeod, 2001). There is also recognition of the need for parasites used for immunisation to be representative of the local strains in an area, since different immunogenic types exist and the immunity is strain or stock specific (Young et al., 1973; Young et al., 1977; Young et al., 1978; Radley et al., 1975a,b,c). Finally, there have been concerns regarding the introduction of “foreign” strains of T. parva by use of the infection and treatment method. Inoculation of these strains, followed by development of carrier status (Young et al., 1981) and infection of the local tick population might create challenge that could break through the immunity of local animals (Brandt et al., 1991). However, this has never been proven and is controversial (de Castro, 1997).

5.1.3.2 Babesiosis

It has long been recognised that inoculation of blood from carrier animals confers immunity to Babesia to susceptible cattle. However, this method is not without risk, since a proportion of animals may succumb to severe clinical reactions, and there is the attendant risk of transfer of other pathogens. A significant improvement in the method was achieved in Australia by using acutely infected splenectomised calves as donors for the infected blood, which increased both the efficacy of vaccination against B. bovis, and also the safety in that it was found that serial passage in at least 8 splenectomised calves serendipitously attenuated the pathogen (Callow, 1974; Callow et al., 1997). The risk of inadvertent spread of other blood borne pathogens remains, notably of bovine virus diarrhoea virus and enzootic bovine leucosis virus, the latter having been responsible for a significant iatrogenic outbreak in 1986 (Rodgers et al., 1988; Callow et al., 1997). In addition, being a live vaccine, maintenance of cold-chain is essential for its effective distribution. Hence the objective of development of safer and more convenient Babesia vaccines remains, and efforts in this direction have been made using effective but expensive irradiated vaccines, in-vitro tissue culture-derived vaccines and the development of recombinant antigens (Ristic and Montenegro-James, 1988; Wright et al., 1992).
5.1.3.3 Anaplasmosis

Vaccination against anaplasmosis has been based on the use of live *Anaplasma centrale*, a naturally occurring, less virulent form of the pathogen (Theiler, 1912). In the USA, where dissemination of live organisms is discouraged, killed vaccines are utilised, although these are of only limited efficacy. Infection of cattle with *A. centrale* results in mild disease, and hence it has been used as a live vaccine to induce cross-immunity against the more pathogenic *A. marginale*. However, *A. centrale* does not fully protect against the most virulent strains of *A. marginale*. Despite the incomplete protection provided, production of vaccine based on *A. centrale* remains the most readily applied control technique in developing countries (Minjauw and McLeod, 2001).

Given that the geographic distribution of anaplasmosis is generally wider than that of its tick vectors, owing to mechanical transmission (see 4.1.3), it is often undesirable to use live organisms for immunisation, thereby introducing infection in areas where the disease might not otherwise occur. For this reason, in the United States where tick transmission is the exception rather than the rule a killed vaccine (Anaplaz®, Fort Dodge) is utilised. Although this vaccine does not prevent infection, it reduces the severity of clinical disease. Vaccinated animals are still capable of becoming infected with *A. marginale*, and subsequently can become carriers. Annual or biannual revaccination is necessary, and complications of iatrogenic isoimmune haemolytic anaemia in calves born to infected dams may occur (Richey, 1992). In view of these difficulties with existing vaccines, alternatives based on recombinant antigens are under development in a number of laboratories, and some potentially promising antigens have been developed. However, it is unlikely that a recombinant antigen based anaplasmosis vaccine will be commercially available in the near future (Minjauw and McLeod, 2001).

5.1.3.4 Heartwater

A live vaccine commercially available against heartwater is produced from blood of sheep infected with the virulent Ball 3 stock of Cowdria. Its adoption has been limited because it requires a strict cold chain and can result in severe clinical reactions (Minjauw and McLeod, 2001). Current research focuses on the development of safer and more effective inactivated vaccines, and also attenuated tissue culture-derived vaccines. Progress in this area was briefly reviewed by Uilenberg (1997). Oxytetracycline treatment is normally successful if administered early and is also used in a prophylactic manner during the peak of *Amblyomma* spp. season on very valuable and susceptible animals. This method, although not recommended by veterinarians, is widely used by commercial farmers in
South Africa and by traditional farmers when they have to transport their cattle to endemic areas (Minjauw and McLeod, 2001).

5.1.4 Genetic resistance

A number of authors have called into question the need and justification for intensive dipping of cattle in Africa to control tick-borne disease (Muriithi, 1984; Tatchel, 1984; Latif and Pegram, 1992; De Castro, 1997). Instead, it has been suggested that the exploitation of tick resistant cattle, possibly in conjunction with enzootic stability (see sections 5.1.6 and 6.1.1, below), would be a more appropriate alternative strategy. Indeed, in Australia, host-tick resistance has been exploited in cattle breeding programmes to reduce the impact of *B. microplus* (Seifert, 1984).

Resistance comprises mechanisms against the tick vectors themselves as well as the tick-borne pathogens. Resistance to ticks varies with the genotype of cattle, with zebu (*Bos indicus*) breeds being generally more resistant than European *Bos taurus* cattle. The West African *Bos taurus* N’Dama cattle also appear to possess a degree of tick resistance, in addition to being trypanotolerant (Mattioli *et al.*, 2000). The resistance mechanism comprises cellular responses, in the vicinity of the tick’s attachment point, and humoral responses, with the former being more effective. The mechanisms show some degree of specificity with heterospecific resistance being low among different genera of tick (Rechav *et al.*, 1989). Resistance to ticks can also affect the transmission efficiency of ticks. The number of infectious kinetes of *Babesia* spp. and the relative infection rate of *Babesia* by *B. microplus* increases with the period of tick attachment (Gaido & Gulielmone, 1995).

Thus host grooming and immunological responses against ticks can reduce the challenging dose of pathogen and hence the probability of disease occurring. In addition, breeds such as N’Dama display immunological responses to *Anaplasma* spp. akin to those against *Trypanosoma* spp (Mattioli, 2001).

An example of an integrated approach to tick and tsetse control, is provided by the work of Mattioli *et al.* (1999) who compared the efficacy of applying pyrethroids strategically and/or selectively to N’Dama cattle in the Gambia. Their results showed that application of pyrethroid during the wet season, and only to the dewlap, axillae, tail brush and ano-genital, udder and abdominal regions was more cost effective than simple strategic application of insecticide alone.
INTEGRATED CONTROL OF TICKS AND TSETSE

5.1.5 Management

5.1.5.1 Pasture spelling

Another early approach to controlling East Coast fever was the use of “pasture spelling”, following Theiler’s (1905) observation that ECF infected ticks on an ungrazed pasture die out in 15 months. Cattle were excluded from pastures infested with *T. parva*-infected ticks for this period, after which they were considered to be safe once again for grazing. However, at higher altitudes infected ticks have been found to survive up to twice as long as at lower warmer altitudes, which may make this method impractical in Africa (Young, 1981a). Moreover, resource poor farmers in Africa do not usually have the option to maintain unused grazing even for relatively short periods.

5.1.5.2 Zero grazing

The “cut and carry” method of stall-feeding cattle, otherwise known as zero grazing has become a popular production system in the smallholder dairy sector of East Africa, particularly in areas of ECF risk. Exotic cattle often of the Holstein, Friesian or other high yielding dairy breeds, or their crosses with local cattle are maintained throughout their lives in a pen with a concrete or similar floor unsuitable for ticks, and ideally fed Napier grass cultivated specifically for the purpose. Use of grass cut from pastures frequented by other cattle may expose the cattle to tick challenge, but many smallholders find it difficult to maintain sufficient cultivated grass to maintain a large taurine high yielding dairy cow throughout the year. Hence some “breakthrough” tick infestation may occur, with risk of tick-borne disease in a naïve animal highly susceptible both immunologically and genetically. Consequently, supplementary acaricide or pyrethroid treatment may also be necessary. On the Kenya coast south of Mombasa, where there is concomitant tsetse and trypanosomiasis challenge, some small-scale dairy farmers have developed the methodology further by surrounding the stalls with tsetse fly-proof netting (M.C.E. personal observations). This has enabled them to dispense with the continuous trypanocidal prophylaxis otherwise found necessary in the area (Mdachi, 1999).

5.1.6 Exploitation of enzootic stability

With a reduction in the practice of short-interval dipping, indeed often of any systematic form of tick control by resource-poor farmers in Africa, control of tick-borne disease has frequently come to rely on exploitation of the phenomenon of enzootic stability. The basis of this phenomenon is discussed in detail in section 6.
However, abrupt cessation of dipping does not result in the immediate development of a state of enzootic stability, and instead under such circumstances as have occurred during times of civil insecurity in the 1970s in both Uganda and Zimbabwe devastating levels of mortality in livestock are experienced before a equilibrium situation develops.

Norval et al. (1983; 1984; 1985) investigated the situation with regard to enzootic stability for anaplasmosis, babesiosis and theileriosis in Zimbabwe during the period after the civil war in a series of studies using serological tests. Enzootic stability was considered to be present for Babesia bigemina in most of the communal tribal areas where dipping had been interrupted for several years, but not where regular dipping was practiced on commercial farms (Norval et al., 1983). Enzootic stability was also considered to be widely present for anaplasmosis, but the inverse relationship with the practice of dipping was less pronounced, and this was attributed to the wider range of tick vectors for this particular pathogen, some of which are less easily controlled by dipping (Norval et al., 1984). Finally, the situation with Theileria parva was rather different; although clinical, parasitological and serological evidence demonstrated that the parasite was widespread in the country, the prevalence of antibodies (seroprevalence) was generally low, and there were large numbers of clinical cases in many locations studied. The lowest seroprevalences (no antibodies detected) were from farms where short-interval dipping was practiced, or overgrazed communal areas where Rhipicephalus was absent. The situation was further complicated by the presence of two forms of the parasite. The cattle to cattle transmitted T. parva bovis (the cause of Zimbabwean theileriosis or January disease) occurred in areas infested with only R. appendiculatus, whereas the buffalo-derived infections of cattle with T. parva lawrencei occurred in areas infested either with R. zambeziensis alone or with both tick species. The two tick species generally occurred in different geographical areas of the country with little overlap. There was no evidence of a state of enzootic stability of the type seen with either B. bigemina or A. marginale.

Hence while it appears that enzootic stability is readily established for some tick-borne diseases such as anaplasmosis and babesiosis, the situation with others such as T. parva infection (see also section 6.1.4.6) is less clear. Similarly, with cowdriosis there has been controversy over whether enzootic stability develops, some authors arguing that low levels of clinical disease in indigenous cattle are simply due to their inherent resistance to the condition (Uilenberg, 1981; 1997), while others maintain that it does occur for
reasons similar to those responsible for its widely-accepted occurrence in other tick-borne diseases (Deem et al., 1997; O’Callaghan et al., 1999).

5.2 Tsetse and Trypanosomiasis Control

5.2.1 Tsetse control

Three aspects of the tsetse life cycle are important in relation to tsetse control. First, only the adult stage can be easily controlled; the occurrence of the larval stage in the mother and the pupal stage in the ground means that these stages are largely protected from insecticide applications. Second, the slow rate of reproduction (~1 fly/10 days) means that modest but sustained (e.g. killing 3%/day for a year) can eradicate tsetse. Third, for each female to reproduce just two flies, she must obtain nine bloodmeals. This frequent contact with hosts provides an important opportunity for control. However, the rapid movement of tsetse also means that an area cleared of tsetse can be rapidly re-invaded from adjacent areas of infestation.

Two main strategies are generally used to control tsetse. One strategy aims to kill all the flies in an area after they emerge and before they manage to deposit a larva in the ground. Control is applied until all the flies in the ground have emerged. This approach is carried out by widespread application of either a persistent insecticide (e.g. DDT, dieldrin or a synthetic pyrethroid) to the resting sites of tsetse, or the aerial application of a non-persistent insecticide such as endosulfan.

The second strategy aims to apply a small but sustained level of mortality to a tsetse population over a longer period, and this is usually carried out by attracting tsetse to lethal baits. The baits may be either artificial devices, such as traps or insecticide-treated targets baited with synthetic host odours, or natural baits such as cattle treated with insecticide. The low reproductive rate of tsetse means that a low density (e.g. 4 targets/km$^2$) of evenly-spaced artificial baits can eradicate tsetse populations within two years (Vale, 1993; Willemse., 1991; Dransfield et al., 1990). Similarly, treating cattle with insecticide has controlled tsetse populations successfully in Zimbabwe (Thompson et al., 1991), Zambia (Chizyuka and Liguru, 1986), Tanzania (Fox et al., 1993), Kenya (Baylis & Stevenson, 1991), Burkina Faso (Bauer et al., 1992, 1995) and Ethiopia (Leak et al., 1995).

Over the past 20 years, there has been a widespread shift from the use of ground and aerial spraying to bait methods of control, partly because the latter methods have steadily
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improved, and partly for financial and institutional reasons. In the 1970s for instance, a
typical tsetse control operation would have consisted of a large army of government-
employed spraymen who applied a persistent insecticide, such as DDT, to the resting sites
of tsetse. The operation would have been conducted over several thousand square
kilometres and been funded, planned and implemented by a government agency. Such
operations eradicated tsetse from large areas of Nigeria, South Africa, Uganda and
Zimbabwe (Jordan, 1986). Today, funding and/or institutional capacity to undertake such
operations has largely disappeared, and in any case there is growing opposition to use of
these persistent insecticides on environmental grounds. Instead, typical contemporary
tsetse control operations are conducted over just a few hundred square kilometres. The
operations generally aim to reduce the tsetse population, rather than eradicate it, are
funded and carried out partly or wholly by local livestock owners and employ some form
of bait technology (Barrett and Okali, 1998; Brightwell et al., 2001).

5.2.1.1 Natural vs. artificial baits

One of the best-documented examples of the change in technology is the case of
Zimbabwe where control by ground- and aerial spraying was replaced by odour-baited
targets and pyrethroid-treated cattle (Figure 1). It is particularly noteworthy that the use
of pyrethroid-treated cattle rapidly superseded all other techniques, and this is typical for
much of Africa. The widespread adoption of pyrethroid-treated cattle for tsetse control
has a number of causes. In the case of Zimbabwe, a national dipping scheme, to control
tick-borne diseases, funded by the government was already established. Thus the cost of
controlling tsetse using pyrethroid-treated cattle was simply the incremental cost of
changing from an acaricide to a formulation effective against ticks and tsetse. Economic
analyses of the various control techniques in Zimbabwe (Barrett, 1997) showed that the
incremental cost was just Z$50-100/km$^2$/year (1990 prices), compared to Z$460-600 for
targets, Z$550-650 for ground spraying and Z$900-1100 for aerial spraying. Even if the
infrastructure to treat cattle needed to be established, the technique was still relatively
cheap (Z$125-250/km^2/year).

The technique also offers several attractions for small-scale tsetse control operations
being conducted by local communities. These include:-

- Local farmers can be easily trained in methods of treating their cattle whereas
  constructing, deploying and maintaining artificial baits is more technically and
  logistically demanding;
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- Only livestock owners, who will be the immediate beneficiaries of tsetse control, need be involved in treating their cattle whereas the use of artificial baits frequently requires assistance from individuals who do not own cattle;
- Cattle are less susceptible to theft and vandalism.
- NGOs and community-based organisations find the promotion and management of schemes based on the use of pyrethroid-treated cattle more amenable.

5.2.1.2 Insecticide-treated cattle: a short history

The earliest attempts at controlling tsetse using insecticide-treated cattle were disappointing, probably because the DDT formulations used did not persist (Whiteside, 1949; Burnett, 1954). In the late 1960s a wide range of insecticides was tested on cattle in Zimbabwe, but none killed the flies or knocked them down for more than about a week after the cattle were treated, confirming the earlier indications that insecticide-treatment of cattle was unlikely to be cost-effective. In the mid 1980s however, when deltamethrin had been shown to be effective on targets, it was also tested on cattle and found to be effective for 2-4 weeks (Thomson, 1987).

Following this, a large-scale trial of the technique was initiated in eastern Zimbabwe (Thomson & Wilson, 1992ab). Thirteen cattle inspection centres were selected for the trial. Cattle were dipped at fortnightly intervals with a 0.00375% formulation of Deltamethrin s.c. Between 80 and 90% of the 22,000 cattle in the area (2,500 km²) were treated at 14 day intervals and the monthly incidence of trypanosomiasis declined from 257 in June 1986 to 35 in August 1987 (Figure 2).
Figure 1: Areas of Zimbabwe treated annually by various methods of tsetse control.

Figure 2: Trypanosomiasis in NE Zimbabwe, reported as either the annual percentage of cattle inspection centres detecting trypanosomiasis or the annual number of cases detected by these centres (inset). The 13 centres monitored ~20000 cattle. Prior to 1986 (open circles), these cattle were treated regularly with a dioxathion dipwash to control ticks. In June 1986 a deltamethrin dipwash active against ticks and tsetse was used (solid circles).
Figure 3: Tsetse control operations in NE Zimbabwe (see inset) between 1986 and 1997. Main map shows areas treated by aerial spraying (sequential aerosol technique, SAT), ground spraying (GS), targets and insecticide-treated cattle (ITC). Solid dots denote dip tanks originally involved in the 1987 trial of insecticide-treated cattle. After 1987, the treatment was expanded to include all dip tanks lying within the green stippled area. Solid, red area denoted M shows the Mudzi control operation where cattle and targets form part of a barrier designed to prevent tsetse invading Zimbabwe from infested areas of Mozambique.
The success of the trial led to an expansion of the area with pyrethroid-treated cattle (Figure 3) that in turn contributed to the general decline in trypanosomiasis in NE Zimbabwe. As the region was cleared of tsetse and trypanosomiasis, the operational area declined. However, the NE border of Zimbabwe was subject to a constant invasion of tsetse from uncontrolled areas of Mozambique. Consequently, cattle grazing within 10-15 km of the border continued to be dipped to act as a barrier to tsetse invading from Mozambique (Warnes et al., 1999). This regime continues to date.

Despite the subsequent use of pyrethroid-treated cattle over many thousands of square kilometres of Zimbabwe, little was done immediately in the country to study the technique further. This was because the governments in southern Africa were considering removing tsetse from large uninhabited areas where cattle were absent and could not be introduced, so emphasising the need to concentrate research on artificial baits. Hence, much of the development of the cattle technique continued elsewhere (Table 2). The outcome of research in the various places is that the most cost-effective means of applying the insecticide is as a dip. Where dip tanks are not available, a pour-on formulation is recommended. Several pyrethroids can be used as substitutes for deltamethrin, including alphacypermethrin and cyfluthrin, but their recommended dose is higher than for deltamethrin, to allow for their lower toxicity to insects. Initial uses of pyrethroid treated cattle took place in areas where dipping against ticks was already practised, so nearly all adult stock were usually treated. As the technique spread to other areas, where dipping was not already practiced and where pyrethroid-treated cattle strategies were often implemented by NGOs, a de facto policy of treating significantly less than 100% of adult cattle was often adopted by default. As scientific knowledge grew on the behaviour of tsetse, the required density of traps, targets or ITCs, and the relative attractiveness of various ages and conditions of cattle, it began to be realised that there was a scientific, as well as an economic and pragmatic justification for such an approach. However, widespread experience with the use of pyrethroid-treated cattle for tsetse control has revealed several problems.

First, the distribution of cattle is largely dictated by various livestock production imperatives such as providing adequate water, grazing and protection from theft and predators. The patchy distribution of these resources means that pyrethroid-treated cattle are inherently patchy in their spatial and temporal distribution and this compromises their efficacy as baits (Hargrove et al., 2002).
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Second, the cost of using pyrethroid-treated cattle is still prohibitively high for poorer livestock owners and sustained uptake of the technology, without subsidies from either government or NGOs, is rare.

Third, as with tsetse control operations, there are inherent problems in initiating and sustaining an operation over an area sufficiently large to be effective. At the very least, an operation needs to be conducted over an area of several hundred kilometres. Such an area is likely to include territory associated with several villages or traditional social divisions, and possibly with different ethnic groups and very different livestock production systems. For example, the operational area of an EU-funded tsetse control project in Tanzania (FITCA: Tanga region project) includes Maasai pastoralists, Zigua crop-livestock farmers and Swahili owners of zero-grazed cattle. No single tsetse control strategy was appropriate or acceptable for all these groups (Torr et al., 2000). At the same time, the territory used, perhaps non-exclusively, by a particular community and their livestock may spill out over the boundary of a technically feasible control area (Morton, 2002).

