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ABSTRACT

The ability of parasites to change the behavior of infected hosts has been documented and reviewed by a number of different authors (Holmes and Bethel, 1972; Moore, 1984a). This review attempts to quantify the population dynamic consequences of this behavior by developing simple mathematical models for the most frequently recorded of such parasite life cycles. Although changes in the behavior of infected hosts do occur for pathogens with direct life cycles, they are most commonly recorded in the intermediate hosts of parasites with complex life cycles. All the changes in host behavior serve to increase rates of transmission of the parasites between hosts. In the simplest case the changes in behavior increase rates of contact between infected and susceptible conspecific hosts, whereas in the more complex cases fairly sophisticated manipulations of the host's behavioral repertory are achieved.

Three topics are dealt with in some detail: (1) the behavior of the insect vectors of such diseases as malaria and trypanosomiasis; (2) the intermediate hosts of helminths whose behavior is affected in such a way as to make them more susceptible to predation by the definitive host in the life cycle; and (3) the behavior and fecundity of molluscs infected with asexually reproducing parasitic flatworms. In each case an expression is derived for R_0, the basic reproductive rate of the parasite when first introduced into the population. This is used to determine the threshold numbers of definitive and intermediate hosts needed to maintain a population of the pathogen. In all cases, parasite-induced changes in host behavior tend to increase R_0 and reduce the threshold number of hosts required to sustain the infection.

The population dynamics of the interaction between parasites and their hosts are then explored using phase plane analyses. This suggests that both the parasite and intermediate host populations may show oscillatory patterns of abundance. When the density of the latter is low, parasite-induced changes in host behavior increase this tendency to oscillate. When intermediate host population densities are high, parasite population density is determined principally by interactions between the parasites and their definitive hosts, and changes in the behavior of intermediate hosts are less important in determining parasite density.

Analysis of these models also suggests that both asexual reproduction of the parasite within a host and parasite-induced reduction in host fecundity may be stabilizing mechanisms when they

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occur in the intermediate hosts of parasite species with indirect life cycles. This contrasts with the case for a direct life cycle parasite where parasite-induced reductions in host fecundity and asexual reproduction are always destabilizing. The consequences of these different patterns of dynamic interaction are discussed in terms of the evolution of complex life cycles in parasitic helminths and the intensity with which modification of host behavior should be expressed in different habitats. Although the available data tend to support the conclusions of the models, the whole area would benefit considerably from further detailed field studies of specific parasite-host systems.

INTRODUCTION

THE PHYSIOLOGICAL interactions between parasites and their hosts often lead to changes in the behavior of infected animals. These changes are usually beneficial to the pathogen and often detrimental to the host. The induced changes in host behavior have the effect of increasing the rate of parasite transmission. The mechanisms used to achieve this effect either directly or indirectly influence the host's survival, and occasionally they also affect its fecundity. Thus a conflict of interest is established between the parasite and its host which has significant effects on both ecological and evolutionary time scales. Although many previous workers have considered the importance of predation and competition as factors influencing both the individual and social behavior of different animal species, only a few studies have considered pathogens in this way (Holmes and Bethel, 1972; Smith-Trail, 1980; Rau, 1982; Moore, 1984a).

In this paper I briefly review the published literature on parasite-induced changes in host behavior and then describe some simple mathematical models that allow an examination of the demographic and evolutionary consequences. I will concentrate on three well-documented situations where the action of pathogens leads to readily quantifiable changes in the behavior of infected individuals. In each case the demographic consequences of these actions are explored using mathematical models that allow one to determine how changes in the behavior of individual hosts affect both the net reproductive success of the parasite and the population dynamics of the parasite-host interaction.

CLASSIFICATION OF PARASITE LIFE-CYCLES

Parasites and pathogens are now recognized as important factors in determining both the density and long-term population dynamics of many animal populations (Anderson and May, 1978, 1979). These authors have suggested that parasites and pathogens can be divided into two broad classes: the microparasites and the macroparasites. The former includes the viruses, bacteria and protozoa, the latter the helminths and other metazoan parasites. Epidemiologically, the major difference is the response of the host to the presence of the pathogen. Microparasites are characterized by their ability to produce a sustained immunological response in the host that effectively divides the host population into susceptible, infected, and immune classes. Macroparasites, in contrast, tend not to produce a sustained immunological response, and mathematical models of their dynamics have to consider the frequency distribution of individual parasite burdens throughout the host population.

Further subdivisions of these two general classes of pathogens may be made depending upon whether they utilize an intermediate host species to facilitate transmission from one definitive host to the next. I will refer here to life cycles where transmission occurs directly from one definitive host to the next as direct life cycles (DLC). This will contrast with life cycles with transmission via one or more species of intermediate host; I will refer to such systems as indirect life cycles (ILC). Many of the best-documented examples of parasite-induced changes in host behavior occur in parasites with indirect life cycles.

Parasite-induced changes in host behavior may be divided into two broad classes: (1) changes that increase or even initiate the transmission of the parasite to another member of the same host species; and (2) changes that increase the transmission of the parasite to a different species of host. The first class is confined to parasites with a direct life cycle, where the pathogen may be spread by one infected individual to many susceptible individuals, with each successful infection usually initiating a complete new cycle of pathogen development in all the newly infected hosts. These

sequence of simple, transient, behavioral events that continue until the original infected individual either dies or recovers and becomes immune.

In contrast, in indirect life cycles, where parasite transmission is between species, the two hosts are usually on different trophic levels and are used in an obligatory sequence by the parasite in order to complete different developmental stages of the same complex life cycle. Here we may differentiate between three classes of indirect life cycles. In the two most common cases the two hosts are linked by some form of predator-prey relationship. Here different classes of transmission may be identified depending on whether the attack concludes with the death and consumption of the infected host. In one class the infected host's blood is fed upon by a much smaller "predatory" species, usually an insect (Waage, 1979; Molyneux and Jefferies, 1986). This vector species then goes on to infect other susceptible individuals by transmitting the pathogen at subsequent blood meals. I shall abbreviate this type of life cycle as ILCV (V for vector). The second subdivision consists of cases where the predator and prey organisms are of similar size or the predator is larger. Here successful transmission leads to the death of the prey host and an increase in the parasite burden of the individual predator host (Holmes and Bethel, 1972; Moore, 1984b); these I shall designate as ILCPP (PP for predator-prey). In both cases transmission usually occurs as a single complex behavioral event, initiated by the recipient of the pathogen (the predator). The primary changes in behavior, however, occur in the infected prey, once initiated by the parasite, and they occur continuously until the host's recovery or its death.

The first two types of life cycle (DLC and ILCV) are most common among the microparasites, although several groups of macroparasites may also be included in these classes. The third type (ILCPP) is characteristic of many macroparasites. A fourth class of life cycle incorporates two transmission stages characterized by free-living larvae that actively seek out the next host in the life cycle—e.g., the free-living miracidia and cercaria of digenean helminths. I shall designate this type of life cycle as ILC2FL (2FL for two free-living). Changes in host behavior that increase rates of transmission in this last class are harder to quantify. They usually manifest themselves as more complex physiological changes that increase the host's survival by reducing its fecundity (Minchella, 1985; Sousa, 1983), or as manipulations of the time and position of the host when the free-living stages are released (Wright, 1971; Theron, 1984, 1985).

BEHAVIORAL CHANGES IN SIMPLE DIRECT LIFE CYCLE PARASITES

Epidemiological models of diseases of direct life cycle pathogens consider the infection process to operate on a simple mass-action principle: the number of successful transmissions varies directly with the numbers of infected and susceptible individuals in the host population (Kermack and McKendrick, 1927; Anderson and May, 1979a; May and Anderson, 1979). Changes in host behavior induced by pathogens of this type are usually only documented speculatively. In general, most of these transmission mechanisms involve the release of a behavioral pattern that is performed in a novel context where otherwise it would only rarely be performed in the absence of the pathogen. This primary stimulation to transmission is then complemented by secondary changes in the rates at which other, usually locomotory, activities are performed. The actions and activities of the hosts that can be included in this category range from the temporally ephemeral sneezes and coughs induced by many air-borne viral and bacterial infections, to the increases in levels of activity and aggression observed in canids infected with rabies (Macdonald, 1980), and the increased thirst that occurs in game animals infected with rinderpest (Plowright, 1982). Many of these mechanisms increase the contact rate between infected and susceptible individuals.

Similar examples occur in the DLC macroparasites. When guppies, *Poecilia reticulata*, are infected heavily with the external monogenean parasite *Gyrodactylus bullatarudis*, they become lethargic and their fins often stick together. This results in abnormal swimming behavior which, in turn, attracts the attention of other guppies and increases the number of contacts between infected and uninfected individuals (Scott, 1985). A more complex example might be the pentastomid (Phylum Pentastoma) *Reighardia sternae*, a species that infests

the air sacs of gulls and terns. After an incubation period of 124 days, the gravid females have only 5 to 11 days in which to lay a relatively limited number of eggs. To increase transmission, the female migrates to the nasopharynx of the host, where irritation eventually causes the bird to vomit. The vomit, contaminated with eggs, is ingested by other gulls and thus the female's low potential fecundity is offset by a high transmission efficiency (Banaja, James, and Riley, 1976; Riley, 1983).