There is a cluster of additional problems concerning farmers’ perception of tsetse and their willingness to pay. Firstly, farmers with poor cash flow may respond to disease by buying costly drugs but be unwilling (in their own perception unable) to pay regularly for ultimately cheaper preventive strategies, such as insecticide treatment. Secondly, farmers may not understand the connection between tsetse and trypanosomiasis (Kamara et al., 1995; Machila et al., 2000). Thirdly and more specifically, they may not realise the need for ongoing insecticide treatments when levels of animal health have already visibly improved. Related to the last two points, farmers are more likely to invest in technologies that demonstrably alleviate a problem and will cease investing as that problem abates. On the one hand, farmers treating their cattle at the edge of a tsetse control operation will not detect any great improvement in their cattle if adjacent areas are infested with tsetse. On the other hand, farmers at the centre of an operation will be less affected by invading flies and they are more likely to see an initial rapid improvement in their cattle, but little improvement thereafter. Thus both groups will have an incentive not to sustain investment in tsetse control, which could ultimately undermine the whole operation.

Issues related to collective action in tsetse control are discussed further in Section 6.
Table 2: Examples of operations to control various species of tsetse using cattle treated with various insecticides at various treatment intervals. Results show the percentage reduction on the abundance of tsetse following control and the prevalence or incidence of trypanosomiasis before and after the control operation. See text and references for details.

<table>
<thead>
<tr>
<th>Country</th>
<th>Site</th>
<th>Year (start)</th>
<th>Insecticide</th>
<th>Interval (weeks)</th>
<th>Cattle nos.</th>
<th>Area (km²)</th>
<th>Species¹</th>
<th>Tsetse (%)</th>
<th>Prevalence (%) or Incidence (cases/month)</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Untreated</td>
<td>Treated</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>Satiri</td>
<td>1991</td>
<td>Flumethrin</td>
<td>4-8</td>
<td>2000-8600</td>
<td>500-1000</td>
<td>Gms, Gpg, Gt</td>
<td>~95</td>
<td>40%</td>
<td>5%</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>Site</td>
<td>1993</td>
<td>Deltamethrin</td>
<td>1</td>
<td>1500-2000</td>
<td>500</td>
<td>Gms, Gpg, Gt</td>
<td>~95</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>Ghibe</td>
<td>1993</td>
<td>Deltamethrin</td>
<td>4</td>
<td>2000</td>
<td>350</td>
<td>Gp, Gms</td>
<td>0-20</td>
<td>38%</td>
<td>27%</td>
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<tr>
<td>Kenya</td>
<td>Galana</td>
<td>1989</td>
<td>Deltamethrin</td>
<td>2</td>
<td>1200</td>
<td>60</td>
<td>Gp, Gl</td>
<td>Variable</td>
<td>14%</td>
<td>4%</td>
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<tr>
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<td>Kajiado</td>
<td>1995</td>
<td>Deltamethrin</td>
<td>2 - ??</td>
<td>500-1000</td>
<td>?</td>
<td>Gp, Gl</td>
<td>0</td>
<td>29%</td>
<td>17%</td>
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<tr>
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<td>Kagera</td>
<td>1991</td>
<td>Deltamethrin</td>
<td>??</td>
<td>27000</td>
<td>25000</td>
<td>Gp, Gmc</td>
<td>95</td>
<td>20%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Tanzania</td>
<td>Mkwaja</td>
<td>1989</td>
<td>Deltamethrin</td>
<td>2</td>
<td>8000</td>
<td>250</td>
<td>Gp, Gmm, Gb</td>
<td>70-99</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
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<td>Zanzibar</td>
<td>Deltamethrin</td>
<td>2</td>
<td>700</td>
<td>20</td>
<td>Ga</td>
<td>99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uganda</td>
<td>Busia</td>
<td>1991</td>
<td>Deltamethrin</td>
<td>3</td>
<td>3000</td>
<td>130</td>
<td>Gf</td>
<td>98</td>
<td>38%</td>
<td>3%</td>
</tr>
<tr>
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<td>Mudzi</td>
<td>1996</td>
<td>Deltamethrin</td>
<td>2</td>
<td>5400</td>
<td>400</td>
<td>Gp, Gmm</td>
<td>0</td>
<td>&gt;0</td>
<td>0%</td>
</tr>
<tr>
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<td>Deltamethrin</td>
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<td>331</td>
<td></td>
<td>Gp</td>
<td>?</td>
<td>8.9%</td>
<td>3.9%</td>
</tr>
<tr>
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<td></td>
<td>Deltamethrin</td>
<td>2</td>
<td>38000</td>
<td>2500</td>
<td>Gp</td>
<td>?</td>
<td>&gt;0</td>
<td>0%</td>
</tr>
</tbody>
</table>

¹Key: Ga = G. austeni; Gf = G. fuscipes; Gl = G. longipennis; Gmc = G. morsitans centralis; Gmm = G. morsitans morsitans; Gms = G. morsitans submorsitans; Gpg = G. palpalis gamebiensis; Gp = G. pallidipes; Gt = G. tachinoides
5.2.1.3 Is there any evidence that tsetse control operations have had an impact on ticks?

In most cases, the vector and veterinary monitoring undertaken during tsetse control operations has not included ticks and tick-borne diseases. However, there are a few exceptions from Burkina Faso, Zimbabwe, Tanzania, Ethiopia and Kenya.

**Burkina Faso.** - In SW Burkina Faso, Bauer et al. (1992) treated 2000 cattle with flumethrin at monthly intervals and observed a >95% reduction in tsetse numbers. Veterinary surveys showed that the percentage prevalence of trypanosomiasis declined from 40% to 7% whereas the rates increased, from 16% to 32%, in a neighbouring untreated area. Similarly, in the treated area mean PCV increased from 26% to 35% as the control programme progressed whereas it declined, from 33% to 29%, in the untreated area. Tick burdens within the treated area were 70-90% less than those in the untreated area, even though the tick predilection sites of animals outside the control area were treated topically with cypermethrin and dimethoate. *Amblyomma, Boophilus* and *Hyalomma* species of ticks all appear to be reduced in the pyrethroid-treated area.

**Zimbabwe.** - In 1995-97, Van den Bossche & Mudenge (1999) undertook a survey of cattle in NE Zimbabwe area to estimate the prevalence of antibodies against *Babesia bigemina* in cattle within and adjacent to a “tsetse barrier” established to prevent re-invasion of cleared areas by tsetse originating in neighbouring the region of Mozambique. The barrier comprised cattle treated with deltamethrin at two-week intervals, while those outside the barrier were being treated with the acaricide amitraz. Their results showed that cattle within the tsetse barrier had a seroprevalence of antibodies against *Babesia bigemina* of only 2%, compared to 43% for cattle outside it. Moreover, *B. bigemina*-naïve sentinel cattle grazed in the barrier zone also exhibited low seroprevalences on seven successive 3-monthly sampling occasionsto *B. bigemina*. The authors did not deploy sentinel herds outside the barrier for comparison and there are no comparable historical epidemiological data for this area. The authors suggested that these results indicated that the use of deltamethrin to control tsetse had reduced transmission of *B. bigemina* by *Boophilus* spp. ticks. However, it is noteworthy that the study does not provide clear evidence to explain why control of ticks in the amitraz-treated area was not as effective as that within the barrier. Amitraz should be effective against *Boophilus* and the authors suggest that the difference was because dipping was carried out more effectively within the barrier under stringent supervision of dipping practices by government services, than in the adjacent zone in which amitraz is used, where dipping is often disrupted owing to problems with water or supply of acaricide.
Tanzania.- In the 1980s, Mkwaja ranch in Tanzania maintained their cattle in a tsetse-infested area by administering isometamidium routinely every two-three months, depending on the number of breakthrough infections detected by microscopy, and treating any obvious cases of trypanosomiasis with diminazene (Fox et al., 1994). To protect the cattle against tick-borne disease, the cattle were dipped weekly with dioxathion. This effectiveness of the trypanosomiasis regimen deteriorated as drug resistance emerged. Moreover, the management of tick-borne diseases was not particularly successful since the major cause of herd mortality was anaplasmosis (3.6% mortality per annum). In 1989, the ranch started dipping with deltamethrin at 7-14 day intervals during the wet and dry seasons respectively. Tsetse numbers were monitored in the treatment and a neighbouring untreated control areas. In addition, various animal health parameters were measured and compared with comparable herd data collected prior to the change in dip formulation.

The results showed that the numbers of tsetse declined by ~90%, the prevalence of trypanosomiasis declined from 10.5% to 3.0% and that of anaplasmosis declined from 21% to 3%. Mortality due to trypanosomiasis and anaplasmosis also declined from 3.6% and 0.4% respectively to 0.6% and 0.1%. Tick counts from treated and untreated herds were not clearly or consistently different and averaged ~3 ticks/head/week. The authors suggested that ‘30 years [of intensive tick control] had reduced tick numbers to a very low level and conventional tick control with dioxathion and hand dressing was providing very good tick control which was not improved by the introduction of deltamethrin’. Thus the data seem to show that the use of deltamethrin-treated cattle reduced the prevalence of trypanosomiasis and anaplasmosis but only the vector of the former disease seemed to be reduced. The authors argued that this unexpected effect on anaplasmosis was because the immunosuppression produced by chronic infection with trypanosomiasis was causing patent parasitaemia and disease to emerge in premune carrier animals.

However, an alternative explanation of the high incidence of clinical anaplasmosis would be the relatively low tick challenge, insufficient for a state of enzootic stability. Other factors might have played a role in the reduced incidence of anaplasmosis following the introduction of frequent deltamethrin dipping. These might include a reduction in the numbers of biting flies, which are important in mechanical transmission of Anaplasma marginale (particularly where tick numbers are relatively low), and reduction in iatrogenic needle transmission resulting from reduced use of drugs.
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**Ethiopia.** - A potential effect on tick-borne disease is reported in Leak et al.'s (1995) study of tsetse control in the Ghibe Valley. They report that tsetse control reduced the abundance of biting flies, notably *Stomoxys* spp. by 88%. *Stomoxys* are mechanical vectors of various diseases including anaplasmosis. Thus it is possible that a reduction in the abundance of this vector could reduce the incidence of this disease. However, mechanical transmission is not as effective as biological transmission and thus large reductions in the abundance of biting fly mechanical vectors, such as *Stomoxys* spp. or Tabanidae are only likely to be important when tick vectors are absent.

A tsetse control operation in the Konso district of Ethiopia found that following the treatment of cattle with deltamethrin pour-on at monthly intervals the numbers of tsetse and the monthly incidence of trypanosomiasis declined and the mean PCV increased (Habtewold & Konde, 1997). During this same period the number of apparently tick-free animals increased from <1% to >98%. However, no independent controls were included in the trial and thus there is no unequivocal evidence that these changes were directly related to the treatment of cattle with insecticide (Torr et al., 2000b).

**Kenya.** - Baylis & Stevenson (1998) report that treating cattle with deltamethrin controlled ticks better than treatment with an organophosphate at 2-3 week intervals. Stevenson et al.'s (unpublished data) study of a community-based tsetse control scheme undertaken by Maasai farmers indicated that their ‘primary motivation for applying the pour-on is to remove ticks’ even though the operation was designed to control tsetse. Intriguingly, they found there was no significant difference in the average tick-burdens of treated (18 ticks/animal) and untreated (20 ticks/animal) animals. Treating the animals with deltamethrin pour-on killed ticks for about a week after treatment but thereafter the ticks survived and thus the low frequency of application meant that there was no significant effect on tick numbers.

The above examples provide some evidence that tsetse control operations have had an effect on tick-borne diseases and/or the vectors of these diseases. However, it is striking that there is not one study unequivocally demonstrating that a tsetse control scheme has (i) reduced the level of tick infestation of cattle and, as a consequence, (ii) changed the immunological status of a cattle population, with an increase in the proportion of naïve, susceptible cattle and thereby (iii) increased the incidence of tick-borne disease. Several of the above arguably demonstrate one of the above facets but not all three. It seems that properly designed studies, with adequate controls and monitoring of vector, clinical and immunological parameters, are required.
5.2.2 Trypanosomiasis Control

5.2.2.1 Drugs

Trypanocidal drugs remain the only widely available control method affordable by farmers. Currently available trypanocidal drugs for use in cattle are limited to the salts of just three compounds, diminazene aceturate (Berenil®, Hoechst; Veriben®, Sanofi; and various other generic formulations), homidium bromide (Ethidium®, Laprovet), homidium chloride (Novidium®, Mérial) and isometamidium chloride (Samorin® /Trypamidium®, Mérial; Veridium®, Sanofi).

There are two main strategies for the use of trypanocidal drugs in the control of bovine trypanosomiasis. Drugs may be used for the therapy of existing trypanosome infections, in which case they are termed chemotherapeutic, or alternatively drugs with a prolonged period of biological activity may be administered at intervals suitable to uninfected cattle at risk of becoming infected, in which case they are termed chemoprophylactic. Some drugs may be used for either purposes, although dose rates and routes of administration may be adjusted for the particular circumstances of use, while others, particularly those which are eliminated rapidly are limited to therapeutic use. Isometamidium chloride is the most widely used and efficacious chemoprophylactic drug, but also has chemotherapeutic activity. Homidium salts are used mainly for chemotherapy, but do have some prophylactic activity. Finally, diminazene aceturate is the most widely used chemotherapeutic agent, but has almost no prophylactic activity (Leach and Roberts, 1981).

There are no published estimates of trypanocidal drug treatments given by country or by year. Geerts and Holmes (1997) estimate that 35 million doses are administered each year, a figure consistent with the estimated amount of US$ 30 million spent annually by farmers (Borne, 1996), on the basis of a cost of approximately US$ 1 per dose (Swallow, 1998).

Numerous studies have demonstrated that cattle can be kept productively under tsetse challenge through the use of therapeutic and prophylactic trypanocidal drugs. Logan et al. (1984) demonstrated that Zebu-type cattle could produce beef in an area of West Africa infested with *G. palpalis gambiensis* and *G. morsitans submorsitans*. Ford and Blazer (1971) showed that drugs allowed susceptible cattle to be kept commercially in tsetse-infested areas, such as Mkwaia ranch in Pangani District of coastal north-east Tanzania, a
commercial beef ranch infested with *G. morsitans morsitans*, *G. pallidipes*, *G. brevipalpis* and probably *G. austeni*.

One of the most comprehensive studies of the use of isometamidium prophylaxis was that of Trail *et al.* (1985) who examined a unique set of 10 years of matching productivity and health records from Mkwaja Ranch. The data set equated to 134 000 trait-years of new data, and amounted to approximately twenty times as much information on livestock productivity under chemoprophylaxis as had been available in the whole of Africa over the previous 25 years. Planned experiments demonstrated that cattle were unable to survive without trypanocidal drugs: untreated animals died or succumbed to predators. Isometamidium prophylaxis was shown to be clearly superior to chemotherapy using diminazene, even in pre-weaning cattle, in which isometamidium had not previously been used in large scale commercial herds. Boran cattle at Mkwaja under isometamidium prophylaxis were 80% as productive as Boran cattle on trypanosomiasis-free ranches in Kenya, and 35% more productive than ranched trypanotolerant N'dama cattle under medium to high trypanosomiasis risk in West Africa. It was therefore concluded that profitable cattle ranching is possible in Africa in areas of high risk of trypanosomiasis through the use of isometamidium prophylaxis.

Another significant study on the use of trypanocidal drugs in the field was that of Bourn and Scott (1978), who described their use to control trypanosomiasis among 40 work-oxen introduced in 1972 to Angar-Gutin, a lowland area of south western Ethiopia for ploughing, traction and other purposes. This area is heavily infested with *G. morsitans submorsitans* and has a high trypanosomiasis challenge. Over the next five years, the success of the project, which relied on high standards of management and veterinary supervision, was such that the number of oxen introduced had increased to 450. Initially, diminazene was employed in a strategic curative regime, on average every 28 days, but later isometamidium prophylaxis was used successfully for the final three years of the study.

In a recent position paper on West African experiences in the control of animal trypanosomiasis, Bauer and Snow (1998) concluded that there are now the technical means to implement control mainly using drugs for improved animal health, supplemented where necessary with vector control. This conclusion was combined with the recommendation that chemotherapy be applied with the aim of reducing the incidence of trypanosomiasis and increasing the average packed red blood cell volume (PCV) to given target values referred to as a template. This template was termed the production
opportunity set (POS) where a reasonable level of animal production can be expected if both values are within the given range.

In many parts of Africa, farmers "control" trypanosomiasis by constant treatment of sick animals with commercial trypanocides, that can be easily obtained through veterinary services or through private stores. Doran (2000) demonstrates that this is the most important strategy actually practised by farmers in the tsetse belts of Zambia, Malawi and Mozambique, and considers it the most sustainable. Barrett (1997) however, suggests that a more wide-ranging analysis of the true economic benefits of smallholder cattle and the loss of productivity associated with trypanosomiasis would show a trypanocidal strategy to be more expensive than thought. A preliminary study of farmers in Konso, Southern Ethiopia (Morton 2002) notes the considerable cattle mortality associated with this practice, as well as the loss of draught animal power (the owner of a working ox loses a conservative 5 days working even if the ox is treated as soon as showing clinical signs). Additionally, scientific opinion is very concerned with the development of resistance to trypanocides if this strategy is continued (Geerts and Holmes, 1997; Eisler et al., 2001; Geerts et al., 2001). Eisler et al. (2000) demonstrated high levels of drug resistance in numerous locations studied in Kenya, Tanzania and Zambia, and related degree of resistance to the historical level of drug usage in each area. Resistance to more than one trypanocide was recorded in some areas, notably the coastal regions of Kenya and Tanzania. Multiple resistance to all trypanocidal drugs commonly used in cattle was demonstrated in *T. congolense* at the clonal level in South Western Ethiopia (Codjia et al., 1993) and this was shown to be persistent over a number of years (Mulugeta et al., 1997).

In summary, although trypanocidal drugs continue to be of use in many areas, in the absence of development of new trypanocides for the disease in cattle, the longer-term outlook for chemotherapy hangs in the shadow of the development of multiple drug resistance that could render useless the control strategy most favoured by small-scale poor farmers. This concern is rendered all the more serious because of the low likelihood of development and marketing of new trypanocides for use in cattle in the foreseeable future (Geerts et al., 2001).

5.2.2.2 Vaccination

The mechanisms of antigenic variation in trypanosomes to evade the host immune system have been discussed above in section 4.2.2. These same mechanisms appear to have been equally effective in thwarting attempts to immunise cattle artificially. In spite of an
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extraordinary research effort directed at this problem over the last 30 years, notably that by the International Laboratory for Research on Animal Diseases (ILRAD, latterly the International Livestock Research Institute, ILRI), the prospect of a vaccine against trypanosomiasis in any species including the bovine is no closer. The one area where there has been some progress has been in the development of an anti-disease vaccine, in which efforts are directed towards preventing the pathogenic effects of the parasite rather than infection itself (Authié et al., 2001).

5.2.2.3 Trypanotolerant livestock

Increasing interest has been paid in recent years to the trypanotolerance trait in a number of cattle breeds, particularly the taurine breeds of West Africa such as the N'dama (Murray et al., 1979). However, the trypanotolerant trait is not absolute, and cattle of trypanotolerant breeds may succumb to the effects of the disease under circumstances of stress, such as poor nutrition, overwork, intercurrent disease or just particularly heavy tsetse challenge. Roelants (1986) analysed data from a number of experimental studies that compared the survival of Zebu and trypanotolerant cattle under different levels of natural tsetse challenge. Under conditions of light tsetse natural challenge, whereas 75% of Zebu cattle died, 98% of N’dama and cattle survived. However, under heavy natural tsetse challenge, overall mortality among Zebu cattle rose to 94%, and 31% of cattle of the trypanotolerant N’dama, Muturu and Baoulé breeds also died. The use of trypanotolerant livestock is thus often supplemented by the use of trypanocidal drugs in areas of heavy tsetse challenge (Roelants, 1986; Otesile et al., 1991). Trypanotolerant cattle also appear to have higher levels of resistance to ticks (see section 5.1.4), helminths and dermatophilosis.

It should also be noted that while classically considered “trypanosusceptible” in comparison to the N’dama and other similar west African taurine breeds, the zebu and Sanga cattle of East and southern Africa are undoubtedly less susceptible to the disease than the many breeds of exotic cattle that have been imported into tsetse-infested countries in the region. Of these, the Orma Boran of Kenya has been studied in some detail (Dolan, 1997).
6 EPIDEMIOLOGICAL ASPECTS OF VECTOR-BORNE DISEASES: A FRAMEWORK FOR INTEGRATING TICK AND TSETSE CONTROL

6.1 Epidemiological basis

In developing a framework for discussing the integrated control of tick- and tsetse-borne diseases, it is important to define some general epidemiological aspects.

Firstly, we need to differentiate between infection and clinical disease. Infection is required to produce disease, but not all infections give rise to clinical disease. Importantly, the probability/or severity of clinical disease following infection in a susceptible individual may vary with age. This is particularly important in the tick-borne diseases theileriosis (Bruce 1910, Norval et al., 1992), cowdriosis (Neitz & Alexander 1941, Du Plessis & Malan 1987, 1988), babesiosis (Mahoney & Ross 1972, Christensson 1989) and anaplasmosis (Rogers & Shiels 1979) where it has long been recognised that clinical disease occurs with less probability/or severity in younger compared to older susceptible animals. The relationship between age and susceptibility to severe clinical disease (Barnett and Bailey 1955) is less pronounced in T. parva infections, but potentially important in disease epidemiology, as discussed below in section 6.1.4.6. By contrast, there is no such relationship between age of susceptibles and clinical disease in tsetse-transmitted trypanosomiasis.

Secondly, immunity may result in a reduction in the probability of subsequent infection or a reduction in the probability that subsequent infection give rise to clinical disease. The relative importance of acquired immunity in tick-borne disease epidemiology and trypanosomiasis has been discussed in sections 4.1. and 4.2.2.

Finally, the rate at which susceptibles acquire infection is known as the force of infection. The force of infection for a vector borne disease is a product of the ratio of vectors to hosts, the rate at which vectors feed on the host, the prevalence of infectious vectors and the probability that a bite from an infectious host results in infection in a susceptible host. Basic vector borne disease epidemiological theory (Ross 1911, Macdonald 1957, Anderson & May 1992) predicts that the force of infections increases as the number of vectors per host increases. Thus, strategies that aim to kill vectors (such as pyrethroid-treated cattle), and so reduce the number of vectors per host, will reduce the force of infection.
6.1.1 Enzootic stability – a simple framework

Armed with these basic definitions it is possible to describe succinctly the epidemiological phenomenon know as enzootic (or endemic) stability displayed by tick-borne diseases in certain settings. Enzootic stability is an epidemiological state, in which clinical disease is scarce despite a high rate of infection in the population. The concept was first developed within tick-borne disease epidemiology to describe patterns of babesiosis in Australian cattle (Mahoney & Ross 1972) and latter adapted as a paradigm for East Coast Fever across east Africa (Norval et al., 1992), although other considerations apply to ECF (see section 6.1.4.6). In its simplest formulation, enzootic stability arises if two conditions are met; (1) disease is more likely, or more severe, in older than younger susceptibles, and (2) after one infection, the probability that subsequent infections result in disease is reduced (Coleman et al., 2001). These criteria may be expressed as a simple mathematical model (see Appendix I). Figure 4 shows the main features of enzootic stability resulting from fulfilment of the two epidemiological criteria.

This simple framework captures two important epidemiological aspects: (1) at enzootic stability the force of infection is high but the level of clinical disease in the population is relatively low, and (2) implementing control strategies that partially reduce the force of infection (e.g. through killing vectors) may result in an increase in clinical disease in the population. Both these features have been observed for tick-borne diseases in Africa, as discussed previously, and the concept of enzootic stability is used to guide the design of control programmes (e.g. Perry & Young 1995, Norval 1983, Cook 1991, Uilenberg 1995, Deem et al. 1996 and O’Callaghan et al. 1998).

From Figure 4, it can be seen that the actual point at which endemic stability is said to occur is somewhat subjective. However, to the left of the climax marked by line A, the slope of the clinical incidence curve with respect to force of infection is positive, while to the right of line A the slope is negative. As force of infection continues to rise the slope of the line starts to plateau out. Endemic stability may be said to occur in some region to the right of the climax point. However, the absolute magnitude of clinical incidence may still be high (although relatively low compared to the climax), even far to the right of the climax point where the slope of the incidence curve is shallow. These issues of defining endemic stability in absolute or relative terms of clinical incidence are discussed in further detail below, particularly in relation to T. parva epidemiology in section 6.1.4.6.

Regardless of the absolute degree of clinical incidence at endemic stability, disruption of
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the epidemiological state by reducing vector numbers and so lowering the force of infection can may the disease situation worse.

6.1.1.1 Extending the framework to trypanosomiasis

The simple mathematical formulation used to describe enzootic stability above may be adapted to capture the general quantitative relationship between the force of trypanosome infection and clinical trypanosomiasis. The first of the two criteria necessary for enzootic stability is not satisfied by trypanosomiasis; rather we assume that the probability of infection resulting in disease is independent of the age of the susceptible animal. The second of the two criteria can also be relaxed to assume no long-term immunity to re-infection, as is generally assumed in eastern and Southern Africa (see section 4.2.2 above), but capture any potential chemoprophylactic effects of widespread trypanocidal drug use. However, the assumption may also be modified to accommodate possible acquired immunity in trypanotolerant cattle. The mathematical formulations of these assumptions are outlined in Appendix I. Figure 5 shows the general relationship between force of trypanosome infection and the level of clinical trypanosomiasis in the population. In contrast to Figure 4, it is clear that enzootic stability does not occur, but rather the level of disease continues to increase with increasing numbers of vectors per host and so force of infection. It should be noted that increasing the average duration of immunity following infection will tend to make the clinical disease incidence plateau. Most importantly, however, the framework predicts that any reduction in the force of infection, through vector control for example, will result in a decrease in the level of clinical disease in the population. There are no non-intuitive perverse outcomes, as with the tick-borne disease enzootic stability model, in which control efforts result in an increase in clinical disease.
Figure 4: Enzootic stability as predicted by the simple criteria. As the number of vectors per host increases, the force of infection (i.e. rate at which susceptible individuals are infected) increases. The graph shows that as the force of infection increases from zero the amount of clinical disease in the population also rises. However, at a certain point, the amount of clinical disease reaches a climax (line A). Thereafter, increasing forces of infection result in a decrease in the amount of clinical disease. Therefore, a situation may arise in which the rate of infection in the population is high but clinical disease is low (line B), either absolutely or relatively – i.e. enzootic stability. Importantly, if a population is at enzootic stability, vector control activities may reduce the force of infection and so perversely increase the amount of clinical disease (e.g. control moving the population from line B to A).
Figure 5: The relationship between force of trypanosome infection and level of clinical trypanosomiasis. The same framework used for describing enzootic stability for tick-borne diseases was used, with the assumptions of age susceptibility to disease and acquired immunity modified to reflect the epidemiology of trypanosomiasis. In contrast to the tick-borne disease pattern, there is no enzootic stability, but rather as the force of infection increases, the level of clinical disease continues to rise.
6.1.2 An integrated framework

The impact of insecticide treatment of cattle on trypanosomiasis and tick-borne diseases will depend on the epidemiological starting conditions and the effects of the control strategy on both the tsetse and tick populations. Table 3, summarises the different possible outcomes, varying from the worst-case scenario, in which control has no impact on trypanosomiasis and actually worsens the tick-borne disease situation, to the best-case scenario, in which the implemented strategy not only impacts favourable on trypanosomiasis but also reduces the burden of tick-borne diseases. The simple framework outlined above for describing enzootic stability and extended to trypanosomiasis may be used to examine quantitatively the outcome of different scenarios. For example in Figure 6, the impact of the intervention will be influenced by whether or not enzootic stability of the tick-borne diseases was established prior to control implementation and also the degree to which the force of infection of the different infections is altered by the intervention.
Table 3: Scenarios for pyrethroid-treated cattle usage. Depending on circumstances, use of pyrethroid-treated cattle may or may not suppress tsetse populations and hence trypanosomiasis challenge. Similarly, pyrethroid-treated cattle may or may not impact on tick populations, and if they do, this may lead to decreases or increases in the incidence of tick-borne disease. Reduction in disease incidence is indicated in green, worsening of the disease situation in red, and no change in blue.

<table>
<thead>
<tr>
<th>Tsetse situation:</th>
<th>Tsetse controlled by pyrethroid-treated cattle</th>
<th>Tsetse not controlled by pyrethroid-treated cattle (low cattle density, &amp;/or alternative hosts available)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBD situation:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>☐ Ticks uncontrolled or partially controlled</td>
<td>PTC* (\rightarrow) ↓trypanosomiasis</td>
<td>PTC (\rightarrow) no effect on trypanosomiasis</td>
</tr>
<tr>
<td>☐ Enzootic stability controls TBD</td>
<td>PTC (\rightarrow) worsens TBD problem</td>
<td>PTC (\rightarrow) worsens TBD problem</td>
</tr>
<tr>
<td>☐ Ticks uncontrolled or partially controlled</td>
<td>PTC (\rightarrow) ↓trypanosomiasis</td>
<td>PTC (\rightarrow) no effect on trypanosomiasis</td>
</tr>
<tr>
<td>☐ No enzootic stability</td>
<td>PTC (\rightarrow) ↓TBD problem</td>
<td>PTC (\rightarrow) ↓TBD problem</td>
</tr>
<tr>
<td>☐ TBDs are a problem</td>
<td>PTC (\rightarrow) ↓trypanosomiasis</td>
<td>PTC (\rightarrow) no effect on TBD</td>
</tr>
<tr>
<td>☐ Ticks already highly controlled</td>
<td>PTC (\rightarrow) ↓trypanosomiasis</td>
<td>PTC (\rightarrow) no effect on TBD</td>
</tr>
<tr>
<td>☐ TBDs not a problem</td>
<td>PTC (\rightarrow) no effect on TBD</td>
<td>PTC (\rightarrow) no effect on TBD</td>
</tr>
</tbody>
</table>

*PTC: pyrethroid-treated cattle
Figure 6: Changes in tick-borne disease and trypanosomiasis clinical disease following insecticide cattle treatment. The graph is an output of the simple framework outlined in the text. The output shows how the effect of the intervention will depend on the epidemiological starting conditions prior to control activities – in particular whether or not the tick-borne diseases are at enzootic stability (i.e. to the left or right of line A, respectively) – and the impact of control on the different vector populations and so the different forces of infection.

6.1.3 Extending the framework

Although the framework outlined here to investigate quantitatively the integrated control of tsetse- and tick-borne disease is very simple, it captures the main epidemiological difference between trypanosomiasis and tick-borne disease and allows the main outcomes of control to be characterised. However, to be useful in understanding under which conditions different outcomes are likely to occur requires the framework to be extended.
to accommodate important epidemiological details. Extension of the framework in five main areas are discussed; (1) Complexity of tick-borne disease epidemiology (e.g. O'Callaghan et al., 1998), (2) Additional variables affecting disease epidemiology and so control impact, (3) Population biology of the vector species (4) Dynamic aspect of control, and (5) Zoonotic aspect of trypanosomiasis.

### 6.1.4 The complexity of tick-borne disease epidemiology

Enzootic stability is a general concept, which embraces a broad spectrum of complex epidemiologies depending on the specific biology of the infectious agent, and the interactions of the parasite with the host and the vector species. In any given setting, several tick-borne diseases may be present each with distinct epidemiological patterns which make a single characterisation of tick-borne disease in terms of enzootic stability a broad generalisation, at best, and misleadingly inaccurate, at worst. The two criteria of enzootic stability discussed in the above provide only a general description of tick-borne disease epidemiology. In reality, the epidemiology of each disease is governed by many complexities. Table 4 summarises the main epidemiological characteristics of the various tick-borne diseases discussed in this report, and indicates the implications of these characteristics for the establishment of enzootic stability.
### Table 4: Transmission and epidemiological features of tick-borne diseases.

<table>
<thead>
<tr>
<th>Disease</th>
<th>Organism</th>
<th>Vectors</th>
<th>Epidemiological features</th>
<th>Duration of immunity</th>
<th>Enzootic stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaplasmosis</td>
<td><em>Anaplasma marginale</em></td>
<td>Many tick species</td>
<td>• Biological transmission&lt;br&gt;• Mechanical transmission&lt;br&gt;• Biting flies&lt;br&gt;• Iatrogenic transmission&lt;br&gt;• Innate variations in age-specific susceptibility&lt;br&gt;• Carrier status</td>
<td>Years</td>
<td>Sometimes</td>
</tr>
<tr>
<td>Babesiosis</td>
<td><em>Babesia bigemina</em></td>
<td><em>Boophilus decoloratus</em></td>
<td>• Colostral Ab protective&lt;br&gt;• Innate variations in age-specific susceptibility&lt;br&gt;• Carrier status?</td>
<td>Months</td>
<td>Frequently</td>
</tr>
<tr>
<td>Babesiosis</td>
<td><em>Babesia bovis</em></td>
<td><em>Boophilus microplus</em>&lt;br&gt; B. annulatus</td>
<td>• Colostral Ab protective&lt;br&gt;• Innate variations age-specific susceptibility&lt;br&gt;• Carrier status&lt;br&gt;• Limited distribution of vector in Africa</td>
<td>Months</td>
<td>Frequently</td>
</tr>
<tr>
<td>Cowdriosis (Heartwater)</td>
<td><em>Cowdria ruminantium</em></td>
<td><em>Amblyomma variegatum</em>&lt;br&gt; A. hebraeum&lt;br&gt; A. gemma</td>
<td>• Vertical transmission occurs&lt;br&gt;• Colostrum protective</td>
<td>Months</td>
<td>Frequently</td>
</tr>
<tr>
<td>East Coast fever Corridor Disease</td>
<td><em>Theileria parva</em></td>
<td><em>Rhipicephalus appendiculatus</em>&lt;br&gt; R. spp</td>
<td>• Colostral Ab not protective&lt;br&gt;• Innate variations age-specific susceptibility&lt;br&gt;• Carrier status&lt;br&gt;• Severity may be dose dependant</td>
<td>Years</td>
<td>Occasionally</td>
</tr>
</tbody>
</table>
6.1.4.1 Relationship between age and innate susceptibility to disease

The relationship between age and innate susceptibility to disease is pivotal to the epidemiological nature of enzootic stability. This is illustrated by considering two stylised tick-borne parasites, 1 and 2, as shown in Figure 7a and b. For both parasites, it was assumed there is life-long immunity to disease following first infection. Overall, susceptible individuals infected with parasite 1 have a higher probability of developing clinical disease compared to parasite 2 (i.e. parasite 1 is the more virulent). Also, the age-window of relative innate susceptibility is smaller for parasite 1 than 2. As shown in Figure 7a, all susceptible individuals greater than about 6 months of age are at equal high risk of developing clinical disease following infection with parasite 1, compared to a window of decreased susceptibility extending to about 3 years in animals infected with parasite 2.

The effects of these underlying relationships of age-related innate susceptibility on the establishment of enzootic stability are shown in Figure 7b. Enzootic stability is likely to be reached at a much lower force of infection with parasite 2 compared to 1, as the climax situation is reached sooner with parasite 2 (line A versus B). Moreover, the enzootic stability established with parasite 2 results in levels of clinical disease that are absolutely low, while for parasite 1 the enzootic stability results in only relatively low clinical disease, with the absolute levels significantly higher than anything seen with parasite 2.

While used illustratively, Figure 7 may be argued to approximate the two extremes of enzootic stability represented by *T. parva* and *Babesia* spp. infections. Overall the severity of clinical disease presented with clinical babesiosis is much less than that seen in East Coast Fever, where mortality rates may vary from around 10%-20% in susceptible calves to over 90% in susceptible adults (Mettam & Carmichael 1936, Norval, Perry & Young 1992). In many settings across East Africa high mortality and morbidity rates due to East Coast Fever have been recorded (see section 6.1.4.6, e.g. Latif *et al.* 1995, Norval *et al.* 1985), with relatively low mortality restricted to areas of extremely high transmission, for example in the Mara region of Kenya where 94% of calves age 6 months of age were found to have antibodies to *T. parva* (Moll, Lohding & Young, 1984). However, even in areas of intense endemic transmission, considerable calf mortality rates have still been recorded (see Mettam & Carmichael, 1936). By contrast, the impact of babesiosis is considered relatively minor, with effective enzootic stability, in which mortality is negligible, readily established at relatively low infection rates across a variety of settings within Africa and elsewhere (e.g. Mahoney, 1972; Ramirez *et al.*, 1998; Figueroa *et al.*, 1998). For both anaplasmosis (Dreyer, Fourie & Kok 1986; Figueroa *et al.*, 1998) and
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cowdriosis (O'Callaghan et al., 1998; Bezuidenhout 1985; Bezidenhout & Bigalke 1987) there is good evidence of epidemiological situations in which there is almost complete absence of clinical disease with high levels of population immunity.

The determinants and shape of the relationship between age and susceptibility will vary between the different tick-borne diseases. Maternally derived antibodies or factors (anaplasmosis - Potgieter & van Rensburg 1987; James et al., 1985; babesiosis – James et al. 1985; cowdriosis – Deem et al., 1996a; Norval et al. 1995, O'Callaghan et al. 1998) and innate age-specific variations in susceptibility (anaplasmosis: Rogers & Shiels 1979; babesiosis: Mahoney & Ross 1972; Christensson 1989; cowdriosis: Neitz & Alexander 1941; Du Plessis & Malan 1987; 1988; theileriosis: Barnett and Bailey 1955) are both important. There are additional considerations in the case of cowdriosis, for which there is evidence of reduced tick attachment rates during the early calfhood period of reduced susceptibility to clinical disease (see section 4.1.4). This has led some authors to conclude that a state of enzootic stability does not exist for this parasite (Uilenberg, 1981). The figures presented in this section do not allow for differential tick attachment rates and hence forces of infection at different ages of the bovine host. However, there is also evidence of vertical transmission of heartwater in the bovine (Deem et al., 1996b), which, if it conferred protection, would mitigate against the effect of reduced tick attachment during the period of reduced susceptibility to disease.

The impact of concomitant infections with other pathogens (e.g. trypanosomes or other tick-borne diseases) on susceptibility to disease needs also to be considered. For example, there is evidence that infection with trypanosomes or *Theileria* increases the likelihood that clinical signs of anaplasmosis are displayed (Ilemobade et al., 1981; Fox et al., 1994; DFID Project R7597, unpublished data; see also sections 5.2.1.3 and 6.1.4.3).
Figure 7(a and b): The effects of age-dependent variations in susceptibility on enzootic stability.
6.1.4.2 Duration of immunity

The development of immunity, to either reinfection or clinical disease, is an essential component in establishing enzootic stability. Again, variation in the nature of immunity is likely to vary between different diseases across different settings. The importance of these variations is illustrated by again considering two parasites, 1 and 2, which differ in terms of duration of immunity. Parasite 1 induces transient immunity, with the average duration of immunity being 90 months (i.e. prolonged but not lifelong). By contrast, parasite 2, confers life-long solid immunity following first infection. As shown in Figure 8, enzootic stability is established at considerably lower infection rates with parasite 2 (to the right of line line A) compared to parasite 1 (to the right of line B). Furthermore, the degree of enzootic stability is significantly more with the assumption of lifelong (parasite 1) compared to slightly more temporary immunity (parasite 2). Within the simple framework used here, the duration of immunity may fall to a level at which it is no longer possible to achieve enzootic stability, with the level of clinical disease continuing to rise with increasing levels of force of infection. The 90 month duration of the “temporary” immunity used in this example is longer than that which may occur naturally in the absence of rechallenge. However, this prolonged period was chosen to illustrate the marked effect of even a modest reduction in the duration of immunity from lifelong.

Determinants of the duration of immunity under field conditions are complex and poorly understood. However, antigenic variability in the parasite population may play an important role in immunity to T. parva infections (Radley et al., 1975; Irvin et al., 1983; Taracha et al., 1995). Again, co-infection with other pathogen parasites (such as trypanosomes) may influence the effective duration of immunity (e.g. Taracha et al. 1986). Finally, in tick-borne disease endemic areas, animals may be repeatedly rechallenged with resultant boosting and prolongation of their immunity.
Figure 8: The effects of duration of immunity on establishment of endemic stability.