Although the mass action principle of transmission is a useful approximation in large homogenously mixing host populations, many individual or social behavioral mechanisms restrict the validity of this assumption. For example, in animals that live in groups the transmission rate between members is much higher than that between members of different groups (Freeland, 1976, 1979). The net rate of transmission within a host population will thus be determined by the social behavior of the host species as well as by its density. Attempts to model the consequences of such behavior are only just commencing for human diseases, such as measles and AIDS (May and Anderson, 1984; Anderson and May, 1986); examples from other than human populations remain restricted to qualitative description.

In animals that live in smaller social groups, such as many ungulates and primates, the within-group transmission rates will vary with group size. Several workers have suggested that pathogens may even provide a constraint on the maximum size of host groups in certain species of animals (Alexander, 1974; Freeland, 1976). Many of the more pathogenic microparasitic diseases of man, such as measles and rubella, require large population sizes if they are to maintain themselves within a host population (Bartlett, 1957; Black, 1966). The comparatively small social groupings that most polygamous species of vertebrates form are usually below the threshold population sizes at which the corresponding pathogenic organisms are able to maintain themselves. These pathogens will thus appear only erratically and will repeatedly go extinct in host populations that are fragmented into small social groups. However, macroparasites with longer-lived free-living stages and with direct transmission from parents to offspring have threshold host population densities that are often very small indeed (May and Anderson, 1979). Species such as bot-flies and ticks can therefore readily establish themselves in small groups of hosts. When this occurs, increases in group size can rapidly lead to a build-up in parasite burdens and considerable reductions in the survival or fecundity of the hosts within the group (Brown, 1985; Hoogland, 1979; Hoogland and Sherman, 1976; Moore, Simberloff, and Freehling, in press). In many species the ultimate determinant of group size is likely to be the distribution of resources used by the females or the ability of males to hold a large harem (Vehrencamp and Bradbury, 1984; Wrangham, 1980). The added cost of the presence of a pathogen, however, may reduce the group size to a value below the level determined by these other considerations.

Where species have complex social organizations and live in very large groups, they are highly susceptible to the accidental introductions of novel pathogens. Thus the more pathogenic microparasitic diseases tend to occur when animals are present at enormous population densities—e.g., rinderpest in the game herds of the Serengeti (Plowright, 1982), myxomatosis in rabbits (Fenner and Myers, 1978), or viral and bacterial diseases in seabird and duck colonies (Duffy, 1983; Smith, 1982). Although factors such as foraging and resource constraints again are likely ultimately to determine the size of the groups in which animals such as wildebeest (*Connochaetes taurinus*) live, such diseases as rinderpest may have a considerable impact on the density and genetic structure of the population. These effects may be felt for many years after the initial pandemic has died away (Ross, 1982; Sinclair, 1977; Sinclair and Norton-Griffiths, 1979).

PARASITE-INDUCED CHANGES IN THE BEHAVIOR OF INSECT VECTORS

Parasites and pathogens with complex life cycles usually provide the best examples of parasite-induced changes in host behavior. Let us first consider some examples for microparasites, particularly those species that utilize insects as transmission vectors (ILCV) [Molyneux and Jefferies (1986) have comprehensively reviewed this subject]. In the majority of cases the pathogens increase the rate at which infected insect vectors attempt to take blood meals from their vertebrate hosts. In some cases fairly sophisticated mechanisms appear to be operating: Jenni, Molyneux, Livesey and Galun (1980) illustrate how the build-up of parasites of *Trypanosoma brucei* and *T. congolense* in the proboscis of infected tsetse flies, *Glossina m. morsitans*, can reduce the rates of blood-flow by a factor of almost ten. Infected individuals are unlikely to be able to detect this reduced flow as the parasites entwine themselves around the mechanoreceptors in the labrum and impair the ability of the sensilla to monitor flow rates. Laboratory experiments suggest that infected individuals probe for blood meals but usually fail to engorge; by moving on and attempting to feed elsewhere they raise the rates of transmission by a factor of about three (Molyneux and Jenni, 1981). Similar mechanisms have been reported to operate in *Leishmania* infections of sandflies *Lutzomyia longipalpis* (Killick-Kendrick, Leaney, Ready, and Molyneux, 1977; Beach, Kiilu, and Leeuwenburg, 1985); with malaria (Rossignol, Ribeiro, and Spielman, 1984; Ribeiro, Rossignol, and Spielman, 1985) and plague (Bacot and Martin, 1914), related mechanisms have been suggested that also change the rates of biting by the insect vectors.

Several recent studies also suggest that changes in the behavior of infected vertebrate hosts increase their susceptibility to being bitten by the insects that act as transmission vectors (Day and Edman, 1983; Ewald, 1983; Rossignol et al., 1985). In a study of lambs infected with Rift Valley Fever virus, infected individuals were fed on more frequently by mosquitos than were uninfected lambs. The frequency of mosquito attacks was also positively correlated with the body temperature of the infected lambs (Turrell et al., 1984). A recent paper by Kingsolver (1987) elegantly describes the dynamic consequences of these preferences for particular hosts on the part of biting vectors.

POPULATION DYNAMIC CONSEQUENCES OF ALTERED VECTOR BEHAVIOR

Although the actual mechanisms involved may vary in different host-parasite systems, the population dynamic consequences of changes in vector behavior may be examined by means of a simple adaptation of the Ross-Macdonald model for malaria (Ross, 1911; Macdonald, 1952; Aron and May, 1982). The model captures the basic features of the interaction between an infected human population and an infected insect vector population by considering changes in the *proportion* of insects and humans infected in each population:

$$dx/dt = a(abM/N)y(1-x) - rx \quad (1)$$

$$dy/dt = ax(1-y) - \mu y. \quad (2)$$

The parameters of the model are defined in Fig. 1, where the life cycle being modelled is also schematically represented. The first equation describes changes in x, the proportion of human hosts infected; the second equation describes changes in y, the proportion of insects infected. If we assume that the parasite is able to alter either the biting rate of infected insects, a, or the proportion of bites by infected individuals that produce an infection, b, then parasite-induced changes in vector behavior may be included as a factor α in Eq. 1. When the parasite has no effect on the insect vector, α equals unity; values greater than this indicate increases in either the biting rate of infected insects or an increase in the proportion of bites that give rise to infections. Although the model is a gross simplification (see Aron and May, 1982; Nedelman, 1985), it allows one to examine the consequences of parasite-induced changes in host behavior common to many of the different pathogens with life cycles of this type.

An expression can readily be obtained for R_0, the "basic reproductive rate" of the parasite (Aron and May, 1982). This is essentially the number of secondary cases of infection generated by the introduction of a single infective individual human into a population of susceptible ones. The parameter is directly analogous to the "net reproductive value" first derived by Fisher (1930). For the simple model described above we obtain

$$R_0 = \alpha m a^2 b/\mu r \quad (3)$$

where $m = M/N$, the ratio of insect vectors (M) to definitive hosts (N). This very simple result suggests that increasing α leads to direct increases in the basic reproductive rate of the parasite. As R_0 has to be greater than unity for the parasite to establish itself in the host population, we may use Eq. 3 to determine expressions for the threshold number of hosts required to allow the disease to become established in the host population. First let us

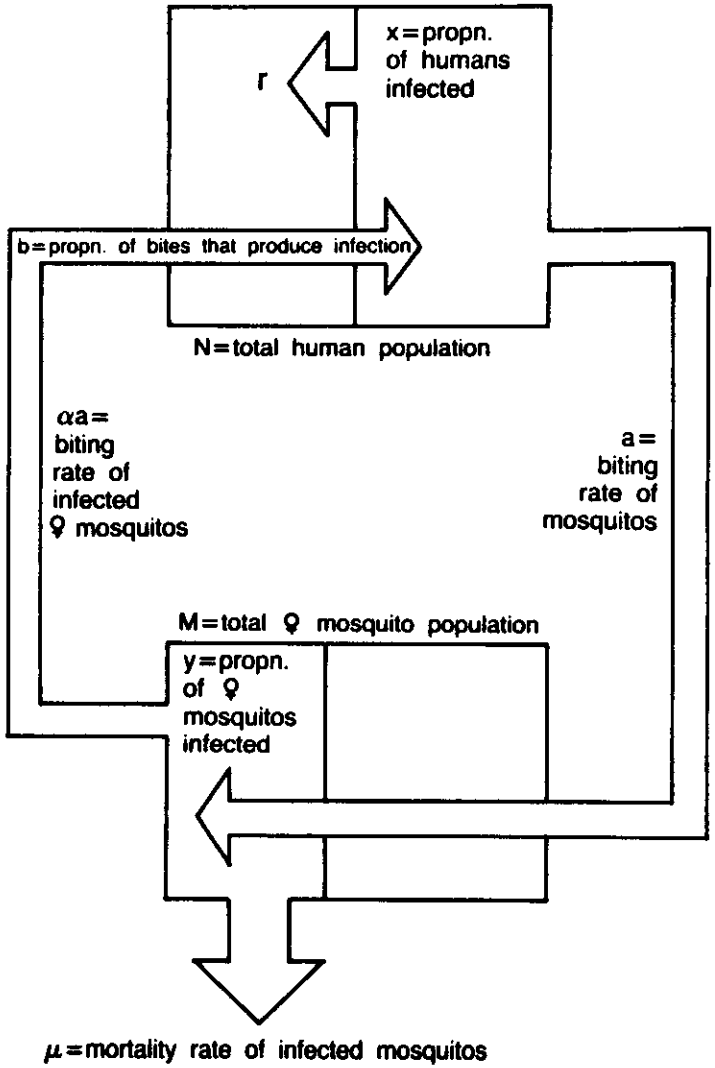

FIG. 1. FLOW CHART FOR THE LIFE CYCLE OF A HYPOTHETICAL "MALARIA-TYPE" PARASITE TRANSMITTED BY AN INSECT VECTOR

There are essentially two populations: the proportion of humans infected (x) and the proportion of female mosquitos infected (y). Other parameters included in the model are the sizes of the human and mosquito populations (N and M, respectively), the biting rate of mosquitos (a), the proportion of bites that produce an infection in humans (b), the mortality rate of infected mosquitos (μ), and the recovery rate of infected humans (r). Changes in behavior are assumed to enter linearly and affect either a or b.

consider the threshold number of insect vectors (M_T):

$$M_T = \mu r N/\alpha a^2 b. \quad (4)$$

Here increasing α will lead to a decrease in the size of the insect population required to sustain the pathogen. Thus selection for changes in host behavior will be particularly advantageous in situations where the vector population density is low, for it will allow the parasite to establish itself in populations of hosts it would otherwise be unable to exploit.