6.1.4.3 Carrier state

The epidemiological importance of a carrier state – subclinically infected animals that are infectious either persistently or periodically – in the long-term persistence of infectious diseases, is well documented (see Anderson & May 1992). The carrier state enables infection to bridge the inter-epidemic gap, thereby allowing the infection to persist in the long-term. The existence of a carrier state is recognised in all the tick-borne disease considered in this report (T. parva: Barnett and Brocklesby, 1966; Neitz, 1957; Young et al., 1978; Young et al., 1981. A. marginale: Gale et al., 1996. Eriks et al., 1989. B. bovis: Fahrimal et al., 1992, Calder et al., 1996. C. ruminantium: Andrew & Norval 1989). The carrier status is also potentially very important in trypanosomiasis particularly in sleeping sickness areas (see section 6.1.8 below). On average, the existence of a carrier state will dampen variations in force of infection and so enable stability to persist (Norval et al., 1984). However, variations in the nature of the carrier state between the different tick-borne diseases may have important implications on the ability of enzootic stability establishment. The role of wild animal reservoirs may be thought of as to act as a carrier state in the sense of maintaining infection rates above a threshold level required for
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persistence (e.g. *T. parva* – Collins & Allsopp, 1999; Allsopp *et al.*, 1999, *A. marginale* – Kuttler 1984)

6.1.4.4 Mechanical transmission

*Anaplasma marginale* transmission is known to occur mechanically by biting flies (Peterson *et al.*, 1977; Ristic 1981a; De Wall 2000), as well as biologically via tick vectors. The relative importance of mechanical transmission in the establishment of enzootic stability in anaplasmosis has yet to be determined, but may be affected by the application of insecticide treatment to cattle. Observations on changes in anaplasmosis incidence following tsetse control (Fox *et al.*, 1994; see section 5.2.1.3) may prove useful in determining the relative importance of biological and mechanical transmission in different settings.

6.1.4.5 Inoculum size

Another important feature in the epidemiology of some tick-borne diseases, notably *Theileria parva* infection, is the relationship between the severity of infection and the dose of sporozoites inoculated. Barnett and Brocklesby (1966) noted that the mortality rate in experimental ECF infections of exotic cattle was dependant on the number of ticks used to transmit the parasite, and this was subsequently confirmed using titrated doses of sporozoites (Jarrett *et al.*, 1969; Radley *et al.*, 1974; Morrison *et al.*, 1981; Dolan *et al.*, 1984). When tick suspensions or sporozoites stabilates are titrated in cattle, the severity of the clinical reaction is dependant on the quantum of infectious material introduced. The same is true to some extent with *T. mutans* (Young, 1981), but it is not the case with either *Anaplasma marginale* (Gale *et al.*, 1996) or *Babesia* (Mahoney *et al.*, 1979). The situation with *Cowdria ruminantium* is unclear, but current epidemiological models of heartwater describe the disease adequately without the inclusion of such an effect (O’Callaghan *et al.*, 1998).

Of relevance to the quantum of infection effect is the fact that the infection rate within tick acini is “overdispersed”, i.e. not that which would be expected if every tick acinus had an equal chance of being infected. Most ticks have no infected acini, most of the remainder have only a single infected acinus, and a very small minority of ticks have many infected acini (Leitch and Young, 1981; Young *et al.*, 1981). Combining this fact with principle of quantum of infection leads to different relationships between the tick attachment rate (represented by force of infection) and infection (represented by seroprevalence) on the one hand and between tick attachment rate and clinical disease
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on the other, as shown in Figure 9. There is clearly a level of tick attachment at which the probability of infection is high, but that of clinical disease and therefore mortality is relatively low. As tick numbers increase, not only does the expected number of infected tick attachments increase, but so does the chance that one of these ticks will have many infected acini and deliver a quantum of sporozoites capable of producing clinical disease.

The effects of variations in inoculum size and establishment of enzootic stability may be analysed by considering two cattle populations, 1 and 2. These two populations experience the same forces of infection, but different average inoculum sizes, such that the age-specific probability of first infection resulting in clinical disease is two times as high in population 1 relative to population 2 (Figure 10a). The model results shown in Figure 10b reveal that there is no difference in the force of infection at which clinical disease peaks in the two populations (line A), but over all forces of infection the levels of clinical disease are considerably higher in population 1 than population 2. Thus, clinical disease is much more likely to be observed in population 1 than population 2, across all epidemiological settings. Moreover, at high forces of infection, levels of clinical disease remain relatively close to those observed at the peak.

The importance of inoculum size, heterogeneities in vector competence and the parasite transmission rates is an area of great importance, which is poorly understood (O’Callaghan et al., 1998).
Figure 9: The effect of inoculum size on clinical disease incidence and population seroprevalence* without the age-dependent effects of susceptibility to disease. It can be seen that as the force of infection rises, seroprevalence approaches 1 while clinical disease incidence remains relatively low; at higher forces of infection the clinical disease incidence rises to approach the seroprevalence level.

*Sero-prevalence is used as a measure of cumulative risk of infection in the population, which takes into account animals of different ages exposed for different lengths of time i.e. it represents a combination of active, sub-clinical and recovered infection. We calculate an idealised seroprevalence, but it should be noted that in practice the sensitivity and specificity of the serological test used, both usually less than 100%, and that antibodies are not usually detectable for at least a week after infection.
Figure 10 (a and b): The effect of inoculum size on enzootic stability for populations exposed to higher (population 1) and lower (population 2) inoculum sizes.

(a) The age-specific probability of first infection resulting in clinical disease.

(b) Comparison of clinical disease index for the two populations over a range of forces of infection.
6.1.4.6 Considerations relating to the epidemiology of Theileria parva

A case can be made that the epidemiology of *Theileria parva* has significant quantitative and qualitative differences to that of the other tick-borne diseases considered in this report. This applies particularly to the establishment of a state of enzootic stability and therefore is highly pertinent to integrating control of tsetse and trypanosomiasis with that of ticks and tick-borne disease in the areas of East and Southern Africa where *T. parva* occurs.

As discussed above (section 6.1.1), it has been shown by Coleman *et al.* (2001) that enzootic stability may arise where two conditions are met; (1) disease is more likely, or more severe, in older than younger susceptibles, and (2) after one infection, the probability that subsequent infections result in disease is reduced. The second of these two conditions is met in all the major tick-borne diseases discussed in this report, including *Theileria parva*. It has long been observed that following recovery from *T. parva* infection, animals may have solid immunity to reinfection (Mettam and Carmichael, 1936). This is particularly so for homologous challenge to which they are solidly immune for at least 3 years (Burridge *et al.*, 1972), although they may show varying degrees of susceptibility to other isolates (Radley *et al.*, 1975).

The first condition, that disease is more likely, or more severe, in older than younger susceptibles may be true to a degree for *T. parva* infection, but is probably far less so than with anaplasmosis, babesiosis and cowdriosis, for which there is much evidence of inverse age immunity (see section 6.1.4.1). Indeed for these three conditions, clinical disease is considered rare in animals under 6 months of age, and there is good evidence of colostral transfer of maternal protective factors (section 6.1.4.1). In contrast, in endemic areas theileriosis was long recognised to be primarily a disease of calves (Bruce, 1910; Mettam and Carmichael, 1936). Some evidence of an inverse-age immunity was demonstrated by Barnett and Bailey (1955); no 1 – 4 month old Zebu calves born in ECF endemic areas died of challenge by a single tick, whereas the same challenge killed 68% of adults. However, this immunity may be overcome by high challenge (Barnett, 1968), as only 40% of calves from the same areas survived a 50-tick challenge. Finally, while the age immunity does not appear to be innate, in that it is not shown by Zebu calves from outside ECF areas, it is unlikely to be due to passive transfer of antibody in colostrum because the rate of decline is slower than would be expected (Young, 1981). Furthermore, antibodies are not protective against the intracellular pathogenic stages of
the parasite (Muhammed et al., 1975), although anti-sporozoite antibodies might account for this effect (Brown and Gray, 1981; Musoke et al., 1982; Musoke et al., 1984).

Another important feature in the epidemiology of Theileria parva infection is the “quantum” relationship between the severity of infection and the dose of sporozoites inoculated (see section 6.1.4.5). Cattle in a typical endemically stable area will be exposed to a low quantum of *T. parva* infection, since only 1-2% of ticks are infected, and the majority of these have only one infected acinus in the salivary gland (Leitch and Young, 1981; Young et al., 1981). This could in part explain the relatively low mortality and morbidity of the disease in these areas (Norval et al., 1992). Variability in tick numbers among years, for instance as a result of climatic variations would be unfavourable for the development of a stable situation, since in those years with high tick attachment rates (and so high forces of infection), higher rates of clinical disease and mortality would be expected (see Figure 9). This was described in Eastern Zambia where year-to-year variation in rainfall causes important fluctuations in tick abundance, the *T. parva* challenge varies greatly from year to year and the infection still causes more than 50% mortality (Billiouw, 1999).

Variations in the size of sporozoite inoculation dose may be linked to the vector competence of the tick species within a given setting (Young, 1981; Norval 1985). Norval (1985) noted variations in clinical incidence of East Coast Fever across Zimbabwe, in areas of comparable *T. parva* infection rates but different vector species, with the level of clinical incidence on average lower in areas infested with *R. zambeziensis* compared to settings where *R. appendiculatus* was the main vector species. Furthermore, it has been suggested that the level of infection within the tick is dependant on the level of parasitaemia in the animal from which it acquires infection. Hence, in endemically stable areas, where there are few clinical cases, most ticks become infected from *T. parva* carriers, which have low parasitaemias, and themselves go on to develop very low infection rates in their salivary glands (Norval et al., 1992, p.233; Leitch and Young, 1981). Young (1981) considered that the calves that die from *T. parva* in endemic areas were those “which became infested with the odd, highly infected tick”. Young (1981) contrasted such areas with the high piroplasm parasitaemias occurring in “unstable epidemic situations” or “scattered outbreaks”, pointing out that strains producing such high parasitaemias might tend to be self-limiting in that they would produce higher infection rates in calves and tend to die out. Finally, the effects of perturbations to the existing status quo may be considered in this context. For instance, exotic cattle of
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higher genetic susceptibility introduced to an endemic area where there was little clinical disease might result in clinical cases with higher piroplasm parasitaemias. These in turn would give rise to higher infection rates in ticks feeding on them and a greater challenge inoculum for the next bovine host (of whatever genotype) fed upon by those ticks. Conversely, use of the infection and treatment method (see section 5.1.3.1) should reduce the overall number of clinical cases in an area, hence reduce the average infection rate in *Rhipicephalus* ticks, and thereby reduce the pathogenicity of the infections transmitted by them even to unvaccinated cattle, as observed by Minjauw *et al.*, (1999) in traditionally managed Sanga cattle in the Central Province of Zambia.

The above observations notwithstanding, the mortality rate from *Theileria parva* infection of indigenous calves in endemic areas is frequently far greater than that associated with *Babesia* and *Anaplasma*, for which very little mortality is expected in endemically stable areas. Early investigators in East Africa recorded case fatality rates in indigenous calves of 20 – 75% (Mettam and Carmichael, 1936). While significantly lower than the 95 – 100% rate observed in an epidemic situation in southern Africa (Lawrence, 1992), this nevertheless represents a high mortality rate and a severe disease burden. A benign form of the disease was seen in 20% of cases, which was largely subclinical, whereas the great majority of calves (80-90%) experienced a clinical form of the disease, for which the mortality rate ranged from 10-25% in well-nursed calves to a loss of up to 40% of all calves amongst the “agricultural tribes” – i.e. mixed crop-livestock farmers. Similarly, in a study involving indigenous cattle in an endemic situation without tick or tick-borne disease control on Rusinga Island in Lake Victoria, the average East Coast fever incidence in calves was 22%, with a case fatality rate of 21% (Latif *et al.*, 1995). In contrast, although *Babesia bigemina* and *Anaplasma marginale* were both detected in 6 – 8 month old calves in the same study, neither was associated with clinical signs. In *Theileria parva* endemic areas of the Eastern Province of Zambia studied by Billiouw *et al.* (1999), the mortality of infections was estimated at above 50%, and hence a state of endemic stability was concluded not to exist. The constraints to its development were considered to be the virulence of the *T. parva* in the region, and the high innate susceptibility of the cattle in the area.

It follows from this that it may be appropriate to relax (partly or completely) the assumption of inverse-age immunity, but maintain the assumption that an infection reduces the probability of subsequent infection resulting in disease (i.e. immunity develops) and further add the principle of quantum of infection. The effect of this on the
epidemiology of *T. parva* is discussed in section 6.1.4.5, and shown in Figure 9 and Figure 10, which show that a state may exist where most animals will be infected without signs of clinical disease. As a result, the epidemiological situation with *Theileria parva* possibly at times mimics the enzootic stability encountered with *Anaplasma* or *Babesia* infection, but the phenomenon of a much lower incidence of clinical disease than that of infection may have a quite different mechanism. In "conventional" enzootic stability, with *Anaplasma* or *Babesia*, the force of infection - clinical incidence curve (Figure 4) has a negative slope over much of its range, i.e. decreasing tick challenge may increase incidence of clinical disease, and vice-versa. However, with *T. parva*, increasing tick challenge may be associated with increased incidence of clinical disease, due to increasing the quantum of infection as shown in Figure 9. In the first instance, decreasing tick challenge may reduce the proportion of animals being challenged and becoming infected and immune during the calfhood period of reduced susceptibility. In contrast, with *T. parva*, because of the quantum effect of infection, a relatively low level of tick challenge may be associated with low clinical incidence, since most ticks will have only a single infected acinus. Increasing the level of tick challenge increases the probability of animals being bitten by ticks with a larger number of infected acini, and therefore receiving a larger quantum of infection and undergoing more severe clinical disease. And conversely and importantly for integrated tsetse and tick control, decreasing tick challenge may further reduce the incidence of clinical disease rather than increase it.

For *T. parva*, true enzootic stability is probably quite rare if it occurs at all. It may be that the appearance of enzootic stability (i.e. incidence of clinical disease is much less than that of infection) is due to a different phenomenon dependent on the quantum of infection. If this were so, then the use of pyrethroids would probably not worsen the disease situation. Further research is required particularly on the extent and mechanisms of age-immunity and in the development of models taking account of the effect of quantum of infection. Use of generic approaches to the epidemiology of tick-borne diseases (O’Callaghan, 1998 [fig. 6]) may therefore have pitfalls in the case of theileriosis.

### 6.1.5 Environmental and socio-economic variables

The above discussion of epidemiological factors affecting the complex nature of tick-borne disease epidemiology has concentrated on parasite-host and parasite-vector interactions. A range of other environmental factors, listed in Table 5, are also important in the complex epidemiology of tick-borne disease, and the establishment of enzootic stability across different epidemiological settings. Other important variables affecting the impact of
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integrated control include whether human sleeping sickness is of concern (see below), the
level at which policy and control planning decisions are being made, the economic status
of livestock keepers and possible private/public good & free rider considerations.

Table 5: Management and environmental factors influencing the epidemiology of
tsetse-transmitted trypanosomiasis and tick-borne diseases.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Tsetse &amp; Trypanosomiasis</th>
<th>Ticks &amp; TBDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle movements</td>
<td>–¹</td>
<td>++²</td>
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<tr>
<td>Relative positions of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>game parks and farm areas</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Mixing of commercial /</td>
<td>–</td>
<td>++</td>
</tr>
<tr>
<td>subsistence systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indigenous/exotic cattle breeds</td>
<td>+(+)⁺</td>
<td>+++</td>
</tr>
</tbody>
</table>

¹– unimportant
²+ slightly important; ++ moderately important; +++ very important.
* Use of trypanotolerant breed of indigenous cattle particularly important in West Africa

6.1.6 Vector Population Biology

In developing a theoretical framework in which to investigate the complex issues
associated with integrated tsetse and tick control, it is important to have an underlying
description of the population biology of the different vector populations to describe
accurately the effects insecticide treatment of cattle on the population dynamics, which
should be linked to the vector:host ratio and so force of infection. In ecological
terminology, tick and tsetse are r- and K-strategists, respectively. The parameter r
describes the intrinsic rate of population increase, or the exponential growth rate of the
population in the absence of any density dependent constraints. Animal populations are
also constrained by some maximum level called the carrying capacity, K, and this level is
dependent on the environment in which the population exists. The parameters, r and K,
can be used to describe the logistic growth of natural populations.
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The population dynamics of some species are characterised by a high $r$ and hence they are described as $r$-strategists or $r$-selected. Such species tend, amongst other things, to produce many offspring per individual, have short generation times and their populations tend to be inherently variable. Thus to control $r$-selected populations, an imposed death rate needs to be high so that death rate exceeds birth rate. By contrast, populations of $K$-strategists tend to be relatively slow-growing and stable in size, existing at, or close to, the carrying capacity of their environment. Thus modest but sustained levels of control mortality can eradicate populations of $K$-selected species.

As a broad generalisation, ticks are often said to be $r$-selected. Thus to impact significantly on tick numbers, control activities need to be aimed at killing many ticks to overcome the high birth rate. Moreover, any relaxation of the imposed control mortality leads to a rapid explosion in the numbers of ticks. The unusual reproductive biology of tsetse (see section 1.1.3) means that they are characterised as $K$-selected species, with slow population growth and relative stability around the carrying capacity. From a control perspective, only moderate increases in mortality rates can have profound effects on their population numbers.

These fundamental ecological differences influence the relative effectiveness of integrated control interventions for tsetse and tick populations. Simple ecological theory would suggest that if pyrethroid-treated cattle had a similar small impact on both tsetse and tick mortality rates, the intervention would have the greater impact on tsetse-transmitted trypanosomiasis rather than tick-borne diseases. This is because, tsetse flies are $K$-strategists, a slight increase in mortality can reduce population sizes that would reduce the force of infection of trypanosomiasis. By contrast, a slight mortality increase in $r$-selected tick populations would have negligible effect on tick numbers and so minimal effects on tick borne disease epidemiology. However, caution should be describing such generalities. Existing ecological models of tsetse (Rogers & Randolph 1985; Williams, Dransfield & Brightwell 1992; Hargrove 2001) and tick (Randolph & Rogers 1997) populations should be utilised within the development of the theoretical framework, to formally assess the likely effects of pyrethroid-treated cattle on population dynamics. The ecological models can also be structured to explore the spatial aspects of disease control and potential differential impacts on tsetse and tick population (see Section 7.1).
6.1.7 Dynamic aspects of control

The simple approach to quantifying the impact of integrated control described above only considers the equilibrium levels of clinical disease in the cattle population. It is important to consider dynamic changes in clinical disease incidence following introduction of control measures before a new equilibrium is reached. Such a dynamic approach is important in capturing seasonal variations in vector abundance driven by environmental variable such as climate and land use changes, which have been shown to be important in the distribution and epidemiology of other vector borne diseases (Kovats et al., 2001; Randolph et al., 2000; Linthicum et al., 1999).

6.1.8 Zoonotic nature of trypanosomiasis

Finally, in evaluating the impact of integrated tick- and tsetse-population control interventions, it is important to consider potential human public health benefits arising from the control of human infective T. brucei species in animal reservoirs (Welburn et al. 2001). Existing models describing the effects of veterinary intervention on human sleeping sickness incidence should be utilised (Coleman et al., 2002) in the developing the framework.

6.2 Existing models of tsetse- and tick-borne diseases

A review of existing model frameworks developed to describe the basic epidemiology of tsetse- (e.g. Rogers 1988b) or tick-borne diseases (e.g. O'Callaghan et al., 1998), predict the effect of intervention strategies (e.g. O'Callaghan et al., 1999), and examine economic issues associated with these disease (e.g. Swallow 1998) and their control (e.g. Minjauw 2000), either in local (e.g. Minjauw) or large-scale (e.g. Budd 1999) settings across Africa, are shown in Table 6 and Table 7. This body of work, provides a sound basis to develop a common framework for investigating the integrated control of tsetse- and tick-borne diseases.

However, to develop a framework for examining integrated control, there are several areas that require further consideration, which are discussed in more detail through this report:

- Linking epidemiological with population models of vector species. There has been considerable progress in developing mathematical models of disease vector populations, which describe the impact of vector-control intervention on the dynamics of tsetse (e.g. Hargrove 1993 and see Section 7.1) and tick (Nokoe et al., 1992;
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Randolph & Rogers, 1997) populations. Incorporating these quantitative descriptions of vector population dynamics with epidemiological models of infection transmission is important in capturing the true of effects of alternative disease control strategies. On a continental scale, adding epidemiological layers to predictive tick (e.g. King et al., 1988) and tsetse (e.g. Robinson et al. 1997) distribution models will provide a basis for more accurate economic impact studies.

The using of epidemiological models as a basis of economic analysis. The majority of economic analyses have made simplifying assumptions about the level of disease before and after control efforts. Such a static approach fails to capture the dynamic and non-linear effects of control on disease epidemiology. The "poor interface" (Norval et al., 1992) between disease epidemiology and economic models, needs to be addressed within a framework investigating integrated control.

Specific tick borne disease model. Within the tick-borne diseases, the model by O'Callaghan et al., 1998 of C. ruminantium infection stands out as the most comprehensive quantitative description of any of the tick-borne diseases. Such models, that explain the observed epidemiology and provide a sound basis for examining control options, are required for Babesiosis sp, Anaplasma sp. and particularly T. parva, infections

Integrated model for multiple tick borne diseases. As well as the need for disease specific models of the different tick-borne disease, a quantitative framework for describing transmission of multiple infections within the same host population is essential (e.g. Chizyuka & Mulilo JB 1990, Young et al., 1988).

Integrated model for multiple tick borne diseases and trypanosomiasis. All the above requirements need also be considered in developing a coherent framework to describe the epidemiology of trypanosomiasis and multiple tick-borne diseases in a cattle population, and examine the consequences (both epidemiological and economic) of integrated disease control.
Table 6: Published models describing the epidemiology of tsetse- and tick borne diseases in Africa.

<table>
<thead>
<tr>
<th>Epidemiological Study</th>
<th>Major Model Outcomes</th>
</tr>
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</table>
| Trypanosomiasis       | • Dynamics of trypanosome infection and prevalence.  
                        | • Accommodates multi-host species  
                        | • Both human and cattle infections  
                        | • Dynamics of trypanosome infection and prevalence.  
                        | • Accommodates multi-host species  
                        | • Both human and cattle infections  
                        | • Patterns of age-prevalence in tsetse flies  
                        | • Possible determinants of these epidemiological patterns  
                        | • Effect of alternative control strategies, targeted at vectors or parasites, on *T. brucei* spp. infections in cattle and humans |
| Rodgers 1988a and b   |                      |
| Milligan and Baker, 1988 |                      |
| Welburn *et al.* 2001 (and Coleman *et al.*, in preparation) |                      |
| Theileriosis           | • Tick population dynamics model  
                        | • “Rule based” model of ECF  
                        | • Incidence of disease in cattle determined by tick, parasite and herd interactions  
                        | • Effect of alternative control strategies including dipping and chemotherapy  
                        | • Transmission dynamics  
                        | • The importance of carrier status on endemic stability  
                        | • Impact of two control strategies – infection & treatment and acaricide use |
| Gettinby and Byrom, 1989 and Byrom 1990 (ECFEXPERT) |                      |
| Medley, Perry and Young, 1993 |                      |
| Cowdriosis             | • Most complete quantitative description of a tick borne disease  
                        | • Transmission dynamics fully described  
                        | • Variation in infection incidence and prevalence with tick attachment rates  
                        | • Description of endemic stability  
                        | • Importance of carrier status  
                        | • Evaluation of the non-linear outcomes associated with vaccines |
| O’Callaghan *et al.* 1998 and O’Callaghan *et al.* 1999 |                      |
| Babesiosis             | • Basic quantitative description of age-seroprevalence  
                        | • Tick population dynamics  
                        | • Age-specific transition rates (e.g. recovery rates)  
                        | • Tick to host ratio required to sustain transmission |
| Mahoney & Ross 1972    |                      |
| Haile, Mount & Cooksey (1992) |                      |
Table 7: Economic models of tsetse- and tick-borne disease control in Africa.

<table>
<thead>
<tr>
<th>Disease</th>
<th>ECONOMIC STUDY</th>
<th>MAJOR MODEL OUTCOMES</th>
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<tbody>
<tr>
<td><strong>Trypanosomiasis</strong></td>
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<tr>
<td>Barrett 1992</td>
<td>Cost analysis of alternative control strategies in Southern Africa</td>
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<tr>
<td>Budd 1999</td>
<td>Economic analysis of controlling animal trypanosomiasis throughout Africa</td>
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<td>20-year time frame and several different control scenarios</td>
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<td></td>
<td>Effect control resulting in estimated annual net benefits of US$1.5-3.5 billion</td>
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<tr>
<td>Swallow 1998 and 2000</td>
<td>Economic impact analysis</td>
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<td></td>
<td>Loses due to mortality, reduced meat and milk production</td>
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<tr>
<td>Kristjanson et al., 1999</td>
<td>Herd simulation model, scaled up to continental level</td>
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<td></td>
<td>Control effects in terms of reduced mortality and improved animal productivity</td>
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<td></td>
<td>Annual economic loses due to African trypanosomiasis estimated to be US$1.3 billion</td>
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<tr>
<td>Shaw 1998, Shaw et al., 1995 and Shaw et al., 2001</td>
<td>Economic analyses of the control of human trypanosomiasis</td>
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<td></td>
<td>Development of an economic framework to consider the costs and benefits associated with vector control, human case detection and treatment of domestic animal reservoirs</td>
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<td>Shaw Putt et al., 1989</td>
<td>Benefit/cost analysis of trypanosomiasis control in Zambia</td>
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<td>Itty et al., 1988</td>
<td>Herd simulation model</td>
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<td>Adapted to assess economic effects of trypanosomiasis control in Kenya</td>
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<td><strong>Theileriosis</strong></td>
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<td>Penne K &amp; D’Haese L 1999</td>
<td>Markov chain model</td>
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<td>Transition probabilities to capture epidemiology of disease</td>
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<td></td>
<td>Comparison of control strategies – treatment, vector control and immunisation</td>
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<td></td>
<td>Range of summary economic outputs – Benefit/Cost ratio, Net Present Value, Internal Rate of Return and Total Economic Cost</td>
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<td>Case study - model parameters chosen to represent situation in Southern Zambia</td>
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<tr>
<td>Muraguri et al., 1998</td>
<td>Spreadsheet based model</td>
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<td>Mukhebi et al., 1999</td>
<td>Cost analysis of immunization</td>
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<td>Minjauw et al., 1999</td>
<td>Spreadsheet based model</td>
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<td>Cost analysis of immunization</td>
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<td>Minjauw et al., 1999</td>
<td>Discounted cash flow model based on field trial data</td>
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<td>Break-even analysis for cost of immunization</td>
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<td></td>
<td>Importance of integration of immunization and seasonal tick control</td>
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<td><strong>Cowdriosis</strong></td>
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<td>Minjauw et al., 2000</td>
<td>Spreadsheet based benefit/cost analysis</td>
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<td>Regional study for Southern Africa</td>
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<td></td>
<td>Analysis broken down by sector and species</td>
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<td></td>
<td>Range of intervention scenarios, including dipping and vaccination, considered</td>
<td></td>
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</tbody>
</table>
6.3 Research recommendations

The development of a comprehensive theoretical framework to investigate and evaluate the impact of integrated tsetse and tick control strategies, is an important and novel research activity, which should be supported. This framework should incorporate population biology models of the vector species that feed into epidemiological models and allow the relative effect of control interventions, such as insecticide treatment of cattle, on tick-borne diseases and trypanosomiasis to be evaluated. It is vital that such a framework could differentiate between the epidemiologies of the different tick-borne diseases in different ecological settings.
7 FUTURE DIRECTIONS IN TICK AND TSETSE CONTROL IN AFRICA

7.1 Attributes desirable in future technologies

The preceding section makes it clear that the challenge is to develop an integrated pest management system to:­

- kill tsetse cost-effectively
- avoid killing beneficial species
- reduce direct damage caused by external parasites
- control ticks and biting vectors to minimise their direct negative effects on livestock while maintaining enzootic stability for tick-borne diseases.

Current knowledge of tsetse biology suggests that there are several opportunities to modify current tsetse control practices to achieve these aims. Specific opportunities relate to adjusting the timing, extent and/or placement of insecticide.

7.1.1 Timing

Vale et al. (1999) showed that the pyrethroid formulations effective against tsetse were effective for only 5-55 days. Thus to achieve continuous high levels of control (e.g. always >50% knockdown), 21 applications/year are required. However, many small-scale users of the technology apply the insecticide at monthly intervals or less (Table 2) to reduce the operational costs of the operation. Reducing the frequency of application could reduce impact on tick populations but could also reduce the impact on tsetse populations.

To examine the trade-off between frequency of insecticide treatment and tsetse control, we used simulation models based on the approach of Williams et al. (1992) and Hargrove (2000, 2002; Hargrove et al., 2002). In short, tsetse population movement and growth are modelled using a numerical solution to the Fisher equation (Williams et al., 1992). The model assumes diffusive movement at rate $\alpha$ and logistic growth at rate $r$ per unit time to a carrying capacity $K$. During a control operation, there may be an additional mortality rate ($d$). The time-course of population changes is modelled using a spreadsheet (Microsoft Excel) associated with various programmes written in Visual BASIC for Applications. Cells in the spreadsheet represented 1 km$^2$ of land and at each time step the model defines how the population in a given square grows due to births in that
square and to immigration from laterally adjacent squares. Details of the model are provided in Hargrove (2000, 2002) and Hargrove et al. (2002).

To assess the impact of various intermittent regimes, we considered control areas of either 100 (10 x 10) km\(^2\) or 400 (20 x 20) km\(^2\). Movement (\(\alpha\)) and growth rates (\(r\)) were set at 0.04 and 0.015 respectively and carrying capacity was 100 for all squares within and outside the operational area. Within the control areas, there was an imposed daily mortality of 0.08 (i.e. 8%/day), roughly equivalent to the mortality produced by 4 pyrethroid-treated targets or two treated herds of five cattle per square kilometre. To model intermittent application regimes, the imposed mortality was set at 0.08, when cattle were treated, or 0 when they were not. A treatment was effective for 30 days. Thus, if all cattle in the operational area were treated on day one, then the imposed mortality would be 0.08 for 30 days and 0 thereafter.

The outputs (Figure 11) show that intermittent application of insecticide reduces the impact of the control operation significantly, especially if the control operation is over a small area. For instance, for an operation conducted over areas of 100 km\(^2\) with continuously effective baits, the population was reduced by 92% 10-12 months after the start of the operation, compared to 69% for intermittent application of insecticide.

The rise in tsetse numbers when cattle are not treated is due to growth in the tsetse population in the operational area and to re-invasion of tsetse from adjacent infested areas. On the one hand, the intrinsically low reproductive rate of tsetse (\(~1.5\%/\text{day}\)) means that isolated populations of tsetse cannot recover rapidly. On the other hand, the relatively high rate of movement (\(~1 \text{ km/day}\) for savanna species such as \(G. \text{ pallidipes}\)) means that tsetse rapidly re-invade. Thus if we consider the case of a 20 x 20 km operational area, there is a rapid recovery at the periphery but the central area shows a far better level of control (Figure 12).
Figure 11: Results of simulations of control operations over 10 x 10 km or 20 x 20 km blocks where it is assumed that ‘pyrethroid-treated cattle’ are evenly distributed and that: (A) the density of pyrethroid-treated cattle (ITC) is sufficient to kill 8% of the female tsetse population per day, or (B) ITC density is reduced by two-thirds to kill 2.7%/day or (C) the cattle density is sufficient to kill 8%/day but the insecticide treatment is only effective for one month in three.

Thus attempting to reduce the impact of pyrethroids on tick populations by reducing the frequency of insecticide application to less than one application a month will undermine tsetse control in areas subject to invasion from neighbouring tsetse infested.

In areas that are not subject to invasion however, intermittent application of pyrethroids appears to be more promising. A characteristic feature of tsetse control operations using baits is that most of the effect of a control operation happens in the in the first three months (Figure 11). A consequence of this and the low reproductive rate of tsetse means that for tsetse populations not subject to invasion, treating cattle continuously for, say, 6 months and then leaving the cattle untreated for 6 months can be as effective as treating...
INTEGRATED CONTROL OF TICKS AND TSETSE

the population every other month. For instance, consider a 20 x 20 km block where cattle were treated for 180 days per year as either one period of 180 days, two period of 90 days or six periods of 30 days. Figure 12 shows the output for cells at the centre of the block. The mean population levels over 360 days were similar with the geometric means being 0.4, 0.5 and 0.8% for the 1x180, 2 x 90 or 6 x 30-day treatments respectively (Fig. 13).

**Figure 12**: Results of simulations of control operations over a 20 x 20 km blocks where ‘pyrethroid-treated cattle’ were treated once on day 1 and thus tsetse within the block was subjected to an imposed mortality of 8% for 30 days only. Lines show the percent carrying capacity, at 30, 60, 90 and 120 days after the insecticide treatment, along a transect running through the centre of the block.

The outputs for the 1- and 3-month simulations (Figure 13) are particularly interesting since they suggest that 99% control is achieved within 3-4 months and thereafter the long-term trend is a decline in tsetse numbers. These results suggest that intermittent applications could be used for areas not subject to invasion, i.e., in isolated pockets, or at least 8 km inside a large area treated with baits. The timing of intermittent application could be adjusted to coincide with periods of seasonal abundance in ticks and/or tsetse.

In practice, the operational area of any tsetse control scheme will generally comprise sections that are at risk of being reinvaded and other sections that are relatively protected. It may therefore be the case that a mixed approach could be developed with intermittent treatments being applied in the invasion-free areas, to reduce impact on tick populations and reduce costs. Such a strategy would exacerbate the differential costs of
control for individual farmers at the centre or edge of the control operation. Accordingly, some solution to balance these costs would be required.

**Figure 13:** Results of simulations of control operations over a 20 x 20 km blocks where ‘cattle’ were treated so as to be effective for six months per year, either as one continuous of six months, or for alternating periods of three months or one month. The plots show the population level, expressed as a percentage of the carrying capacity, for cells at the centre of the block, which are not subject to high levels of invasion.

![Graph showing population levels over time for different treatment periods.](image)

### 7.1.2 Selective treatment of cattle

Tsetse attracted to herds of cattle feed show a bias towards feeding on older and/or larger animals. Torr *et al.* (2001) showed for instance, that in herds comprising a mixture of 2 oxen, 4 cow/steers and 2 calves, ~80% (range, 67% - 91%) of meals were from the two largest animals within the herd and only 0 - 3 % were from the calves (Table 8). These findings indicate that the practice of not treating young animals, to allow the development of natural resistance to tick-borne disease, does not compromise the efficacy of using pyrethroid-treated cattle to control tsetse. Moreover, confining insecticide treatments to the larger adults will improve the cost-effectiveness of the technique.
INTEGRATED CONTROL OF TICKS AND TSETSE

Table 8: Percentage of meals taken from adult male, adult female or young cattle hosts. The test herds consisted of 8 animals, each comprising two oxen/bulls, four heifer/cows and two calves. Percentages were either based on all identifications, including mixed meals, or only those meals where a single host was identified. The percentages for all meals sum to >100% because a mixed meal comprises blood from at least two hosts. (Data from Torr et al. 2001).

<table>
<thead>
<tr>
<th></th>
<th>April 2000</th>
<th></th>
<th>October 2000</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>All meals</td>
<td>Single meals</td>
<td>All meals</td>
<td>Single meals</td>
</tr>
<tr>
<td>Oxen/bull</td>
<td>81</td>
<td>76</td>
<td>71</td>
<td>72</td>
</tr>
<tr>
<td>Cow/heifer</td>
<td>28</td>
<td>23</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>Calves</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>N</td>
<td>224</td>
<td>149</td>
<td>273</td>
<td>257</td>
</tr>
</tbody>
</table>

There is a strong correlation between the liveweight of an animal and the percentage of feeds from that animal and thus an animal’s liveweight provides a good rule of thumb to judge which animals to treat. To illustrate the efficacy of selectively treating herds using this rule, Torr et al. ranked animals from their experimental herds according to their weight and plotted the rank against the percentage of meals from the animal. Their results (Fig. 14) show that the proportion of tsetse that would contact pyrethroid-treated cattle as increasing numbers of cattle were treated. Generally, treating the two largest animals in the herd would kill ~75% of the flies visiting the herd. Slightly higher efficiencies of ~90% are obtained with the herds studied in April 2000. This arises because in April, 16% (n=261) of meals were mixed compared to 1% (261) in October. Consequently in April, 16% of tsetse contacted at least two animals in the herd whereas only 1% did so in October. The higher rates of mixed meals are thought to be due to increased rates of host-defensive behaviour elicited by the larger numbers of Stomoxys that are present in April at the end of the wet season (Schofield & Torr, 2002).

For the herds considered here, treating more than 2/8 animals would only produce slight (1-5%/animal) improvements in the percentage of tsetse ‘killed’ by the herd. For the herds used in these studies, the two largest animals constituted ~44% of the liveweight of the entire herd. Given that the dosage of pour-on is directly related to the liveweight of the animal, treating the two largest animals in the herd, rather than the entire herd, would half insecticide costs and, by not treating the young cattle there would be less
likelihood of disrupting enzootic stability to tick-borne diseases, where it existed. The benefits of this approach would be influenced by the cattle management practices of the owners. For instance, Maasai and Konso in tsetse-infested areas of Tanzania and Ethiopia respectively (Torr et al., 2000; Morton, 2002) graze the adult cattle separately from the calves and small stock while the Shona in Zimbabwe graze all their livestock together (Hargrove et al., 2002).

**Figure 14**: Percentage of tsetse contacting pyrethroid-treated cattle assuming that 1-8 cattle were treated with insecticide and treatment was based on the relative weight of an individual within the herd. Thus the heaviest and lightest animals are ranked 1 and 8 respectively. Each herd comprised 8 animals (2 oxen, 4 cow/heifers, 2 calves), studies were undertaken in the dry (A, B) or wet (C, D) seasons and percentages are based on sample sizes of 135 (A), 130 (B), 112 (C) and 81 (D) fed tsetse.

### 7.1.3 Selective application to tsetse feeding sites

Several studies (Thompson, 1987; Vale et al., 1999, Torr & Hargrove, 1998; Schofield & Torr, 2002) have shown that ~80% of *G. pallidipes* land on the legs of cattle. Most ticks on the other hand attach to the ears, peri-anal and genital regions of cattle. Thus it may be that applying insecticide to the legs of cattle will kill tsetse but not ticks. Such an
application regime would also reduce the impact on non-target species, such as dung fauna, and reduce insecticide costs (Vale, 2002).

Dr Glyn Vale has recently initiated a study in Zimbabwe to determine whether applying deltamethrin to the legs of cattle is as effective as treating the whole animal. His initial results are very encouraging: Decatix applied to the legs, for instance, appears to be as effective as treating the whole animal, has no significant impact on non-target species and reduces the use of insecticide by 90%.

However, this approach may not be suitable for all cases. For instance, Vale et al. (1999) found that only 30% of G. m. morsitans fed on the legs of cattle compared to 70% for G. pallidipes; most (70%) G. m. morsitans fed on the torso of the host whereas only 30% of G. pallidipes fed here. There are also exceptions to the general view of tick attachment sites. For instance, Stachurski (2000) found that A. variegatum initially attached to the lower limbs of cattle and only moved to their final attachment sites, around the genitalia and axillae of the host, when the cattle lay down in the evening. Consequently, the author suggested that treating only the limbs of cattle would provide a more cost-effective means of control this tick species.

Nonetheless, it appears that there are opportunities for mitigating the effects of pyrethroids on ticks by applying the formulation to specific regions of the host. Such an approach will also provide important environmental and economic benefits which will contribute to the overall sustainability of the approach. The last benefit is probably the most important. Currently, the cost of using pyrethroids to control tsetse is still prohibitively expensive for poor livestock owners. For livestock owners in tsetse infested areas of southern Ethiopia, a single curative dose of trypanocide (5 Birr/animal) is cheaper than treating their cattle with deltamethrin pour-on (9 Birr/animal). In these circumstances, owners show a poor uptake of tsetse control technology even though the predicted production benefits of tsetse control suggest that treating cattle with pyrethroids is the best long-term strategy. Reducing the cost of deltamethrin by 90% would make insecticide-treatment substantially cheaper than chemotherapy and thus greater uptake might be expected.