In contrast, the threshold density for vertebrate hosts is an *upper* boundary, above which the ability of insects to bite both an infected and an uninfected individual is too low to sustain the infection. In this case the threshold number of hosts (N_T) is given by

$$N_T = \alpha a^2 b M/\mu r. \quad (5)$$

Here parasite-induced increases in the biting rate of the vectors will lead to increases in the size of the population of hosts within which the parasite may maintain itself. Thus in both cases, the parasite's ability to change the behavior of the host is important in determining the size of the community in which it is able to establish itself.

The dynamic consequences of these mechanisms may be briefly explored by considering a graphical analysis of this simple model (Fig. 2). The stability of the system, i.e., its ability to withstand perturbation, is essentially determined by the initial slopes of the zero growth isoclines for x and y (Aron and May, 1982). The single stable equilibrium point occurs when

$$a/\mu > r/\alpha abm. \quad (6)$$

Increasing α tends to increase the stability of the system by widening and deepening the valley in which the stable point lies. It is also interesting to note that small increases in α lead to small changes in the proportion of insects infected but to *large* changes in the proportion of the human hosts infected. This will be particularly important when sudden epidemic outbreaks are likely. This occurs when the values of both slopes are initially low (Fig. 2b), and corresponds to the case termed "unstable malaria" by Macdonald (1952). Here even small changes in the biting rate of infected mosquitos are likely to be very important in determining patterns of epidemic outbreaks.

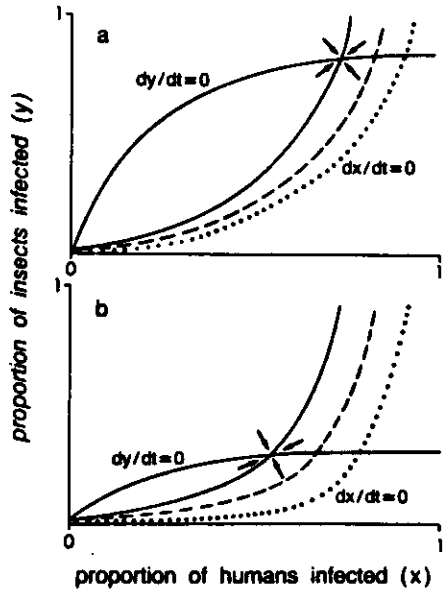

FIG. 2. PHASE PLANE ANALYSES OF THE SIMPLE VECTOR TRANSMITTED PARASITE MODEL

In each case dx/dt = 0 is the zero growth isocline for the proportion of humans infected and dy/dt = 0 is the isocline for the proportion of mosquitos infected. In both graphs the solid isocline for dx/dt indicates the case when α = 1 and the parasite has no effect on the behavior of infected insect vectors. The dashed and dotted isoclines for dx/dt = 0 indicate increasingly larger levels of parasite-induced changes in the behavior of infected mosquitos. The upper diagram illustrates a case where the parasite will be endemic at fairly constant levels, the lower illustrates the case where frequent outbreaks are likely to occur.

One further characteristic of the interaction between microparasites and their insect vectors is worth brief consideration within this crude general framework. The work reviewed by Molyneux and Jefferies (1986) provides some evidence to suggest that parasites can alter the survival rate of infected insect vectors; in some cases the survival rate of infected host individuals increases (e.g., Baker and Robertson, 1957), whereas in other cases it decreases (Hawking and Worms, 1961). The dynamic

TABLE 1

Synopsis of observed data for parasite-induced changes in behavior that affect the host's susceptibility to predation

PHYLUM Parasite Intermediate Host	Site of Infection	Effect on Hosts S	F	M	P	Reference
CESTODA						
Echinococcus granulosus		–	?	–	?	Rau & Caron (1979)
Moose	Lungs					
Ligula intestinalis		– –	?	?	?	van Dobben (1952)
Various Fish	Body cavity	–	– –	0	?	Arme & Wynne Owen (1968)
Hymenolepis diminuta		– –	– –	0	?	Keymer (1980)
Tribolium confusum	Haemocoel	?	– –	?	?	Macma (1986)
H. citelli		– –	?	0	?	Schom, Novak & Evans (1981)
T. confusum	Haemocoel					
Trianophorun nodulosus		–	0	?	?	Lawler (1969)
Perca flavescens	Liver					
Schistocephalus solidus		–	?	– –	?	Lester (1971); McPhail &
Gasterosteus aculeatus	Body cavity	?	–	?	?	Peacock (1983)
Parcterotaenia paradoxa		?	– –	?	?	Burt (1970)
Allolobophora terrestris	Body cavity					
DIGENEA						
Parvatrema affinis		?	?	+ +	?	Swennen (1969); Hulsher
Macoma balthica	Liver & body cavity					(1973)
Diplostomum spathaceum		–	0	+ +	+ +	Crowden & Broom (1980)
Leuciscus leuciscus	Eye					
Nanophyetus salmincola		– –	?	– –	?	Butler & Millemann (1971);
Salmo gairdneri &	Eyes ?					Millemann & Knapp (1970)
Oncorhynchus kisutch	Muscle tissue					
Ornithodiplostomum ptychocheilus		?	?	+	?	Radabaugh (1980)
Pimephales promelas	Brain					
Brachylecithum mosquensis		?	?	– –	?	Carney (1969)
Carpenter ants	Brain					
Uvulifer ambloplitis		– –	?	0	0	Lemly & Esch (1984)
Lepomis macrochirus	Muscle tissue					
Microphallus papillorobustus		?	?	?	+ +	Helluy (1984)
Gammarus spp.	Body cavity					
ACANTHOCEPHALA						
Moniliformis moniliformis		?	?	+ +	+ +	Moore (1983b); Wilson &
Periplaneta americana	Haemocoel	?	?	+ +	?	Edwards (1986)
Acanthocephalus dirus		–	?	+ +	+	Seidenburg (1973); Camp &
Asellus intermedius	Coelom					Huizinga (1979)
A. jacksoni		?	?	+ +	+	Muzzall & Rabalais (1975a,b)
Lirceus lineatus	Coelom					
Corynosoma constrictum		?	?	–	+ +	Bethel & Holmes (1973, 1977)
Hyalella azteca	Coelom					
Pomphorynchus laevis		?	?	+	+ +	Kennedy et al. (1978)
Gammarus pulex	Coelom					
Polymorphus marilis		?	?	?	+ +	Bethel & Holmes (1973)
G. lacustris	Coelom					
P. minutus		?	?	?	+ +	Hindsbo (1972)
G. lacustris	Coelom					
P. paradoxus		?	?	–	+ +	Bethel & Holmes (1973, 1974,
G. lacustris	Coelom					1977)
Plagiorhynchus cylindraceus		?	– –	+ +	0	Moore (1983a)

TABLE 1
(continued)

PHYLUM Parasite Intermediate Host	Site of Infection	Effect on Hosts S	F	M	P	Reference
Sphaerechinorhynchus rotundocapitatus		?	?	0	?	Daniels (1985)
Sphenomorphus quoyii	Body cavity					
NEMATODA						
Trichinella spiralis		–	?	– –	?	Rau (1983b); Rau & Putter
Mice	Muscle					(1984)
Elaphostrongylus rangiferi		– –	– –	?	?	Skorping (1985)
Arianta arbustorum	Body cavity					
Dispharynx nasuta		?	0	0	?	Moore & Lasswell (1986)
Armadillidium vulgare	Coelom					

The data presented in this table are from a variety of published field and laboratory studies. The four variables considered—survival (S), fecundity (F), motility (M), and phototactic response (P) were not examined in all the studies. The symbols +, 0, and –, denote, respectively, positive, neutral or negative changes in these variables. Where these are quantified the symbol – – or + + is used; if the evidence is anecdotal, the symbols used are – or +; ? indicates that this factor was not considered in the experiment.

implications of these changes are apparent if we modify our simple model to include the incubation time of the parasite in its insect host. The resultant expression for the basic reproductive rate of the parasite is again derived by a simple extension of the model given in Aron and May (1982):

$$R_0 = \alpha m a^2 b e^{-\mu\tau}/r\mu \qquad (7)$$

where τ is the incubation period of the infection in the insect host. The most important point to emerge here is that parasite-induced changes in vector survival affect R_0 exponentially; even small reductions in the mortality rate of infected individuals give rise to large increases in the basic reproductive rate of the parasite. This would tend to suggest that strong selection pressure will be exerted on the parasites to minimize their impact on the survival of infected insect vectors, or even to extend the life expectancy of these individuals. Although the experimental results obtained so far are equivocal, the above analysis suggests that this area of vector biology would benefit considerably from further study.