Several aspects need study however if this approach is to be developed further. In particular, the following questions need to be answered:

- What are the feeding sites of the epidemiologically important species of tsetse?
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- Will the selective application of pyrethroids to the feeding sites of tsetse be as effective as treating the entire animal?
- What impact will selective application have on the abundance of various species of tick?
- Would non-standard application methods (e.g. insecticidal 'bracelets') and formulations (e.g. low volume/high concentration formulations) improve efficacy and practicability?
- What are the likely economic, social and environmental benefits of selective insecticide application?

Vale et al.’s work in Zimbabwe will answer most of the above questions as they relate to animal trypanosomaisis transmitted by G. pallidipes. If this research indicates that the basic concept is sound, then it should be replicated for other vector-disease complexes.

7.1.4 Would selective application of insecticides preserve enzootic stability?

It is clear from the above that selective application of pyrethroids could reduce the impact on tick populations without greatly undermining efforts to control tsetse. However, selective application of insecticides will still have some impact on tick populations; the treated cattle would have an area-wide effect on the local tick population. Consequently, the numbers of ticks attaching to the untreated animals will still be reduced. Moreover, the area-wide effect would be dependent not only on the proportion of treated cattle but also on the relative abundance of wild hosts. As a result, it is impossible to state unequivocally that even selective application of insecticides would not affect the epidemiology of tick-borne diseases.

7.1.5 Low-technology approaches to tsetse control

The root cause of the conflict between tsetse and tick control strategies is that killing tsetse can kill ticks. Thus the conflict does not arise where trypanosomaisis control does not entail tsetse control. This generally means using trypanocides. However, in East Africa there is a tradition of using various physico-chemical methods to prevent vectors biting cattle.

An example of this approach is provided by small-scale dairy farmers from Tanga region in Tanzania. These farmers typically keep 1-2 Friesian Zebu-cross cows to produce milk.
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for sale, either locally or via various regional and national milk distribution networks. This region of Tanzania is heavily infested with tsetse and ticks and the two main causes of mortality and morbidity in cattle are ECF and trypanosomiasis. For instance, the 1998 annual report of the Tanga Dairy Development Programme records an annual mortality of 6% (435/6790) for adults and 10% (124/1250) for calves. Nearly half of these deaths were diagnosed as being due to tick- and tsetse-borne diseases, including ECF (35%), trypanosomiasis (9%) and anaplasmosis (4%).

To protect their cattle from ticks, farmers use a zero-grazing feeding system which means that cattle do not graze in tick-infested pastures. There is still a risk that ticks will be carried in with fodder brought to the animals and so the animals are also treated with various acaricides, including pyrethroids.

The zero-grazing system does not provide any protection against tsetse and thus farmers regularly treat their cattle with various trypanocides. In high-risk areas, such as Pangani District, many farmers treat their cattle with Berenil at ~20-day intervals (Torr, Kulanga & van Munster, unpublished data).

Farmers also employ various strategies to reduce the numbers of tsetse biting their cattle. In principal, zero-grazed cattle might provide a particularly suitable group for such strategies. The cattle are at one site continuously, usually in some form of kraal with a roof and walls. Thus it seems feasible that a kraal could, for instance, be modified to provide a physical barrier to tsetse; recent results from Kenya (B. Bauer, unpublished data) suggest that simply surrounding cattle with a 1.5-m high wall of pyrethroid-treated netting can protect cattle.

Surveys of farmers in Pangani district revealed that virtually all farmers used wood smoke to reduce the numbers of flies, including tsetse, attacking their cattle. Many farmers also treated their cattle with insecticide, which they believed repelled tsetse, and a few farmers have also fitted their kraals with netting to prevent tsetse from biting their cattle. Farmers also reported that tsetse traps placed adjacent to cattle could be used as protection, although no farmers were actually found using this strategy.

Torr et al. (unpublished data) assessed the efficacy of these livestock protection strategies using the protocol developed by Vale (1977). In short, cattle, with or without the various putative feeding deterrents, were placed within an incomplete ring of electric nets. The nets intercept a known proportion of the flies approaching or leaving a host and thus the effect of the deterrent on the numbers of tsetse attracted to and/or feeding on the cattle can be assessed.
Their results (Table 9) showed that neither placing an unbaited Epsilon trap (Hargrove & Langley, 1990) next to a cow or treating the cow with insecticide had a significant effect on the numbers of tsetse attracted to an ox or the percentage that fed. However, surrounding cattle with a 1.5-m high wall of pyrethroid-treated netting protected cattle and producing smoke near the cattle were both remarkably effective.

These preliminary results suggest that there are strategies that individual farmers can undertake to reduce the probability of cattle being bitten by tsetse without having any effect on tick numbers. However, if a cow receives ten infective bites a day by judicious use of smoke and netting reduces this to 1 per day then, at the end of the day, the cow still gets trypanosomiasis. It seems likely therefore that current methods of protecting cattle from tsetse will be more relevant for areas of relatively low disease incidence as part of an integrated package which includes the use of trypanocides.

Table 9: Mean catch and feeding success of tsetse (G. pallidipes and G. m. morsitans) attracted to an ox with or without various tsetse deterrents. Comparisons were made over 8-12 replicates; asterisks indicate that the numbers or feeding success of tsetse is significantly smaller (P<0.05, ANODEV) on cattle with the deterrent than those without.

<table>
<thead>
<tr>
<th>Deterrent</th>
<th>+1 (N)</th>
<th>-2 (N)</th>
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<tr>
<td>Decoy trap</td>
<td>46</td>
<td>34</td>
</tr>
<tr>
<td>Feeding success (%)</td>
<td>66</td>
<td>56</td>
</tr>
<tr>
<td>Insecticidal net</td>
<td>41</td>
<td>57</td>
</tr>
<tr>
<td>Feeding success (%)</td>
<td>4*</td>
<td>37</td>
</tr>
<tr>
<td>Wood smoke</td>
<td>22*</td>
<td>74</td>
</tr>
<tr>
<td>Feeding success (%)</td>
<td>69</td>
<td>72</td>
</tr>
</tbody>
</table>

¹+: with deterrent  ²–: without deterrent

7.1.6 Environmental impact of pyrethroid-treated cattle.

While assessing the susceptibility of tsetse to cattle treated with various pyrethroids, Vale et al. (1999) noticed dead beetles in the vicinity of dung pats produced by treated cattle. Subsequently, they confirmed that insecticide was detectable, at concentrations of up to 0.15 pmm, in the dung of treated cattle for 12 days post-treatment. Other workers have
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also produced results indicating that pyrethroids used to control ticks can affect dung fauna (Wardhaugh et al., 1998; Sommer et al., 2001; Kruger et al., 1998, 1999). These observations are particularly serious for the crop-livestock farming systems prevalent in sub-Saharan Africa where cattle dung is an important fertiliser. A significant impact on dung fauna could arrest the incorporation of dung into the soil.

The demonstration that pyrethroids kill beneficial insects such as dung beetles does not necessarily mean that the method could affect the nutrient cycles that depend on these species. However, Vale & Grant (2002) recently modelled the impact of insecticide-contaminated dung on the abundance and distribution of dung fauna. Their results show that the risk to dung fauna provided by treating cattle with pyrethroids is substantial, especially for slow-breeding beetles such as *Heliocopris dilloni* and flies contacting insecticide on cattle such as various species of *Musca*.

The latter are frequently nuisance pests and/or disease vectors in their own right. For instance, *M. autumnalis* is implicated in the transmission of mastitis, *M. lusoria* and *M. xanthomelas* transmit *Parafilaria bovicola* which causes parafilarisis in cattle and *Stomoxys* spp. transmits *Trypanosoma evansi* and *Anaplasma* spp. All these species are also considered to be nuisance pests of livestock. Thus an impact on these non-target species is probably a further benefit. There may even be ‘accidental’ benefits for human health: pyrethroid-treated cattle kill some species of mosquito which are important in the transmission of malaria (Torr et al., 2001; Torr, unpublished data). However, the scale and significance of these incidental benefits are largely unknown.

In contrast to these potential benefits however, an impact on dung beetles might however be an important cost. A DFID-funded project is currently addressing this issue and the preliminary results were presented by Dr Glyn Vale at the recent workshop on ”Integrated vector control including synergistic use of drugs and bait technologies for the control of trypanosomiasis and tick-borne diseases” held in Antwerp under the EU-supported Concerted Actions on Integrated Control of Pathogenic Trypanosomes and their Vectors (ICPTV), and the International Consortium on Ticks and Tick-Borne Diseases (ICTTD-2).

The main findings of the research undertaken to date are:-

- Deltamethrin applied at the recommended doses as Decatix spray or SpotOn pour-on produced detectable residues in the dung produced by treated cattle for ~2 two weeks after treatment;
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- Residues are greater with pour-on formulations than with spray/dip formulations;
- Various species of dung beetle (Scarabaeidae), predatory beetles associated with dung (*Hister* spp), and Dipteran larvae were highly susceptible to dung contaminated with pyrethroids;
- Dung is contaminated by insecticide accumulating in the peri-anal region of cattle and ingestion through licking;

The upshot of these findings is that serious environmental impact on dung fauna is possible if many pats were contaminated by cattle treatments performed in a large area for many months. Such a situation might occur with a large-scale tick and/or tsetse control programme. However, this risk could be mitigated by not using a pour-on formulation, and by applying the minimum amount of insecticide over the minimum area of the body, well away from the mouth and anus. This policy suggests that pyrethroids should be applied to the legs, which is coincidentally where, at least some, species of tsetse and tick feed and/or attach.
8 POLICY ISSUES AND INFORMATION PROVISION FOR INTEGRATED TSETSE- AND TICK-BORNE DISEASES CONTROL

The preceding sections identified several of the potential synergies and conflicts inherent in the integrated control of ticks and tsetse. Livestock keepers in rural Africa already have some knowledge of these and incorporate this knowledge into their livestock management practices. However, from the preceding sections it is also evident that some of the optimal disease management strategies are either counterintuitive and/or the true costs and benefits are not readily discernible. As a consequence, farmers, and the institutions and policies that provide the enabling environment, are not necessarily able to devise optimal strategies empirically. We therefore consider the implications of integrated vector control for farmers, communities and governments.

8.1 Towards integrated vector-borne disease control

The control of vector-borne disease is now converging for three reasons:

1. There is recognition of the value of integrated disease control. Tsetse flies, trypanosomiasis, ticks and TBDs all affect the same population of animals. Integrated control may have a synergistic effect on animal health, and has important implications when it comes to differential diagnosis and treatment. For example, diminazene aceturate is effective against trypanosomiasis and babesiosis, but not against anaplasmosis, theileriosis nor cowdriosis, and tetracyclines can be used against several TBDs (when given early on in infection), but do not work against trypanosome infections.

2. Increasingly, disease control is being devolved from government-level to farmer/animal keeper-level. Livestock productivity is greatly dependent on the livestock producers who make decisions regarding the health of their livestock (Tambi et al., 1999).

3. Development of technologies which may be effective against both types of diseases and vectors, e.g. use of pyrethroids and exploitation of genetic resistance.

The use of pyrethroid-treated cattle increasingly appears in many circumstances to be the cheapest option for tsetse control (Barrett 1997), especially where there is already widespread use of acaricides for tick control and/or high densities of tsetse and cattle, and hence widespread use of trypanocides.
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The use of pyrethroid-treated cattle therefore presents great opportunities for the integrated and more cost-effective control of ticks and tsetse, but these opportunities are greatly complicated by the issue of enzootic stability, whereby in certain circumstances a reduction in force of infection will result in an increase in disease.

This section explores the context for integrated control of vector-borne diseases in terms of institutions and policies, farmers' knowledge, attitudes and practices, and issues of public and private benefits and collective action. The implications for control programmes of different scenarios of tsetse and tick-borne diseases are sketched out, with further discussion of appropriate institution-building and communication strategies.

8.2 The Context for Integrated Control

8.2.1 Institutions and policies

Historically, the science and practice of controlling vector-borne diseases of livestock has been riven with divisions. The control of vectors and of vector-borne diseases was undertaken by scientists from different disciplines, e.g. control of tsetse flies and ticks by entomologists and control of trypanosomiasis and TBDs by veterinarians, with little overlap. In addition, researchers concerned with ticks and TBDs worked independently of those working on tsetse and trypanosomiasis. The funding of projects for these vector-borne diseases has not been geared towards integrated control, largely because donor or government funding for such projects may have separate budgets and administrative structures for different animal diseases. Furthermore, government veterinary departments in Africa also have separate units to tackle these vector-borne diseases. In Kenya for example, there is the Kenya Trypanosomiasis Research Institute (KETRI) that works solely on tsetse and trypanosomiasis, and the Kenya Agricultural Research Institute (KARI) that tackles tick-borne and other infectious diseases. The European Union has previously funded large regional trypanosomiasis and tsetse projects that have not had a component of tick-borne diseases control (RTTCP and FITCA). Among the groups working on TBDs, the tendency has also been for projects to tackle single TBDs each, e.g. the IFAD/SADC Heartwater project.

Patterns of veterinary service provision in Africa are in a state of transition. Until recently, animal health service provision has been the domain of the public sector, with most services being provided free of charge (de Haan et al., 1992, Mlangwa et al., 1994, Tambi et al., 1999, Holden, 1999). In most sub-Saharan African countries, veterinary services
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are currently undergoing restructuring, with the public sector having a reduced role due to budgetary constraints and increasing pressure from the international donor community to privatise. Privatisation of veterinary services means a shift from project-driven to demand-driven activities, and from external funding to cost recovery from the livestock owners themselves (Bauer and Snow, 1998). Indeed, in many African countries, government veterinary services now lack the funds and institutional capability required to implement large-scale disease control programmes (Barrett, 1997). The withdrawal of state run veterinary services through privatisation and reduced budgets has resulted in a varied range of animal healthcare providers. Livestock keepers now obtain these services from government and private animal health workers, NGOs, local agro-veterinary traders, traditional healers and fellow-farmers and themselves.

Table 10 shows some of the principal stakeholders in the veterinary aspects of disease control before and after privatisation.

**Table 10: Stakeholders in aspects of disease control.**

<table>
<thead>
<tr>
<th>Level</th>
<th>Pre-privatisation</th>
<th>Post-privatisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>National</td>
<td>Central veterinary research institutes Pharmaceutical companies</td>
<td>Government veterinary laboratories Private veterinary laboratories Pharmaceutical companies</td>
</tr>
<tr>
<td>Provincial</td>
<td>Regional veterinary laboratories</td>
<td>Private veterinarians</td>
</tr>
<tr>
<td>District</td>
<td>District veterinary office</td>
<td>Animal health assistants Farmers' associations NGOs</td>
</tr>
<tr>
<td>Village</td>
<td>Animal health assistants Extension workers</td>
<td>Women's groups  Schools churches Extension workers Local agro-veterinary retailers</td>
</tr>
<tr>
<td>Farm</td>
<td>-</td>
<td>Smallholder farmers</td>
</tr>
</tbody>
</table>

8.2.1.1 The changing role of government

Governments generally assume a significant role in the management of contagious animal diseases such as foot-and-mouth (FMD), contagious bovine pleuropneumonia (CBPP) and rinderpest. In such cases, national regulations, regarding for example livestock movement, disease reporting and sales, are combined with government-sponsored
interventions (e.g. animal culls, mass vaccinations) to control the spread of these epizootics. Moreover, since international trade in livestock can affect the transmission of such diseases, they are also the subject of international agreements and the concern of various international organisations (e.g. OIE, PARC, PACE). In contrast, when a disease is not contagious such regulation is less necessary since livestock production is less likely to affect disease transmission.

In the absence of a vector, tsetse- and tick-borne diseases are not contagious and are generally regarded as one of many constraints on livestock production. Consequently, governments currently tend to expect livestock producers to decide how to manage such constraints and to bear any associated costs. This, however, was not always the case.

For trypanosomiasis, the older methods of tsetse control (e.g. ground spraying, aerial spraying) could only be applied on a very large scale to be effective (c.f. fig. 1 showing tsetse control in Zimbabwe) and only government agencies had the financial and logistical capacity to undertake such operations. The aforementioned decline in institutional and financial capacities in Africa mean that few governments are now able to undertake large-scale operations themselves. However, the development and uptake of bait methods of tsetse control by local communities means that there has been a general shift towards privately-funded, small-scale operations aimed at controlling, rather than eradicating, tsetse and trypanosomiasis.

Similarly with tick-borne diseases, governments have played a substantial role in their control. In the 1910s for instance, countries such as Rhodesia (now Zimbabwe) and South Africa initiated intensive dipping strategies to control ECF. In contrast to tsetse control, tick control operations were underpinned by legislation aimed at maximising the number and frequency of cattle treatments. In Zimbabwe for instance, commercial and communal farmers faced various financial penalties if they failed to dip their cattle. Like tsetse control, intensive government-funded dipping of cattle has declined in recent years and livestock owners themselves are now generally responsible for treating their cattle. However, in contrast to tsetse, farmers can, and do, use the same control methods previously employed by the government. Paradoxically, many of the statutory instruments regulating, for example, cattle movement and treatment still remain in place although they are no longer enforced so rigorously.

The greater historical importance of legal instruments in managing TBDs compared to tsetse-borne diseases is because the former are, in some respects, similar to contagious diseases. In such diseases, infection is heavily dependent upon the proximity of infected
and naïve cattle. In the case of tsetse-borne diseases, vectors such as *G. pallidipes* will on average move ~20 km a year. Since cattle tend to remain within just a few kilometres of their kraals, the spread of disease is largely dictated by the vector’s movement. Moreover, cattle movements, for grazing or for sale, will not have any major impact on fly distribution; a few flies may be transported with cattle but they will be too few in number to establish a new population. In contrast, the movement of ticks are largely dependent on the movement of hosts and the few ticks carried out by cattle can result in a new recurrent source of infection. Thus an infected cow infested with ticks can carry the disease into a new area, contaminating the pastures with infected ticks and subsequently infecting naïve cattle. Indeed such movements have played an important role in the transmission of various TBDs, as evidenced by the introduction of ECF into southern Africa in the early 1900s (Norval *et al.*, 1992) and Texas fever (Babesiosis) into Kansas in the late 1800s.

Table 11 shows several examples of factors that are important in the transmission of tick- and tsetse borne diseases. Each of these factors have at various times and/or places been the subject of legal control and serve to illustrate the importance of such regulation in tick management.

The withdrawal of government from active involvement in vector control has generally been accompanied by a relaxation of these legal controls. However, the complete absence of any government regulation or guidance on vector control activities may not be appropriate. First, the unrestricted use of pyrethroids and trypanocides can lead to the rapid development of resistance in tick populations (Beugnet and Chardonnet, 1995); *Boophilus* spp. have already developed resistance to pyrethroids in South Africa and Zimbabwe and there is widespread resistance to trypanocides. This risk is likely to increase as patents for pyrethroids expire and local production increases with concomitant increases in availability and reductions in price. Second, the increasing importance of vaccines for control of TBDs will inevitably require government involvement with production, distribution and delivery of vaccines. And third, if enzootic stability is to be a component of disease management, then the previous sections make it clear that unregulated use of pyrethroids can exacerbate tick-borne diseases. It therefore seems clear that, at the very least, governments need to be informed of the potential consequences of the various control options and hence devise an appropriate vector control policy.
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8.2.1.2 Non-governmental organisations

In practice, NGOs and community-based organisations are assuming an increasingly important role in the local promotion and management of operations to control tsetse and tick-borne diseases. In the absence of a national government policy and appropriate technical information, there is a risk that NGOs could encourage interventions that will, for instance, lead to acaricide resistance, exacerbation of tick-borne diseases and ineffective tsetse control. Such organisations are however receptive to guidance and can play an important role in the dissemination of knowledge and best practice to local communities and livestock owners. It is therefore important that NGOs are alerted to the potential synergies and conflicts inherent in controlling vector-borne diseases of livestock and assisted in developing appropriate management strategies.

Table 11: Legislative factors affecting the transmission of tick- and tsetse-borne diseases.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Tsetse &amp; Trypanosomiasis</th>
<th>Ticks &amp; TBDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grazing patterns</td>
<td>−¹</td>
<td>+²</td>
</tr>
<tr>
<td>Cattle sales</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Dipping regime</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Mixing of commercial / subsistence systems</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Relative positions of game parks and farm areas</td>
<td>++</td>
<td>+</td>
</tr>
</tbody>
</table>

¹– unimportant
²+ important; ++ very important.

8.2.2 Knowledge, Attitudes and Practice of Farmers’ towards Vector-borne Diseases

The trends described above have now resulted in farmers, together with private veterinarians and the suppliers of pharmaceuticals, being the major stakeholders in the
control of vector-borne diseases rather than professional animal health workers. This
focuses attention on the knowledge that farmers have of vector-borne diseases and their
real-life strategies for controlling them.

8.2.2 Knowledge of and attitudes to vector-borne diseases

The importance of vector-borne diseases is widely recognised by livestock producers in
sub-Saharan Africa (Catley and Irungu, 2000; Machila et al., 2000; Morton, 2002).
Varying levels of understanding of the aetiology of disease exist amongst farmers and
livestock keepers, ranging from lack of any knowledge through traditional beliefs such as
witchcraft to fairly detailed understanding of pathogenic micro organisms and their
transmission (Kamara et al., 1995; Kamuanga et al., 1995, Delehanty, 1996, Heffernan et
Definitive diagnosis of vector-borne diseases usually requires microscopic demonstration
of the causal haemoparasites in association with typical clinical signs, as discussed in
earlier sections. However, primary animal healthcare providers, i.e. farmers and para-
veterinarians, can rely on none of the decision-support tools available to (well-equipped)
 veterinary practices. Instead they rely on visible clinical signs, the history of the sick
animal, post-mortem observations, and occasionally on the perceived cause of the disease
(Delehanty, 1996, Heffernan et al., 1996, Machila et al., 2000). However, some studies
have showed that farmers’ disease diagnoses are not always reliable (Machila et al., 2000,
Catley et al., 2002).
The apparent lack of knowledge results in misuse or overuse of drugs, which is
uneconomic, environmentally unsound and may lead to drug resistance and other
problems such as toxicity (Geerts & Holmes, 1997; Stevenson et al., 1993; Eisler et al.,
1997).

8.2.2.2 Management of vector-borne diseases
Farmers’ attempts to manage vector-borne diseases range from use of curative
treatments (both traditional and modern) to use of preventive measures. These activities
are mostly conducted by individual farmers, and occasionally, by groups of farmers.
Dipping as a means of controlling ticks, and therefore tick-borne diseases, has been
mentioned in Section 4.1.1 above. As stated there, its use has declined heavily in much
of Africa. Hence many farmers have resorted to individual animal tick treatments,
including hand dressing with acaricide, use of pour-on and manual removal of ticks.
Outside areas where there have been large-scale attempts to control tsetse by spraying, or the generally small-scale initiatives using traps, targets or insecticide-treated cattle, farmers have generally relied on the use of drugs to control trypanosomiasis. Doran (2000) states that 80-85% of cattle owners in parts of Zambia had purchased trypanocides in the twelve months before the survey. Studies conducted in western and coastal Kenya showed that more than half the farmers in the study administer drugs to their own livestock (Machila et al., 2000). Similar findings apply to wide areas of Africa (see also Catley 2002). Such use is in varying degrees strategic, in terms of administering drugs prophylactically at certain times of year and/or to the most valuable animals, but often it is responsive with drugs being given to any animal following clinical signs of trypanosomiasis. Quite apart from the issue of encouraging drug-resistance, there is much evidence that farmers’ use of drugs is based on incorrect information, and not cost-effective even in its own terms.

In a trypanosomiasis study in Eastern Zambia, Doran and van den Bossche (1988) found that the choice between use of therapeutic drugs and prophylactic drugs was made on the basis of cost per dose, without a clear understanding by farmers of the advantages of prophylactic drugs used in appropriate circumstances. Similar studies in Uganda indicate that trypanocidal drug treatments are not given appropriately, i.e., the treatment rate does not reflect the prevalence of disease, and that treatments may be given unnecessarily (Olila, 1999). In Yalé Province of Burkina Faso, the amount spent by livestock keepers on trypanocides was not related to the prevalence of the disease (Kamuanga et al., 1997). Similarly, in Northern Côte d’Ivoire owners who raised trypanosusceptible cattle administered prophylactic trypanocidal drug treatments regardless of the disease prevalence (Pokou Koffi, cited by Swallow, 1998).

The major sources of drugs and advice are local agro-veterinary traders (Machila et al., 2000, Heffernan and Misturelli, 2000, Bett, 2001). A study conducted by Bett (2001) in western Kenya on the ‘role of local agro-veterinary traders in animal healthcare provision’ showed that the shopkeepers who sold drugs to and advised clients did not have any training in animal healthcare. Preliminary findings from a study in six districts including Baringo in Kenya show that 71% of participating farmers obtained their livestock drugs from agro-veterinary traders, even when they perceived these traders to know ‘no more or less’ than the livestock keepers themselves (Heffernan and Misturelli, 2000).

The issue of trypanotolerant livestock, which is a major form of farmer-level management of trypanosomiasis, has been discussed in Section 4.2.2.3 above. The use of low-cost
techniques, notably smoke, to physically prevent tsetse from biting cattle, especially stall-fed cattle, has been discussed in Section 6.2.5 above.

**8.3 Public and Private Benefits and Collective Action**

The design of strategies for the integrated control of vector-borne diseases, is complicated, but in the end favoured, by the different balances of private and public benefits from tsetse and from tick control. This section will examine the issues of private and public benefits and collective action, leading to an attempt to represent certain options for approaches to control and future research.

The high mobility of tsetse means that any localised control, over say 10 km², will have no discernable effect on tsetse numbers and hence trypanosomiasis. Since tsetse control must be applied over a large area, the use of pyrethroid-treated cattle for tsetse control in African smallholder, agro-pastoral or pastoral systems, requires *collective action*. This may be pre-planned collective action, but may also be individuals using pyrethroids for tick and/or biting fly control, or optimistically for tsetse control in an unplanned “collective action”. It is important to stress that while tsetse are killed by deltamethrin, they are not prevented from infecting cattle with trypanosomes before dying. Consequently, in terms of tsetse and trypanosomiasis control, there is virtually no benefit to a cattle-owner of treating his/her cattle with insecticides if his/her neighbours are not doing so. We suggest a relationship between compliance with a pyrethroid-treated cattle strategy for tsetse control and private and public benefits as shown in Figure 15. It is only above a certain threshold proportion of the total cattle in the community being treated that benefits in terms of tsetse control may rise suddenly. Above this threshold, the benefits are felt by the community of cattle owners as a whole. There is then, at least theoretically, a possibility of *free-riding*, where cattle-owners can avoid sharing the costs of tsetse control, while sharing the benefits. A pyrethroid-treated cattle strategy shares this feature with strategies using traps and targets. We suggest that this is a very important reason why these technologies have seen virtually no uptake in the absence of concerted support from governments and/or NGOs.
There are many factors that assist or constrain real-life communities in overcoming these problems:
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Technical

- The proportion of cattle to be treated (Torr et al., 2002a), the choice of which cattle are treated (Torr et al., 2001b), and the frequency of their treatment, which are functions of cattle density (Hargrove et al., 2002) and the action of particular insecticides on tsetse in particular environments (Vale et al., 1999).

- Whether the costs can be evenly spread across cattle-owners, or whether circumstances such as the need to treat proportionately more cattle in zones more prone to re-invasion favours differential contributions.

Economic

- The costs of insecticide treatment, which is a function of the first factor above and the cost of insecticide.

Social

- The degree of trust and of existing co-operation activities within the community, which can be referred to as social capital.

- Whether the boundaries of the geographical area where a programme of tsetse control is appropriate coincide with the physical and social boundaries of an existing community or set of related communities.

- The extent to which the communities feel themselves owners of the tsetse control strategy, rather than simply being required to treat their cattle (Barrett and Okali, 1998).

- The understanding by cattle-owners of the link between trypanosomiasis, tsetse, and the pyrethroid-treated cattle strategy, the need to maintain certain levels of compliance across the community, and the need to maintain them indefinitely, even when there is no longer a visible threat of trypanosomiasis or tsetse.

Of the "social" factors listed, the first two are givens of the situation. The third requires planning at the earliest stage to involve the community, and the fourth requires work both at the farmer level, to promote awareness of the facts of tsetse control, and at the level of the community, to stimulate collective action.

The situation with the control of ticks, and nuisance flies, is very different. Even if no other cattle-owners are treating cattle for ticks, most benefits accrue to the individual cattle-owners. We suggest a relationship between compliance and public and private benefits as shown in Figure 15. As the proportion of cattle in the community rises, so
does the net benefit, which is the sum of individual benefits. It is only when compliance, both in terms of proportion of cattle treated and regularity of treatment, rises to very high levels indeed (possibly higher than is feasible in a smallholder or agro-pastoral system), that there is any (marginal) effect on tick levels in the environment, which can be considered a public benefit.

It might be possible to formulate the above ideas in terms of the well-known schema of public and private goods based around the concepts of excludability (whether potential users can be excluded from access to the good) and subtractibility (whether using a portion of the good shrinks the supply that remains); see Table 12. Such a schema, which also allows the possibility of toll goods and common property goods, is found for example in Holden (1999). Such an analysis is useful in relation to the case of vector borne diseases, although there are additional problems to be addressed. The question of who bears the cost of the good should not be ignored, and care should be taken to avoid confusion between the means of control (a chemical that has to be paid for) and the benefit of control (a tick- or tsetse free life for one's cattle), and between exclusion of cattle from a geographical area and exclusion of cattle-owners within that area from the benefits of control.
Table 12: Classification of control options for vector-borne diseases into private-goods and public-goods

<table>
<thead>
<tr>
<th>Excludability</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Public goods</strong></td>
<td>Public funding</td>
<td>Toll goods</td>
</tr>
<tr>
<td>- Epidemic or zoonotic disease control (including surveillance, movement control, quarantine services)</td>
<td></td>
<td>- Private finance</td>
</tr>
<tr>
<td>- Some extension</td>
<td></td>
<td>- Vaccine production</td>
</tr>
<tr>
<td>- Some research</td>
<td></td>
<td>- Diagnostic services</td>
</tr>
<tr>
<td>- Control of food borne diseases</td>
<td></td>
<td>- Veterinary clinics</td>
</tr>
<tr>
<td>- Drug quality control</td>
<td></td>
<td>- Dips</td>
</tr>
<tr>
<td><strong>High</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Common pool goods</strong></td>
<td>Public funding</td>
<td>Private goods</td>
</tr>
<tr>
<td>- Tsetse control on communal land using traps, targets or aerial spraying</td>
<td></td>
<td>- Enzootic disease prevention and control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Sales of drugs and vaccines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Some extension</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Some research</td>
</tr>
</tbody>
</table>


Swallow et al. (2000) state that "Farmers who treat their cattle with pourons (sic) obtain private benefits...private treatment of animals with pourons also generates local public benefits...Pourons are thus described in economic terms as mixed public-private goods or impure public goods". This is a useful formulation but Swallow et al. (2000) do not follow up the implications of the private benefits relating mainly to tick control and the public benefits relating mainly to tsetse control.

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3 The authors cite Cornes and Sandler 1986
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The combination of private and public benefits from pour-ons may explain why this strategy has had relatively greater success than strategies based on traps or targets, which have no private benefit at all. Moreover, for pour-ons, their very nature may suggest to cattle-owners that they are a private good, in that they are applied directly onto their owner’s cattle, even if much of their benefit is public. This will not be the case for traps or targets. In this context there may also be cultural issues influencing levels of uptake, with pastoralists for instance being more receptive to investing in preventive interventions directly involving their cattle than mixed crop-livestock smallholder farmers.

8.4 Scenarios for Integrated Control of Vector-Borne Diseases

Following Table 3 above (Scenarios for Insecticide-Treated Cattle Usage), we can distinguish three very different scenarios where considerations of TBD control affect the conduct of pyrethroid-treated cattle strategies for tsetse control (taking the left-hand column and reading upwards):

1. Where ticks are already intensively controlled e.g. by short-interval dipping (or some treatment of individual cattle), and TBDs are not a problem
2. Where ticks are uncontrolled, or limited control is practiced, but enzootic stability does not prevent all TBDs, some or all of which remain a problem,
3. Where ticks are uncontrolled, or limited control is practiced, and enzootic stability controls TBD.

In scenario 1, tsetse control can be instituted relatively simply and cheaply by changing to an insecticide active against both ticks and tsetse. Because there is a significant private benefit in the form of tick control, free riding will be minimised. The existence of a tick control system therefore greatly favours the adoption of tsetse control. This has been the situation in Zimbabwe.

This scenario requires ensuring that an insecticide active against tsetse is distributed all the way down whatever distribution system, public or private, has previously been used. This may involve communication with veterinary workers and/or traders in veterinary products. Depending on the incremental cost, it will require varying degrees of communication to cattle-owners, explaining the benefits of a new chemical in terms of tsetse and therefore trypanosomiasis control.

In scenario 2, tick control presents an additional, visible and private incentive for cattle owners to engage in tsetse control through pyrethroid-treated cattle. This scenario may
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particularly apply to ECF areas. A pyrethroid-treated cattle programme that would otherwise present a significant cost, to farmers and/or in subsidies by governments or donors may be instigated by individual farmers by their own initiative. If the strategy is to pass that cost on to cattle-owners, problems might well arise of a) cattle-owners perceiving it (rightly or wrongly) as greater than the costs of control using trypanocides b) of compliance flagging over time as the visible threat of tsetse receded, and c) of "free-riding". The integration of tick control increases the benefits of a pyrethroid-treated cattle strategy, and thus the chances of success.

Such a pyrethroid-treated cattle strategy will still require communication with cattle-owners in the fullest sense. This will include initial consultation to discuss the various tsetse/trypanosomiasis control options, and facilitate their participation in the design of a strategy, institution building to ensure the continued supply of insecticides and enforcement of compliance through community pressure (also to operate any traps or targets that may be needed in peripheral areas prone to re-invasion), and continued education on the links between insecticide-treatment, tsetse and trypanosomiasis and the need for indefinite maintenance of the control strategy.

In Scenario 3, the strategies mentioned in 5.2.2 (selective treatment of cattle, selective placement of insecticides) may be necessary to mitigate the effects of insecticide-treatment on tick populations, enzootic stability and TBD incidence. This points to the need for further research on these and similar techniques. Compared to Scenario 2, there is no real private benefit to cattle-owners, only a public benefit, which may constrain uptake. On the other hand, these techniques are likely to be cheaper to cattle-owners at the same level of effectiveness against tsetse. The need not to affect tick populations will in the long run be concordant with the need to bring down the prices of tsetse control.

This scenario will therefore need the same sorts of communication with cattle-owners as scenario 2, with an even more urgent requirement for institution-building to promote collective action, and an additional need for explanation of the difficult concepts of the need to maintain the exposure of young stock to ticks, and communication of the technically more difficult tasks of selective treatment.

However, and it is a major qualification, our existing knowledge of enzootic stability is still very limited. Its importance differs for various diseases and in various situations: for instance, it may be that reducing tick populations will be beneficial for the control of East Coast fever, but have an adverse effect on babesiosis incidence. We do not yet have the tools to quantify the effects involved in enzootic stability at a field level, outside the
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confines of intensive research programmes. We therefore do not have the ability to predict the effects on TBDs of uptake of pyrethroid treatment at various levels.

There are therefore several research priorities:

1. Continuation of strategic research on the mechanisms and effects of enzootic stability
2. Development of cost-effective methods for identifying enzootic stability at the field level, and estimating the likely impacts of its disruption on different TBDs
3. Development of guidance to agencies, frequently NGOs, who are managing or considering setting up area tsetse control programmes: until 1 and 2 are further developed these will necessarily be incomplete
4. Development of guidance for drug companies and formal and informal sector retail networks to cope with the increasing spontaneous use of pyrethroids outside organised projects.

As regards task 3, the above discussion shows that the balance between institution-building, technical communication with farmers, and managing the supply chain for chemicals, will be different in the different scenarios. The following decision-tree (Figure 16) attempts to present this graphically. It also shows how important research priorities relate to the needs of these agencies.
Figure 16: Idealised decision tree for situations where treatment of cattle pyrethroid for tsetse control is the method of choice. Red diamonds indicate key questions requiring research (green arrows), green hexagons indicate dissemination and institutional strengthening.
8.5 Community- or village-level interventions

The establishment of tsetse control through collective action will require some degree of institution-building, institutional strengthening or "community development" in the communities concerned. Many of the issues are the same as those that arise for "pure" tsetse control strategies based on traps or targets. Some of the important principles are as follows.

*The "free-rider" problem:* the "free-rider problem" is a theoretical construct, that in practice works itself out very differently depending on culture, "social capital" and the institutions existing within a community. Barrett and Okali (1998) considered that "Voluntary collective action for improving people's well-being" is a reality in the context of vector control, albeit with some degree of free-riding and discuss this in more detail with reference to the work of Uphoff (1996). Having said this, it is noteworthy that there are few if any extant examples of uptake of purely public good tsetse control technologies such as the use of traps and targets.

*The participation of communities should be profound:* cattle-owners should be involved in the most important levels of project decision-making and from the beginning of project design (Barrett and Okali, 1998). This includes involvement in decisions over required suppression levels and technologies, and may result in "a whole series of partnerships - some possibly even excluding community participation - and a whole range of sites where control programmes can be initiated" (ibid.). Such community involvement in the design of a tsetse project requires that the community is fully informed on many of the technical aspects of tsetse and tick-borne diseases; education is a prerequisite to effective participation.

*Communities should not be expected to pay for benefits experienced outside their own boundaries:* communities that live in areas treated as barriers, to prevent re-infestation of tsetse-free areas elsewhere, should not be subject to the full cost, which is likely to be higher than that of the degree of suppression the community itself would choose.

*Technical considerations influence the participatory nature of control strategies:* Inequalities are inherent in the practice of tsetse control for several reasons. First, farmers in areas of low cattle density, wildlife areas, and/or subject to high levels of tsetse invasion may need to treat proportionally more cattle and/or use artificial baits. Second, different livestock production systems will have inherently different effects on tsetse populations, derive different benefits and will differ in their ability to invest in tsetse
control. Compare for instance traditional pastoralists owning large mobile herds of indigenous cattle with small-scale owners of zero-grazed dairy cattle. The former group will be more effective at controlling tsetse but the latter might expect better improvements in livestock production from tsetse control (Torr et al., 2001). Third, there are strong temporal inequalities. At the start of any tsetse control initiative, owners have to pay for tsetse control while still sustaining the costs of trypanocides. Thus in the first few months of any operation there is an increase in cost with no discernible benefit. Over time, owners at the centre of an operation will benefit more than those at the periphery. These inequalities are obstacles to the uptake and sustainability of community-based tsetse control and call for some form of equalisation. NGOs, governments and donors have attempted to tackle some of these inequalities through the use of subsidies, but these have not generally been sustainable (Brightwell et al., 2001).

Farmers' existing knowledge, attitudes and practices regarding animal diseases need to be understood: fortunately there is now a large body of literature applying the principles of Participatory Rural Appraisal (PRA) to animal health problems (for example Kirsopp-Reed 1996), including a recent article on trypanosomiasis (Catley et al., 2002). The importance of such PRA methods is not only that they are a cost-effective way to understand the situation in depth, but also that they pave the way for the participatory development of a strategy.

Local institutions must be understood: PRA methods will also be of use in understanding local institutions, considered in the broadest sense, and including both "traditional" and modern institutions. It will depend greatly on local circumstances whether existing institutions are used for tsetse control, or whether new institutions, such as tsetse control committees, will be needed.

8.6 Communicating with farmers

The preceding discussion highlighted the need for communicating information on disease, vectors and control to farmers, as well as building institutions for collective action - although in practice the two activities will be interconnected. It is essential to invest in 'human capital' through education and training of farmers, as well as their social capital through institutional strengthening for successful integrated tsetse- and tick-borne disease control.

Extension services would formerly have played an important role in such communication, but in most African countries, public systems of extension have withered under the
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inability of governments to fund them. Besides, there has in many cases been a problem in the collaboration of extension services centred around the needs of arable crop farmers, and veterinary services centred around curative veterinary medicine (Morton et al., 1996).

New institutional models for extension in Africa have yet to emerge. For the time being, much communication with farmers may have to be done "vertically", by particular projects. But certain general principles apply.