PARASITE-INDUCED CHANGES IN SUSCEPTIBILITY TO PREDATION

We now turn to the macroparasites, which provide some of the best documented examples of parasite-induced changes in host behavior. These occur in the intermediate hosts of many of the indirect life cycle helminths. We will first consider life cycles where transmission is mediated by a predator-prey relationship (ILCPP), and concentrate on behavioral changes that render intermediate hosts more susceptible to predation by definitive hosts. Perhaps the most familiar example of this type of behavior occurs in the snail *Succinea putris*, the tentacles of which become brightly colored and pulsate as a result of infection by the digenean *Leucochloridium paradoxum* (Wesenberg-Lund, 1931). When combined with an increased phototaxis, this pulsating greatly increases the susceptibility of snails to predation. The classic study of van Dobben (1952) succinctly illustrated that roach (*Rutilus rutilus*) parasitized by the plerocercoids of the cestode *Ligula intestinalis* were nearly five times more common in the diets of cormorants (*Phalacrocorax carbo*) than they were in the prey population as a whole. Other examples of increased susceptibility to predation have been recorded in all the major groups of parasitic helminths. Table 1 lists a number of examples and indicates the types of behavior involved. Although the parasite species use a range of different hosts and sites of infection, several fairly clear trends are apparent from this table. In all cases where it has been checked for, the

70 per cent of the parasites were also demonstrated to reduce host fecundity. Changes in motility are less clear-cut; 30 per cent of the studies indicate no difference between infected and uninfected hosts, whereas in 30 per cent of the cases, infected hosts are less motile and in 40 per cent they are more motile. The cestodes always appear to reduce motility, whereas the other groups show no clear trend. Only the acanthocephala and one digenean seem to have the ability to affect the host's phototactic response. Unfortunately, not all variables were examined in each study, so it should be emphasized that the above trends are based on subsets of data where the authors actually made some attempt to monitor the variable of interest.

The authors of several studies also mention that infected hosts behave in a fashion similar to that of uninfected hosts that have either recently engaged in exhausting aerobic physical activity or have been nutritionally stressed (Bailey, 1975; Pascoe and Mattey, 1977; Schall, Bennett, and Putnam, 1982). The former behavior reduces the ability of infected individuals to escape from predators when attacked; the latter often leads to increases in foraging activity. In some cases these nutritionally based alterations in behavior are combined with reversals of the taxic response of the animal to light or gravitational stimuli (Bethel and Holmes, 1973, 1977; Moore, 1983a,b), actions that further increase the probability that an infected animal will be detected and attacked by a predator. As an example, consider Crowden and Broom's (1980) study of Dace infected with the parasitic eye-fluke *Diplostomum spathaceum*. Fish infected with the parasite spend a greater proportion of their time feeding in the better-illuminated surface waters than do their uninfected counterparts. This renders them more susceptible to predation by the fish-eating birds that act as definitive hosts for the parasite. Furthermore, their reduced visual acuity diminishes their ability to locate and capture their food. This leads to further increases in the net amount of time they have to spend feeding to obtain the same amount of food compared to uninfected fish. Similar, but more detailed results have been obtained for this system by Brassard, Rau, and Curtis (1982a,b); workers on other fish-parasite systems, in addition to being more "sluggish" in their behavior, are also often less gregarious and leave the groups that afford them protection against the predators that act as definitive hosts (Dence, 1958; Orr, 1966). In a similar vein, Milinski (1984) observed changes in the foraging behavior of hosts concomitantly parasitized by *Schistocephalus solidus* and *Glugea anomala*. More recent experiments suggest that *S. solidus* alone may be responsible for the greater risks infected fish take when foraging in the presence of predators (Milinski, 1985).

Perhaps the most dramatic examples of parasites changing their host's behavior occur in the invertebrate intermediate hosts of the acanthocephala (Holmes and Bethel, 1972; Moore, 1984a,b). In isopods infected with *Acanthocephalus dirus* and *A. lucii*, the nutritional stressing may be taken a stage further by the fact that the parasite impairs the ability of the host to use its chromatophores as an effective camouflage mechanism (Crompton, 1970; Camp and Huizinga, 1979; Oetinger and Nickol, 1982; Brattey, 1983). Thus while uninfected hosts remain relatively inconspicuous when feeding on a similarly colored substrate, the infected hosts are not only more visible, but their increased locomotory activity when searching for food also renders them more susceptible to predation (Seidenburg, 1973). Similarly, gammarids (*Gammarus lacustris*) infected with *Polymorphus paradoxus* cling to surface vegetation and fail to dive to the bottom when disturbed (Holmes and Bethel, 1972). In a later paper Bethel and Holmes (1974) have further shown that the changes in host behavior do not take place until the parasite has developed to the stage where it is infective to the definitive host. All of these activities considerably increase the parasites' chances of being transmitted to the large variety of aquatic vertebrates that act as definitive hosts (Moore, 1984b).

POPULATION DYNAMIC CONSEQUENCES OF PARASITE-INDUCED INCREASES IN SUSCEPTIBILITY TO PREDATION

Although parasite-induced changes in host behavior that increase rates of predation on infected hosts have been recorded from a variety of different host-parasite systems, studies of the acanthocephala present the best examples for attempting to quantify the effects of

and Holmes, 1973, 1977; Dobson and Keymer, 1985; Moore, 1984b). Most acanthocephalans have two-host indirect life cycles (Fig. 3). In all cases the intermediate host is a prey item in the diet of the definitive host, and all reproduction in the life cycle occurs between the dioecious adults in the vertebrate definitive host. The life cycle of a hypothetical acanthocephalan can thus be modeled by using the following set of coupled differential equations:

$$\frac{dP_2}{dt} = \alpha\rho H_2 H_1\left(\frac{P_1}{H_1} + \left(\frac{P_1}{H_1}\right)^2\right) - \pi P_2 - \delta H_2\left(\frac{P_2}{H_2} + \left(\frac{P_2}{H_2}\right)^2\left(\frac{k+1}{k}\right)\right) \quad (8)$$

$$\frac{dW}{dt} = \lambda P_2 - \gamma W - \eta W H_1 \quad (9)$$

$$\frac{dP_1}{dt} = \eta W H_1 - (\mu + b)P_1 - \alpha\rho H_2 H_1\left(\frac{P_1}{H_1} + \left(\frac{P_1}{H_1}\right)^2\right) \quad (10)$$

$$\frac{dH_1}{dt} = (a-b)H_1 - \rho H_1 H_2 - \alpha\rho H_2 P_1. \quad (11)$$

The definitions of the parameters used in this model are listed in Table 2. The model is derived more formally by Dobson and Keymer (1985). It assumes that the parasite eggs, W, released from the definitive hosts, H_2, are ingested by the intermediate hosts, H_1, at a low constant rate. The intermediate hosts are already items in the definitive host's diet and the presence of the parasites increases their susceptibility to predation by a factor α, per parasite, per intermediate host. The predators attack the prey at a low constant rate, and the effects of satiation are thus ignored. All the regulation of the parasites occurs in the definitive hosts where the parasites are aggregated in a way describable by the negative binomial distribution. The distribution in the intermediate hosts is assumed to be Poisson. The consequences of relaxing these assumptions are discussed in Dobson and Keymer (1985).

To investigate how changes in the parasite's ability to increase the infected intermediate host's susceptibility to predation affect its net life-time reproductive success, we again derive an expression for the basic reproductive rate

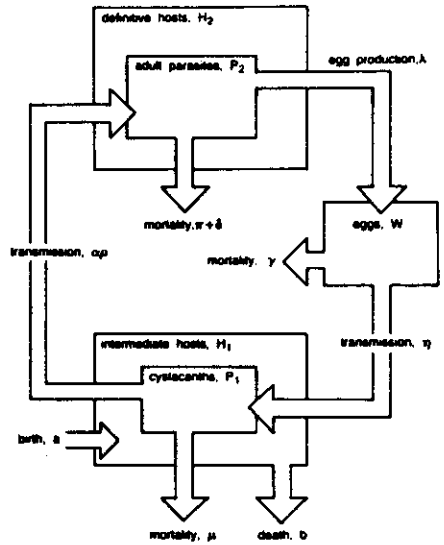

FIG. 3. FLOW CHART FOR THE LIFE CYCLE OF A HYPOTHETICAL ACANTHOCEPHALAN PARASITE
The parameters are as defined in Table 2.

defined as "the average number of female offspring produced throughout the lifetime of a mature female worm, which would achieve reproductive maturity in the next generation in the absence of density-dependent constraints on establishment, survival, or reproduction." If we initially assume that the densities of the definitive and intermediate host populations are constant, then Eqs. 8 to 11 may be collapsed to give a single expression for the basic reproductive rate of the parasite (Anderson, 1982, in press):

$$R_0 = \frac{T_1 \cdot T_2}{M_1 \cdot M_2 \cdot M_3} \quad (12)$$

where $T_1 = \lambda\eta H_1$, $T_2 = \alpha\rho H_2$, $M_1 = (\pi + \delta)$, $M_2 = (b + \mu + \alpha\rho H_2)$ and $M_3 = (\eta H_1 + \gamma)$. The basic reproductive rate is thus the product of the net rates of transmission and reproduction of the parasite, T_1 and T_2, and the expected lifespans of the eggs ($1/M_3$), cystacanths ($1/M_2$) and adult worms ($1/M_1$). The effects of changing the rate at which the parasite increases the intermediate host's susceptibility to predation are illustrated in Fig. 4.