The last 30 years have seen a shift in communication methods in rural community development. It has gone from being a one-way process of knowledge and/or information transfer through extension workers to farmers, to a two-way interactive social process which starts with farmers and brings together both groups as equal partners – in short, participatory communication (Coldevin, 2001).

There is a new farmer-oriented extension science (see Röling, 1988), which is about awareness raising, knowledge acquisition, attitude change, confidence building, participation in decision-making, and action. If used carefully and strategically as a tool, extension can enhance the delivery of technologies and services targeted at integrated disease control.

Education and training of stakeholders is imperative if livestock productivity under enzootic vector-borne disease challenge is to improve. Information transfer of integrated tsetse and tick-borne diseases to grass roots level can achieve this by empowering stakeholders with principles that they can apply within their own context to any situation that may arise.

An understanding of the farmers’ motivating factor to learn is a key to whether or not they will attend a training/awareness campaign or accept/adopt the extension message(s). Adults are voluntary learners who perform best when they have decided to attend a training/awareness campaign for a particular reason. They need to know why a topic is important to them. A non-formal education set-up would be a suitable form of systematic teaching outside the formal system for farmers. Farmers are best taught with a real-world approach, and they learn best when it is clear that the context of the training is closer to their own tasks and production objectives (van den Ban and Hawkins, 1988).

In view of this, information transfer to farmers should be based on teaching through discussion, practical demonstration and participation. Farmers have experience and can help each other to learn, and this sharing of experiences should be encouraged. They do
not require definitive and ready-to-use solutions, but principles, ideas and suggestions that can be tested in their own specific situation. The knowledge supporting sustainable agriculture is locally specific knowledge with which farmers can themselves experiment. With these views in mind, one can argue that it is necessary to provide appropriate information for integrated vector-borne disease control based on current understanding of epidemiology, and incorporate farmers’ know-how and their socio-economic constraints.

Training should not only be for the livestock producers but also for the extension workers who form the link between researchers and producers. Wadsworth’s study (1994) with Costa Rican farmers showed that adoption of technologies increased when information bulletins distributed to farmers were combined with dialogue between extension workers and client farmers. Attitudes of extension workers towards farmers should not be that of teacher, but that of partner working at overcoming the same problem.

8.6.1 Uptake pathways for integrated tsetse- and tick-borne diseases control technologies and information

An understanding of farmers’ information networks is required when attempting to form linkages between them and researchers (FAO, 2000, Coldevin, 2001, Garforth, 2001). Farmer Field Schools (FAO), Farm Field Days, Group extension, school-based campaigns, community meetings, community-based organisations, clinics and health centres and Religious Organisations all offer strategic opportunities for information dissemination in rural communities. Bauer and Snow (1998) suggest training for key representatives of stakeholder groups such as farmers' associations using visual aids or leaflets explaining the proper use and dosage of drugs thus increasing their technical competence.

Because a large proportion of farmers are illiterate or semi-literate, appropriate communication techniques and channels will need to be employed to transfer information on vector-borne disease control to them. Communication tools such as print, audio, television/video, folklore and interpersonal communication can be used as media for message dissemination. Combinations of these tools can act as communication strategies in multi-media campaigns to support group meetings conducted by extension workers to aid and strengthen interpersonal communication. Use of audience-oriented communication strategies has been known to play a role in accelerating the rate of technology transfer through providing relevant information, changing negative attitudes, and skills training (Coldevin, 2001).
8.6.2 Some Examples of Communication in Animal Disease Control

The helminthology OVI group of NARP II produced a technical manual targeted at stakeholders and containing the important extension messages resulting from research conducted under NARPs I and II (Bain, 1999). A recent DFID/KARI project used a comic book (KARI/DFID, 1998) to test the efficacy of targeting schoolchildren as a means to convey extension messages to parents about husbandry of smallholder dairy cattle. Initial results from impact analysis showed this had achieved a 30% unprompted recall rate and a 10% knowledge conversion rate (Bain, NARP II DFID/KARI). These approaches are well known in major animal disease control programmes. For instance the PARC/VAC rinderpest campaign used communication tools as strategies for controlling and eradicating the disease (Villet, 1998).

8.6.3 Animal health messaging for a sustainable integrated approach to controlling vector-borne diseases of livestock in Africa

The farmers’ holistic approach to disease management is well suited to integrated vector-borne disease control, although much of their knowledge and practices are not adequate for complex disease management. It is imperative that appropriate information is provided to the farmers to improve the quality of animal health services by enhancing their current knowledge and practices. For effective control, vector-borne diseases require immediate and appropriate treatment to avoid losses of livestock through debility from prolonged illness and death. Below is a list of key messages targeted at primary animal healthcare providers, including farmers, who are faced with several of these vector-borne diseases.

- Raise awareness of disease transmission to enhance farmers’ understanding of preventive measures.
- Enhance diagnostic skills by pointing out how to look for key clinical signs; some useful clinical signs are missed by not conducting a thorough physical examination.
- Enhance differential diagnostic skills. Given that most vector-borne diseases have no pathognomonic signs and also share some similar clinical signs, it is essential to provide primary animal healthcare providers including farmers with information packages that highlight the similarities and differences.
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- Raise awareness of drug specificity and efficacy to avoid misuse, underuse or overuse of drugs.
- Provide information on how to use medicines appropriately.
- Provide information on the differences between vaccinations and treatments for farmers to have an informed choice of disease control strategies on their farms and communities.
- Provide area-specific vector-borne disease control strategies: The prevention and control of tick-borne diseases is very complex and varies in different areas. Farmers must be encouraged to consult their nearest animal health worker(s) for advice about disease management strategies in their area. The importance of local advice means that frontline animal health personnel should be provided with this information as well as the farmers. Local strategies might include:
  - Use of insecticides for protection against both tsetse flies and ticks
  - Exposure of animals to the vectors at a young age so that they can develop natural immunity in areas where the diseases occur
  - Strategic tick control is it prevents them from becoming a nuisance, but allows enough ticks to remain for infection to occur at an early age and, thus, animals become protected against the diseases
  - Use of vaccines (heartwater vaccine is live and should not be used in pregnant animals)
  - Strategic use of isometamidium for trypanosomiasis where cases are common at certain times of the year or season; routine use of isometamidium should be avoided to prevent/delay drug-resistance
  - Use of indigenous breeds of animals as they have some natural immunity to vector-borne diseases
- Encourage farmer-to-animal health practitioner and farmer-to-farmer interactions – this will facilitate diffusion of sound disease management practices.
- Encourage farmers to keep livestock health and production records to monitor productivity and emerging health problems.
- Encourage good husbandry practices – good animal nutrition helps animals fight off infections, and if animals become infected, they have a better chance of recovering from the infection.

Providing farmers and their primary animal healthcare providers with a wide range of strategies is necessary for sustainable integrated vector-borne disease control. This has another advantage in that it offers farmers with a choice of control strategies that they
can use to suit their diverse socio-economic and environmental circumstances. In order to have sustainable agriculture and extension, Garforth (1993) suggests that the technical content of extension advice and information needs to be complex to match the complexity of the productivity and environmental problems facing farmers.
9 CONCLUSIONS AND RECOMMENDATIONS

A recurrent theme in this report has been the impact of institutional change on animal health and production. The transition from public to private provision of healthcare for African livestock has been especially marked for poorer livestock owners who benefited from government provision of therapeutic drugs and vector control. The shift from public to private provision has been accompanied by a decline in investment for the control of vector-borne diseases and a shorter-term view of disease management; the large-scale government- and donor-funded vector control operations of the 1970s and 80s having all but disappeared. And even while African organisations such as PATEC discuss the merits of area-wide approaches to vector control, there is little support – financial or technical - for such an approach by African governments or donors. The general decline in government and donor funding for animal health has also had an impact on research and, with the possible exception of recent initiatives to develop vaccines for tick-borne diseases, there seems little likelihood of there being any radical improvement in the technologies available in the near future.

Against this background, livestock owners attempting to control vector-borne diseases are left with a small range of technical solutions, many of which were originally developed with a view to being used in government-supported control operations. This difference between the original and actual mode of operation means that either the technology is completely inappropriate for most communities and/or there is scant information on how to use the technology effectively. To add to these woes, livestock farmers are also faced with technically evermore-challenging problems as the vectors and/or parasites evolve resistance to acaricides and drugs, thereby blunting the few tools that are available. Thus there is an urgent need for robust approaches to disease control that are financially, technically, socially and environmentally acceptable.

While the preceding paragraphs paint a bleak picture, this report provides ample evidence that effective community-based strategies can – and are – being used to control vector-borne diseases. Moreover, several of the strategies selected by livestock keepers themselves are generally effective against several vectors and/or pathogens and thus the cost and benefits of the interventions are improved. The uptake of technologies such as treating cattle with pyrethroids and anti-parasitic drugs is due to the perceived private nature of their benefits, their ease of use, their apparent efficacy and their relatively low financial and logistical cost. These farmer-selected interventions are generally combined
with livestock systems based on indigenous breeds of cattle that are innately less susceptible to vector-borne diseases.

However, while the technology of using, say, pyrethroid-treated cattle to control tsetse or natural immunity to control tick-borne diseases looks simple, the report provides ample evidence that the natural processes underlying this technology are complex. This complexity means that farmers and rural communities are not able to readily discern best-bet solutions. Indeed, the counterintuitive nature of some of the processes, means that empirical approaches might actually worsen a local disease situation irrevocably. Consequently, if communities are to use these integrated approaches to control vector-borne diseases, the processes need to be adequately and appropriately explained. Having said that, this review has also highlighted a number of factors where there is a fundamental lack of basic knowledge, especially with regard to the processes underlying enzootic stability. Thus if a robust approach to vector-borne diseases is to be developed there is a need to increase, synthesise and disseminate knowledge.

### 9.1 Basic questions

General expressions about the merits of using enzootic stability to manage tick-borne diseases tend to ignore the important point that TBDs are a complex of diseases and that the relative likelihood of enzootic stability occurring varies between them. Enzootic stability for *Anaplasma* and *B. bigemina* appears to be widespread and very common whereas it is very rare – if it exists at all - for *T. parva*. For *Cowdria ruminatum*, opinion is divided, but there is an increasing consensus that enzootic stability for this disease does occur. Some of the uncertainties surrounding enzootic stability for ECF and cowdriosis arise because we lack basic knowledge of the immunological processes surrounding the diseases. In the case of cowdriosis for instance, there are important questions concerning: the role of vertical transmission, maternal immunity and interactions between ticks and calves. For ECF, areas of apparent enzootic stability, where the incidence of clinical disease is much less than that of infection, may actually reflect an effect caused by the low infectious dose of pathogen delivered when a tick bites. Basic research aimed at establishing if, and how, enzootic stability is established for cowdriosis and, for ECF, the extent and mechanisms of age-immunity and the ‘quantum’ effect of infection is clearly needed.

Such basic knowledge would of course contribute towards understanding whether the use of pyrethroids can affect enzootic stability. However, it is striking that, to date, there is
no unequivocal evidence that the use of pyrethroids to control tsetse has exacerbated the incidence of tick-borne diseases. There is evidence that this can happen, for babesiosis for instance, and thus empirical evidence of the impact of pyrethroids on tick populations and levels of infection are also required. There are many tsetse control operations currently being undertaken in areas where one or more of the tick-borne diseases are likely to be enzootically stable. Many of these operations would provide excellent opportunities for assessing their impact on tick-borne disease.

While establishing that tsetse control has a deleterious effect on all tick-borne diseases has not been firmly established, there is a priori evidence that it can. Equally there is good evidence that this effect could be ameliorated by application of pyrethroids to selected hosts and/or parts of hosts. Selective application would also provide significant financial and environmental benefits to the users and thus seems to be a particularly profitable area for research. It is striking that various tick research initiatives in west Africa have considered the use of selective treatment of cattle for tick control whereas the same approach is being considered for tsetse control in southern Africa. The development of an integrated approach might therefore benefit from contact and possibly collaboration between these groups.

### 9.2 Synthesis

While there are several outstanding basic questions regarding enzootic stability, there is much that we do know, especially regarding the population biology of vectors. This knowledge needs to be synthesized to allow the development of a comprehensive framework to investigate and evaluate integrated approaches to disease control. To achieve this synthesis, there is a need to overcome some of the institutional and academic hurdles that hinder collaboration between specialists concerned with ticks, tsetse and the diseases they transmit. In this regard, the impetus provided recently by the joint meetings of tick and tsetse workers should be further exploited to promote joined-up research and control.

### 9.3 Dissemination and institutional strengthening

It seems certain that Africa’s farmers will continue to be largely responsible for funding and implementing any interventions to control tick and tsetse-borne diseases. Accordingly, they need to be informed of appropriate strategies to allow them to make rational decisions. The case of trypanosomiasis and tick-borne diseases are especially
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difficult in this regard because the epidemiological processes are not intuitively and/or empirically obvious. Consequently, there is much evidence that farmers are already using many of the components of integrated vector control inappropriately because they are not sufficiently aware of how the technology controls disease. Thus the main priority must be to disseminate appropriate knowledge to farmers.

NGOs and community-based organisations can play an important role in this dissemination. Moreover, in practice these organisations play a key role in initiating vector control activities. There is evidence that some of the inappropriate vector control operations undertaken in recent years were due to misguided advice from local NGOs. Consequently, it is important that NGOs are also fully informed of best practice regarding disease and vector control. In particular, we suggest that NGOs should be informed of the rationale underlying the various interventions so that they are in a position to explain why, for instance, difficult issues such as collective action for tsetse control is *sine qua non*.

Despite the declining role of governments and donors in the practice of vector disease management, we suggest that there are areas where they still have an important role to play. First, they need to provide a suitable market environment to allow farmers and their communities to obtain appropriate drugs and chemicals at reasonable prices. This is not always the case; in Ethiopia for instance, pyrethroids for tsetse control are generally overpriced and not widely available. Second, they need to provide appropriate guidance and legislation to delay the development of resistance to drugs and pyrethroids.
10 APPENDIX I

10.1 Mathematical basis of the simple model used for comparing the possible effects on insecticide treatment of cattle on trypanosomiasis and tick borne diseases

10.1.1 Basic model – Tick borne diseases

The force of infection, $\lambda$, is the per capita rate at which susceptible individuals acquire infection which we assume to be age independent. The reciprocal of the force of infection, $1/\lambda$, is the average of age at infection. We assume that first infection results in life long immunity to re-infection. Therefore, if $\lambda$ remains constant through time, an endemic situation will arise in which the proportion of individuals of aged $a$ that are susceptible to infection, $S_a$, is given by the simple expression

$$S_a = \exp(-\lambda a).$$

(equation 1)

The probability of infection in a susceptible individual of age $a$ resulting in clinical disease is $P_a$. We describe $P_a$ using a logistic function logistic function (that is bound between 0 and 1), taking the form

$$P_a = C \left[ \frac{1}{1 + \exp(\alpha + \beta a)} \right].$$

(equation 2)

where $\alpha$, $\beta$ and $C$ are constants. The maximum probability of clinical disease following infection is $C$ and occurs in the oldest susceptible individuals ($a>>0$). The minimum probability of clinical disease resulting from first infection occurs is in the youngest individuals (when $a=0$) and is given by $C[1+\exp(-\alpha)]$. 
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For a given $\lambda$ the per capita rate at which susceptible individuals aged $a$ acquire disease is the product of $\lambda$ and the probability that infection at age $a$ causes disease, $P_a$. If we then multiply the proportion aged $a$ susceptible to disease, $S_a$, by the per capita rate at which susceptible individuals acquire disease, $\lambda P_a$, we can derive an expression for the age-specific per capita clinical disease incidence, $I_a$, which is

$$I_a = \lambda P_a S_a.$$  \hspace{1cm} \text{(equation 3)}

For a given $\lambda$, the over population level of clinical disease incidence, $D$, is calculated as the sum, across all ages, of $I_a$ weighted by the proportion, $N$, of the population aged $a$. Thus, if $a_1$ and $a_2$ (where $a_2 > a_1$) are the age range of susceptibility to disease, then

$$D = \int_{a=a_1}^{a=a_2} I_a N_a \, da.$$  \hspace{1cm} \text{(equation 4)}

The demography of the cattle population, described by $N_a$, is modelled assuming a age-independent death, $\mu$, such that the average life expectancy is $1/\mu$.

The model predicted variation in $D$ with respect to $\lambda$ (varied between 0.0001 per year 1 peer year) are shown in Figure 4 and Figure 6, Section 6, for model parameter values $\alpha=-4.1$, $\beta=1$, $C=0.6$, $a_1=0$, $a_2=10$ years and $1/\mu=5$ years. The values of $\alpha$ and $C$ correspond to a minimum value of $P_0=0.01$.

10.1.2 Basic model – Trypanosomiasis

The assumptions of the model were adapted to describe changes in the clinical incidence of trypanosomiasis in a cattle population, $D$, with variations in $\lambda$. We assumed that following trypanosome infection effective immunity is lost at rate $r$, such that $1/r$ is equal to the average duration of immunity. Following loss of immunity the individual was assumed to be fully susceptible. If $\lambda$ and $r$ remain constant through time then the proportion of individuals aged $a$ that are susceptible to disease, $S_a$, is given by Dye & Williams 1993 as

$$S_a = 1 - \left[ \frac{\lambda}{\lambda + r} \left( 1 - \exp(- (\lambda + r)a) \right) \right].$$  \hspace{1cm} \text{(equation 6)}

We further assumed that the probability of infection in a susceptible resulting in clinical disease was age independent, such that $P_r=p$ where $p$ is constant.
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With these modified assumptions, we can use equation 3 and 4 described above to describe how $D$ varies with $\lambda$, as shown in Figure 5 and Figure 6, Section 6, with parameter values $a_1=0$, $a_2=10$ years, $1/r=0.25$ years and $p=0.02$.

10.1.3 Adapting the model to the complexities of tick borne diseases

In all the following adaptations to the basic model of tick borne diseases, $a_1=0$, $a_2=10$ years and $1/\mu=5$ years.

The effects of the underlying relationship between age and innate susceptibility to disease are illustrated in Figure 7a and b. The parameters values for the more virulent "parasite 1" were set at $\alpha=-1.6$, $\beta=1$ and $C=0.9$ (with the values of $\alpha$ and $C$ corresponding to a minimum value of $P^0=0.15$). In contrast, the parameter values for the less virulent "parasite 2" were $\alpha=-4.1$, $\beta=0.25$ and $C=0.6$ (with the values of $\alpha$ and $C$ corresponding to a minimum value of $P^0=0.01$).

The effect of waning immunity, shown in Figure 8, was investigated by introducing a recovery rate, $r$, from immunity to susceptibility in "parasite 1", while assuming life-long immunity in "parasite 2". For "parasite 1" we set $1/r=7.5$ years, while all other parameters values for "parasite 1" and "parasite 2" were the same, with $\alpha=-4.1$, $\beta=0.25$ and $C=0.6$ (with the values of $\alpha$ and $C$ are corresponding to a minimum value of $P^0=0.01$).

To investigate the impact of inoculating dose in T. parva epidemiology, we first relaxed the assumption of age-dependent susceptibility to diseases by changing the logistic function of $P_a$ to a constant $p$ and looked at the relationship between population sero-prevalence and clinical disease incidence. We set $p=0.01$ so that the probability of any infection resulting in severe disease was 0.01 regardless of age. We calculate the overall, equilibrium cross sero-prevalence, across all ages, in the population for each value of $\lambda$ from 0.0001 to 10. This is calculated as

$$\int_{a_1}^{a_2} N_a [1 - \exp(-\lambda a)].$$

In Figure 10a and b, we again assumed that cattle in “population 1” were exposed to infected ticks that transmit an average inoculating dose that is significantly higher than the average inoculating dose transmitted to cattle “population 2”, but reintroduced an age-dependent variation in age and clinical disease probability. The effect of the higher inoculating dose is that for each age, $a$, the probability of infection resulting in disease is
twice as high for “population 1” than “population 2”. The parameter values for “population 1” were $\alpha=-0.29$, $\beta=0.25$ and $C=0.7$, with the values of $\alpha$ and $C$ corresponding to a minimum value of $R_0=0.3$, and “population 2” were $\alpha=-0.29$, $\beta=0.25$ and $C=0.175$, with the values of $\alpha$ and $C$ corresponding to a minimum value of $R_0=0.075$. 
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