TABLE 2

Notation used for various population rate parameters in the macroparasite models

These are also illustrated diagrammatically in Fig. 3, for a hypothetical acanthocephalan (ILCPP) and in Fig. 6 for a hypothetical digenean (ILC2FL).

Parameter	Description
In Fig. 3	
a	Instantaneous birth rate of intermediate hosts (/host/unit of time)
b	Instantaneous death rate of intermediate host owing to natural causes (/host/unit of time)
α	Increase in rate of predation of definitive hosts on intermediate hosts owing to the presence of the parasite (/parasite)
μ	Instantaneous mortality rate of the parasite in the intermediate host owing to natural causes (/host/unit of time)
ϱ	Instantaneous rate of predation of definitive hosts on uninfected intermediate hosts (/def. hosts · int. hosts/unit of time)
π	Instantaneous mortality rate of the adult parasite in the definitive host owing to natural causes (/host/unit of time)
d	Instantaneous density-dependent death rate of the parasites in their definitive host owing to pathogenicity or competition for space and resources (/host/unit of time)
λ	Instantaneous birth rate of parasite transmission stages where birth results in the production of eggs that pass out of the host (/parasite/unit of time)
γ	Instantaneous mortality rate of the free living eggs (/egg/unit of time)
η	Instantaneous rate of ingestion of the free-living eggs by the intermediate host (/host/unit of time)
H_0	Transmission efficiency constant: the ratio of γ/η, which varies inversely with the proportion of eggs that are successfully ingested by members of the intermediate host population
H_1	The population density of the intermediate host
H_2	The population density of definitive hosts or predators; this is assumed to remain constant
P_1	The population density of parasites in the intermediate host; these stages produce the changes in behavior that affect the susceptibility of the intermediate hosts to predation
P_2	The population density of adult parasites in the definitive hosts
W	The population density of free living eggs
k	A parameter of the negative binomial distribution that measures the degree of aggregation of the parasite within the definitive hosts [occasionally $(k+1)/k$ has been abbreviated to k']
In Fig. 6	
Δ	Instantaneous rate of parasite-induced intermediate host mortality (/parasite/int. host/unit of time)
ϵ	Change in the fecundity and mortality of the parasite owing to the parasite's effect on host fecundity; essentially this parameter alters the intrinsic growth rate of the intermediate host $(a-b)$
Θ	Instantaneous rate of asexual reproduction of the parasite in the intermediate host, where reproduction results in the production of cercaria that pass out of the intermediate host (/parasite/unit of time)
C	The population density of free-living cercaria, the parasite stages that actively seek and infect the definitive hosts
W	The population density of free-living eggs and miracidia, the parasite stages that infect the snail intermediate hosts
γ_1,γ_2	Instantaneous mortality rates of the free-living miracidia and cercaria (per individual/unit of time)
η_1,η_2	Instantaneous rates of infection of the intermediate and definitive hosts by the miracidia and the cercaria respectively (/host/unit of time)

increases in parasite-induced susceptibility to predation produce quite large increases in the basic reproductive rate of the parasite. However, continuous increases eventually lead to diminishing returns as the system becomes restricted by other constraints such as the number of definitive and intermediate hosts available. Empirically, it is worth noting that the values of α observed in natural systems usually range between 2 and 10 (Table 3). These correspond to the model's predicted rates for the greatest increase in the potential lifetime reproductive success of the parasite for ranges of parameter values that correspond to those measured for acanthocephalan popula-

Equations 8 through 11 may also be used to estimate the minimum population sizes of predator and prey necessary if the parasite is to sustain itself in the host population. These thresholds will occur when R_0 is exactly equal to unity:

$$H_{1T} = \frac{\gamma M_1 M_2}{\eta(\lambda T_2 - M_1 M_2)} = \frac{\gamma M_1(b+\mu+\alpha\varrho H_2)}{\eta(\lambda\alpha\varrho H_2 - M_1(b+\mu+\alpha\varrho H_2))} \quad (13)$$

$$H_{2T} = \frac{M_1 M_3(b+\mu)}{\alpha\varrho(T_1 - M_1 M_3)}. \quad (14)$$

These expressions illustrate a further important influence of the parasite-induced changes in host behavior. In both equations any increase in α leads to a decrease in the minimum population size of the host populations required to sustain a constant infection of the parasite. However, changes in α produce much larger changes in the minimum number of definitive hosts required. These hosts are likely to be considerably more motile than the prey species that act as intermediate hosts, and almost certainly utilize more than one prey species from a number of different habitats. It thus seems likely that increases in α will be particularly adaptive in situations where ephemeral predators only occasionally visit the habitat occupied by the intermediate hosts and the parasite. Two effects of this will be that the parasite may colonize smaller habitats than would otherwise be possible and may also invade expanding populations at an earlier stage in their growth.

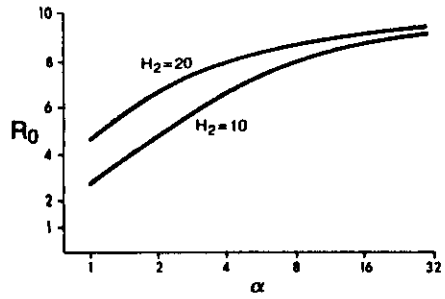

FIG. 4. EFFECT ON THE BASIC REPRODUCTIVE RATE OF THE PARASITE CHANGING THE RATE OF PARASITE-INDUCED SUSCEPTIBILITY TO PREDATION

The two different lines indicate the effect at two different predator/definitive host densities. The other parameters of the model were fixed at values characteristic of acanthocephalan populations monitored in the wild (see Dobson and Keymer, 1985).

Insight into the dynamic behavior of the model may be gained by considering the tem-

TABLE 3

Changes in the susceptibility to predation of infected hosts in a number of different field and laboratory studies

Parasite species	Intermediate host	Definitive host	Ratio of infected/uninfected predated	Ref.
CESTODA				
Ligula intestinalis	*Rutilus rutilus*	Cormorants	4.62	(a)
ACANTHOCEPHALA				
Phlymorphus paradoxus	*Gammarus lacustris*	Ducks	4.14	(b)
Acanthocephalus dirus	*Asellus intermedius*	Creek Chub	1.68	(c)
			7.50	(d)
A. lucii	*A. aquaticus*	Perch	2.42	(e)
Pomphorynchus laevis	*Gammarus pulex*	Chub	3.50	(f)
		Grayling	4.33	
Plagiorhynchus cylindraceus	*Armadillidium vulgare*	Starling	1.62	(g)

The data given in the above table were taken from the following references: (a) van Dobben (1952), (b) Bethel and Holmes (1977), (c, d) Camp and Huizinga (1979), (e) Brattey (1983), (f) Kennedy, Broughton and Hine (1978), and (g) Moore (1983b). In experiment (c) the predation experiments were performed against a light background, whereas in (d) the substrate was darker. As the parasite affects the chromatophores of the host, infected individuals

poral disparities in the rates at which different stages operate and by collapsing Eqs. 8 through 11 into a pair of equations (May and Anderson, 1978, 1979; Dobson and Keymer, 1985). Here it is assumed that the free-living stage of the parasite is relatively short-lived and that infection of intermediate hosts proceeds at a sufficiently rapid rate to be always at equilibrium. The resultant equations describe the dynamics in terms of the population density of the intermediate hosts whose behavior is affected by the presence of the parasite and by the mean parasite burden of adult worms in the definitive hosts N, (where $N = P_2/H_2$):

$$\frac{dH_1}{dt} = H_1\left(r - \varrho H_2 - \frac{\lambda c_1 N H_2}{(H_1 + H_0)}\right) \quad (15)$$

$$\frac{dN}{dt} = N\left(\frac{\lambda H_1(1+n)c_1}{(H_1 + H_0)} - (\pi + \delta) - \delta N k'\right). \quad (16)$$

Here $r = a - b$, $k' = (k+1)/k$, $c_1 = a\varrho H_2/(a + \mu + \varrho H_2(a-1))$ and n, the mean parasite burden of the intermediate hosts, is $(r - \varrho H_2)/a\varrho H_2$. Fig. 5 illustrates the phase plane analysis of the model's behavior. There are two intersections of the zero-growth isoclines, one stable (A) and one unstable (B). The unstable equilibrium, B, determines the position of a boundary that divides two regions of different dynamic behavior. In the region of high intermediate host population density, transmission is proceeding at maximum efficiency; the parasites and predators have failed to regulate the intermediate host abundance, and they have broken away to a higher population density controlled by some factor other than the parasite. Here we may ignore the dynamics of the intermediate host stage of the life cycle, and the model has all the properties of the Anderson and May (1978) models for simple direct life cycle macroparasites. In contrast, the lower equilibrium has properties similar to those of a simple predator-prey relationship; it exhibits either damped oscillations or may even enter a limit cycle. The stability of this

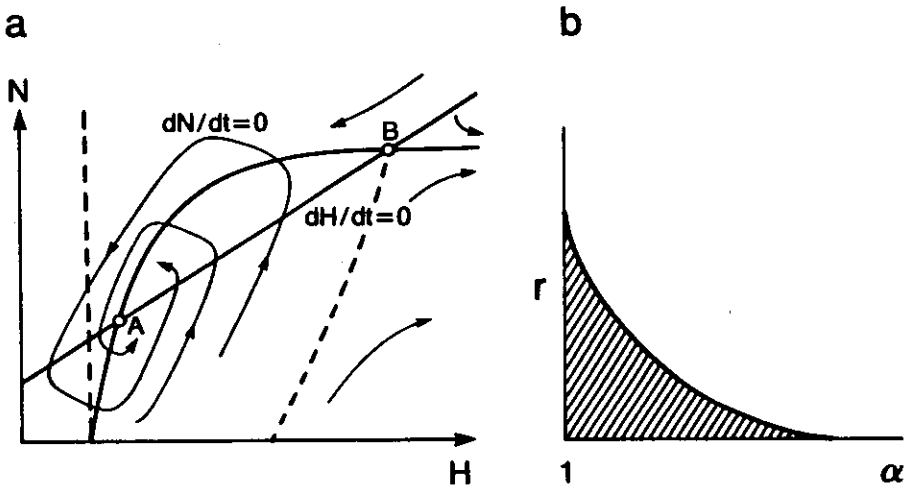

FIG. 5. PHASE PLANE ANALYSIS OF THE MODEL'S BEHAVIOR FOR A CHARACTERISTIC SET OF PARAMETER VALUES

(a) The two zero growth isoclines have two intersections. The arrowed lines indicate the behavior of the model in the vicinity of these equilibria. The intersection at higher intermediate host densities (B) is unstable and divides the plane into a region of oscillatory behavior at low intermediate host densities and exponential growth of the intermediate host population at intermediate host population densities. The position of this line is marked by the right-hand dashed line, while the position of the threshold number of intermediate hosts is indicated by the left-hand broken line. (b) Sketch of the dynamic behavior of the model for different combinations of values of r and a. In the upper region of the graph the parasites are unable to regulate the intermediate host population and the hosts grow exponentially.

lower equilibrium and the position of the two intersections depend on the slopes of the two isoclines. For any intersection to occur it must be true that

$$\frac{c_1\lambda}{H_0\delta k'} > \frac{r - \varrho H_2}{c_1\lambda H_2}. \quad (17)$$

Increases in a tend to reduce the value of the left side of this inequality while increasing the value of the right side. In cases where rates of change in the host's behavior greatly increase the host's susceptibility to predation, the unstable equilibrium and the lower stable equilibrium tend to coalesce and ultimately disappear (Fig. 5b). Thus at low a, or at low intermediate host population densities, both parasite and intermediate host display a tendency to oscillate. However, as a or r, the intermediate host population growth rate, increases, the joint action of the predators and the parasites is insufficient to regulate the intermediate host population at a low level. The resultant limit cycle eventually breaks down, with further increases in the population growth rate, and both populations break away and either grow exponentially or become constrained by factors not considered in the model. At this point, the intermediate host density will be mainly determined by intraspecific competition for resources. Transmission of the parasites from intermediate hosts to the definitive hosts is effectively stalled, for the definitive hosts are saturated, and the parasite's density is controlled by the interaction between its pathogenicity and the other regulatory constraints on its survival and fecundity operating in the definitive hosts.

A review of the published data for acanthocephalans (Dobson and Keymer, 1985) illustrates that both oscillatory and asymptotic stability are observed in long-term studies of field populations. Similar patterns are also observed in many of the longer-term studies of cestodes and digeneans with life cycles of this type (Chubb, 1980, 1982). Although many of the authors of these studies have attributed variations in the prevalence and intensity of infection to seasonal variations in the transmission rates, it is possible that some of the higher-order cycles observed in these systems will be due to dynamic mechanisms such as

An intuitive feeling for the dynamics of the populations when large numbers of intermediate hosts are present may be gained by substituting the expression for R_0 into the basic model formulated by Anderson and May (1978) for a direct life cycle macroparasite. These equations can be written as

$$\frac{dH_2}{dt} = r_2 H_2 - \delta N H_2 \quad (18)$$

$$\frac{dN}{dt} = N\left(R - 1 - \frac{\delta N k'}{(\mu + \delta)}\right)(\mu + \delta). \quad (19)$$

Here r_2 is the net growth rate of the definitive host population and R is the net reproductive rate of the parasite at the present host population density H_2. The appropriate expression for R_0 can then be substituted into Eq. 19. In the original model for direct life cycle macroparasites (Anderson and May, 1978), $R_0 = (\lambda H_2)/(H_2 + H_0)(\mu + \delta)$; here, we will use Eq. 12. We thus assume that the intermediate host density is sufficiently large that it can be assumed to be constant, and we have collapsed the equations for transmission of the parasites through the intermediate host stage of the life cycle into a single expression. At equilibrium $dH_2/dt = dN/dt = 0$ and

$$N^* = r_2/\delta \quad (20)$$

$$R^* = 1 + \frac{r_2 k'}{(\mu + \delta)} = \frac{T_1 a\varrho H_2}{M_1 M_3(b + \mu + a\varrho H_2)}. \quad (21)$$

Thus the number of definitive hosts at equilibrium is

$$H_2^* = \frac{M_1 M_3 R^*(b + \mu)}{a\varrho(T_1 - M_1 M_3 R^*)}. \quad (22)$$

This expression says that increasing the value of a decreases the number of definitive hosts present at equilibrium; a consequence of this reduced size of the definitive host population is that the number of *parasites* present at equilibrium is also reduced. This occurs primarily because increases in the efficiency of parasite transmission lead to an increase in the number of deaths owing to parasites in the definitive host population. Although this reduction in parasite density may be countered

by selection to reduce the pathogenicity of the parasite towards the definitive host, δ, such selection may require sustained periods of stable association between the parasite and its definitive host.

PARASITE INDUCED REDUCTIONS IN HOST FECUNDITY

There are a variety of ways that parasites may reduce a host's fecundity by changing its behavior. At the simplest level the presence of a pathogen, by reducing the stamina of an infected male, may prevent him from obtaining or holding a mate. In their classic study of red grouse (*Lagopus lagopus scoticus*), Jenkins, Watson, and Miller (1963) reported considerably higher burdens of parasitic nematodes in male grouse that had been unable to obtain territories than in those that were holding them. This indirectly suggests that parasite burdens may be important in determining a male bird's ability to obtain, or hold, a territory.

More direct evidence is available from studies on the influence of parasite burden on the position of male mice in dominance hierarchies. Freeland (1981) has demonstrated that the dominance status of male mice correlates inversely with the doses of nematode larvae administered to them; Rau (1983a) has been able experimentally to manipulate the status of males by changing the intensity of *Trichinella* infections. Similar actions operating in wild populations would again reduce the effective reproductive success of infected male individuals.

At a more complex level, Hamilton and Zuk (1982) have suggested that parasites may affect the intensity of expression of the visual and auditory cues used by males to attract females. They use this argument to suggest that differences in the coloration and song patterns of different bird species may be due to differences in the number of parasite species associated with them. Although their results are supported by the available comparative evidence (Harvey and Partridge, 1982; Read, 1987), initial experimental studies present conflicting results. Data from a long-term study by Borgia (1986) on Satin Bowerbirds suggests that parasite burdens have no influence on mate choice. In contrast, a study by Zuk (1987) provides some evidence that gregarine parasites male crickets. She argues that this supports a modified form of the "Hamilton-Zuk" hypothesis. Plainly the potentially revolutionary implications of these ideas require further empirical studies at both the intraspecific and interspecific level.

Changes in the reproductive success of infected males and parasite-induced changes in the cues used by males to attract mates may thus have profound effects on the population genetics and long-term evolution of parasite-host relationships. It is the direct influence of the parasite on the fecundity of individual *females*, however, that will be most important for the shorter-term population dynamic behavior of the relationship. Here documented mechanisms range from direct reductions in the fecundity of infected females (Pan, 1965; Weatherly, 1971; Meuleman, 1972; Minchella and Loverde, 1981; Schall, 1983), through host-castration (Reinhard, 1956; Kuris, 1974; Baudoin, 1975) and changes in the sex-ratio of the offspring of infected hosts (Bulnheim and Varra, 1968), to sex-reversal of infected individuals (Kat, 1983; Whitfield, 1982). All of these mechanisms are likely to have profound effects on both the shorter-term population dynamics of the parasite-host relationship and the longer-term, evolutionary interaction. Unfortunately, the majority of these effects are only thinly documented, and we shall therefore continue to focus our attention on the areas of study where some data are available, while emphasizing in passing the need for more empirical work in this area.

In models of simple direct life cycle macroparasites, any reduction in host fecundity that is due to the presence of the parasite tends to be destabilizing and may induce long-term oscillations in the numbers of parasites and hosts (May and Anderson, 1978). Work on the impact of the nematode *Trichostrongylus tenuis* on the fecundity of infected female red grouse *Lagopus lagopus scoticus* suggests that parasite-induced reductions in female fecundity may be a major factor in determining the long-term population cycles observed in this species (Hudson, 1986; Hudson, Dobson, and Newborn, 1985). Similar mechanisms may occur in the parasites of the snowshoe hare (Boughton, 1932; Erickson, 1944). Although Keith, Cary, Yuill, and Keith (1985) dismiss parasites

their analysis is based on patterns of parasite prevalence rather than upon parasite burden. This tends to ignore the actual burdens of worms in hares at different times in the population cycle and may bias the analysis in favor of rejection of the null hypothesis that suggests the parasites are having an effect on host density. Similarly the experiments to determine the effect of parasites on host fecundity have *not* been done for the snowshoe hare system. Since experiments from other related systems suggest that parasite burden does have a significant effect on lagomorph fecundity (Dunsmore, 1980; Yuill, 1964), it seems sensible to suggest that parasites should be reconsidered as a factor contributing to the well-known ten-year cycle observed in this species (Keith and Windberg, 1978; Cary and Keith, 1979).

POPULATION DYNAMIC CONSEQUENCES OF CHANGES IN INTERMEDIATE HOST FECUNDITY

It is in the intermediate hosts of indirect life cycle parasites that we again find the best-documented examples of parasites changing most dramatically the fecundity and behavior of infected hosts. In infections of molluscs by the asexually reproducing intermediate stages of digeneans, reductions in host fecundity are often accompanied by *increases* in the survival of infected animals (Wright, 1966, 1971; Obrebski, 1975; Minchella, 1985). This is assumed to occur by the diversion of nutrients away from host reproduction for use either to produce more parasites or to increase the body size of infected host individuals. Some aspects of the evolutionary and population dynamic consequences of parasite-induced reductions in intermediate host fecundity may be examined using the following set of equations:

$$\frac{dP_2}{dt} = \eta_2 H_2 C - \pi P_2 - dH_2\left(\frac{P_2}{H_2} + \left(\frac{P_2}{H_2}\right)^2 \frac{k+1}{k}\right) \quad (23)$$

$$\frac{dW}{dt} = \lambda P_2 - \gamma_1 W - \eta_1 W H_1 \quad (24)$$

$$\frac{dP_1}{dt} = \eta_1 W H_1 - (\mu + \varepsilon b) P_1 - \Delta H_1\left(\frac{P_1}{H_1} + \left(\frac{P_1}{H_1}\right)^2\right) \quad (25)$$

$$\frac{dC}{dt} = \Theta P_1 - \gamma_2 C - \eta_2 C H_2 \quad (26)$$

$$\frac{dH_1}{dt} = (a-b)H_1 e^{-\pi} + \varepsilon(a-b)H_1(1-e^{-\pi}) - \Delta P_1. \quad (27)$$

The life cycle of the hypothetical digenean whose dynamics we are attempting to model is illustrated in Fig. 6. Several new assumptions are incorporated into this model; the most important of these is that very few of the intermediate hosts are infected (Wright, 1971; Anderson and May, 1979b). Since the majority of infected hosts will only carry one parasite, the mean parasite burden in the intermediate hosts, π, is likely to be less than unity. It is again assumed that the parasites are distributed randomly in their intermediate hosts and thus $(1 - e^{-\pi})$ of these hosts are infected and may be unable to reproduce owing to parasitic castration. [Since π is small, $(1 - e^{-\pi}) \cong \pi$.] The intermediate hosts are thus divided in Eq. 27 into infected and uninfected classes whose relative contribution to the population growth rate is determined by the parameter ε. When ε equals unity infected hosts have the same survival and fecundity as uninfected hosts; values of ε less than unity correspond to parasite-induced reductions in host fecundity; and values greater than unity correspond to increases in the fecundity or survival of infected intermediate hosts. The parameter Δ corresponds to the parasite-induced mortality rate of infected intermediate hosts, and this pathogenicity is assumed to operate independently of ε. Finally Θ is the rate of asexual reproduction of the parasite in the intermediate host; since only a very few hosts are infected by more than one parasite, Θ will roughly correspond to the rate at which free-living cercaria are produced by any infected snail.

The equations can again be collapsed to obtain an expression for R_0, the basic reproductive rate of the parasite (Anderson, 1982, in press):

$$R_0 = \frac{T_1 T_2}{M_1 M_2 M_3 M_4}. \quad (28)$$

Here $T_1 = \lambda\eta_1 H_1$, $T_2 = \Theta\eta_2 H_2$, $M_1 = (\varepsilon b + \mu + \Delta)$, $M_2 = (\pi + \delta)$, $M_3 = (\eta_1 H_1 + \gamma_1)$,

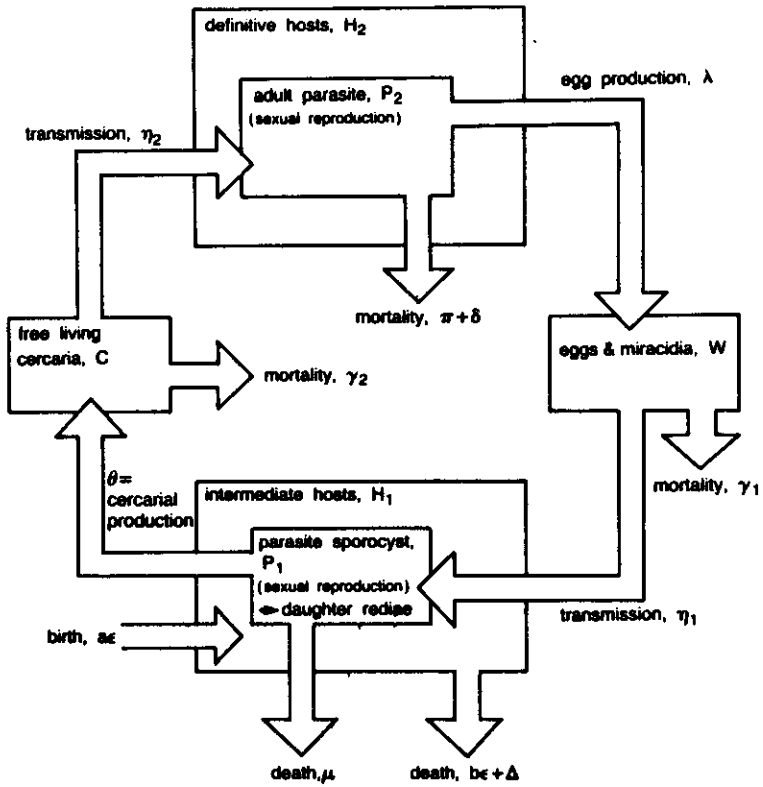

FIG. 6. FLOW CHART OF THE LIFE CYCLE FOR A "DIGENEAN-TYPE" PARASITE, WITH TWO FREE-LIVING STAGES

The parameters are essentially the same as those listed in Table 2 with the exception that Δ is now the per capita rate of parasite-induced host mortality of the intermediate snail hosts, and Θ is the rate of asexual multiplication of the parasites in their intermediate hosts. The two free-living stages, eggs/miracidia, W, and cercaria, C, have average life expectancies of $1/\gamma_1$, and $1/\gamma_2$, and are able to locate and infect the next host stage in the life cycle at rates η_1 and η_2, respectively. The definitive host population is assumed to remain constant with respect to all other stages in the life cycle.

the product of the transmission terms and the life expectancies of the parasite at each stage of the life cycle. Although parasite-induced reductions in intermediate host mortality, Δ, produce only small increases in R_0, these reductions may be important in providing a more stable environment in which the parasite may complete its development before reproducing asexually (Minchella, Leathers, Brown, and McNair, 1985). In contrast the terms for the rate of production of stages that of contact of these cercaria with hosts η_2, have a more direct effect on the magnitude of R_0. This suggests that changes in behavior that increase the contact rate between free-living parasitic stages and the definitive host are more important than changes in the intermediate host's survival and fecundity in determining the parasite's reproductive success. An example of such behavior would be the change in chemosensitivity and orientation behavior of the snail *Biomphalaria glabrata* when infected

changes seem to keep infected snails in the warmer surface waters of ponds where the released cercaria may more readily locate the next host in the life cycle (Etges, 1963; Wright, 1971). Similar effects may operate in the estuarine snail *Ilyanassa obsoleta* when infected with the trematode *Gynaecotyla adunca* (Curtis, 1987).

There is evidence to suggest that increases in the rates of asexual reproduction by digeneans in their intermediate mollusc hosts tend to produce a corresponding increase in pathogenicity (Pan, 1965; Wright, 1966, 1971). This increase in snail mortality is due mainly to the increased tissue damage that occurs as more cercariae are released, and to the increased rate at which the parasite uses the host's resources to produce its own offspring. If we assume a simple linear relationship between Θ and Δ, we obtain a relationship between R_0 and Δ that suggests that the basic reproductive rate of the parasite is maximized by intermediate to high levels of pathogenicity (Fig. 7). This result makes an interesting comparison to the result obtained by Anderson and May (1982b) for direct life cycle microparasites, where intermediate levels of pathogenicity tended to maximize R_0. The above analysis, however, has ignored the fact that too large an increase in parasite pathogenicity will result in the snail host dying before the cercaria have had sufficient time to develop. The incorporation of suitable time for development into the model may well produce a more realistic relationship between R_0 and Δ, which would show intermediate levels of pathogenicity to be optimal. Again a more detailed empirical understanding of the interaction between parasite pathogenicity and cercarial production would help clarify our understanding of this important area of parasite-host ecology.

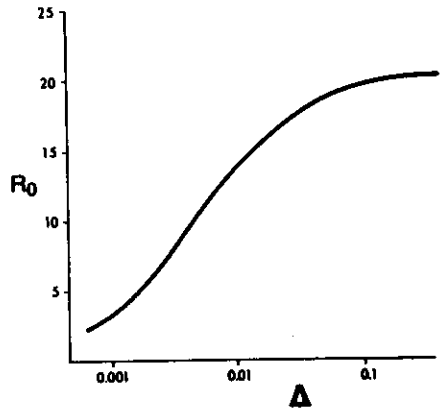

FIG. 7. THE RELATIONSHIP BETWEEN THE BASIC REPRODUCTIVE RATE, R_0, AND THE PATHOGENICITY OF THE PARASITE TO ITS INTERMEDIATE HOST, Δ

In this case increases in the rate of asexual reproduction lead to increases in the rate of parasite-

We may again use the equation for R_0 to obtain a pair of expressions for the minimum host population size that will allow the parasite to persist:

$$H_{1_T} = \frac{\gamma_1 M_1 M_2 M_4}{\eta_1(\lambda T_2 - M_1 M_2 M_4)} = \frac{\gamma_1 M_2 M_4(\epsilon b+\mu+\Delta)}{\eta_1(\lambda T_2 - M_2 M_4(\epsilon b+\mu+\Delta))} \quad (29)$$

and

$$H_{2_T} = \frac{\gamma_2 M_1 M_2 M_3}{\Theta\eta_2(\lambda T_1 - M_1 M_2 M_3)}. \quad (30)$$

Here H_{1_T} is the threshold number of intermediate hosts and H_{2_T} is the threshold number of definitive hosts. In both cases values of ϵ less than unity produce slight decreases in the size of the minimum population in which the parasite can just sustain itself. Increases in Θ and η_2 produce more direct reductions in the size of the threshold density of definitive hosts required to sustain the infection.

The dynamic behavior of this type of life cycle may again be explored by collapsing the equations to produce a two-equation system for the dynamics of the intermediate hosts and the adult parasites:

$$\frac{dH_1}{dt} = H_1\left(r - \frac{\Delta}{r}(1-\epsilon) - \frac{\Delta\lambda c_1 H_2 M}{(H_0 + H_1)}\right) \quad (31)$$

$$\frac{dM}{dt} = M\left(\frac{\lambda c_1 c_2 H_1}{(H_0 + H_1)} - (\pi + \delta) - \delta MK\right) \quad (32)$$

where $c_1 = 1/(\epsilon b+\mu+r+\Delta) = 1/(M_2+r)$ and $c_2 = T_2/M_4 = \Theta H_2/(H'_0+H_2)$ (where $H'_0 = \gamma_2/\eta_2$). This pair of equations is similar to those

prey relationship (Eqs. 15 and 16). The phase diagram is essentially identical to that of Fig. 5, with the position of the two intersects and the stability of the lower equilibrium again determined by the relative magnitudes of the initial slopes of the isoclines. For a pair of intersects to be present we must have it that

$$\frac{\lambda c_1 c_2}{H_0 \delta k'} > \frac{r - (\Delta/r)(1 - \epsilon)}{\Delta \lambda c_1 H_2}. \quad (33)$$

When this inequality fails, or when the intermediate host population density is sufficiently large, the parasites are unable to regulate the population density of the intermediate host. The influences of Θ, ϵ, and Δ on the stability of the interaction are illustrated diagrammatically in Fig. 8. The analysis suggests that asexual reproduction of parasites within an intermediate host, and parasite-induced reductions in intermediate host fecundity, can be important in stabilizing the dynamics of parasites with *indirect* life cycles. This is an important contrast to *direct* life cycle macroparasites where these mechanisms are usually destabilizing (May and Anderson, 1978). Intermediate levels of pathogenicity of the parasite to its intermediate host are also important if the parasite is to regulate intermediate host population density. The analysis also suggests that parasites with life cycles of this type will again display a tendency to oscillate when intermediate host densities are low, and a tendency to break away to higher parasite densities when intermediate host densities are high.

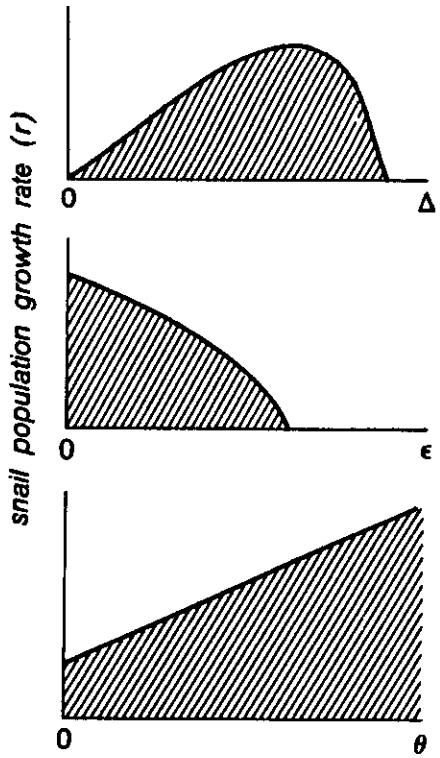

FIG. 8. THE INFLUENCE OF THREE DIFFERENT PARAMETERS ON THE DYNAMICS OF THE MODEL FOR AN ILC2FL PARASITE

In all cases the top region of the graph is a region of parameter space where the parasite is unable to control intermediate host population density; the lower shaded region corresponds to a region where the parasite and intermediate host show oscillatory patterns of abundance. The top graph illustrates the influence of Δ, or parasite-induced intermediate host mortality. The middle graph illustrates the effect of ϵ, or parasite-induced reduction in intermediate host fecundity or mortality. The bottom figure illustrates the effect of the parasite reproducing asexually in the intermediate host (Θ).

DISCUSSION

This review may appear fairly chauvinistic in that few examples have been given of changes in host behavior that are adaptive to the host and maladaptive to the parasite; this "bias" is a fair reflection of the published literature. There are examples of changes in host behavior associated with parasitism that decrease transmission. For example, Hausfater and Meade (1982) report that baboons (*Papio cynocephalus*) alternate periods of a few consecutive nights use of a sleeping grove with much longer periods of avoidance of that grove. They suggest that the period of absence from a grove coincides with the peak of emergence of intestinal nematode larvae from the feces deposited by the baboons in their first few nights at

ample, Keymer, Crompton, and Sahakian (1983) have reported that rats exhibit a learned taste aversion for food items that they can positively associate with a previous parasitic infection. Although it could be argued that this taste aversion would be beneficial to the parasites already in the infected host, as it would it seems more likely that such a mechanism is simply an adaptive response of the host.

Similarly, although the above analysis of the interaction between parasite infection and host fecundity suggests that increases in the survival of infected intermediate hosts may be advantageous to the parasite, it could be argued that changes in the fecundity and size of molluscs infected with digenean larvae might be adaptations that allow individual hosts to survive while sustaining a parasite infection and then resume reproduction once the parasite has died. If changes in body size of infected hosts were an adaptation of the hosts, it seems likely that they would be more common in perennial host species than in annual species where infected individuals are unlikely to outlive the parasite. The available evidence shows the opposite trend with gigantism appearing more common in annual mollusc species than in perennial ones (Sousa, 1983; Minchella et al., 1985). This suggests that changes in the size of short-lived mollusc species are more likely to be manipulations of the host that are adaptive to the parasite, rather than responses of the host to minimize the impact of the infection. As prevalences of infection of molluscs by these species rarely exceed 10 per cent and are usually around 1 per cent (Wright, 1971; Anderson and May, 1979b), it might also be argued that only relatively weak selection pressures act on intermediate host species to adapt to infection by any specific parasitic helminth.

Recent work on coevolution of microparasites and their hosts (Anderson and May, 1982b; May and Anderson, 1983; Fenner, 1983) suggests that the traditional view of parasite-host relationships evolving towards minimal virulence may well be an oversimplification. As most parasites with indirect life cycles are very specific towards their intermediate host species while utilizing a variety of species as definitive hosts, it seems likely that coevolutionary interactions between the parasite and its obligatory intermediate host species will be under much stronger and more constant selection pressure than interactions between the parasite and its definitive hosts. On this count it is encouraging to note that the most highly evolved and sophisticated modifications of host biology occur in the host with which the parasite has been associated for while we see excellent examples of subtle manipulations of the host's physiology and nervous system in the invertebrate hosts of the acanthocephalans and the insect vectors of protozoan parasites, the changes in the behavior of the intermediate hosts of cestodes are less subtle and usually only involve simple reductions in survival and fecundity (Keymer, 1980; Schom, Novak, and Evans, 1981). Although similar arguments may apply to the changes in behavior of the paratenic or secondary intermediate hosts of parasitic helminths that utilize three hosts in their life cycle, some of these interactions tend also to show quite subtle behavior particularly in cases where the host species is used obligatorily (Carney, 1969; Helluy, 1984). Obviously many more studies of the influence of parasites on their hosts' behavior are going to have to be undertaken before a more quantitative empirical comparison of how these traits evolve may be undertaken.

In conclusion, it seems fair to say that the costs and longer-term evolutionary benefits of changing the influence of the parasite on the host's behavior will vary depending on the habitat utilized by the various species involved. Although mechanisms that increase rates of transmission will always be adaptive, they have the further advantage in patchy environments of reducing the threshold host population size required to sustain an infection, and of increasing the basic reproductive rate of the parasite when first introduced into new host populations. Selection for these traits will thus be stronger when the parasites are attempting to colonize small host populations than when they are continuously present in larger more stable host populations. The parasite-induced changes in host behavior observed in many parasites with indirect life cycles would thus seem to be primarily adaptations to allow exploitation of host populations that are either naturally fragmented into small groups or species whose ephemeral or migratory behavior produces low and irregular densities of hosts through time. We should therefore expect to see variability in the intensity with which parasite-induced changes in host behavior are expressed as we move from ephemeral populations in constantly fluctuating habitats to more stable populations in larger more homogeneous habitats. The more detailed determi-

will require further comparative field and laboratory experiments with a variety of different closely related parasite species and their hosts. The importance of long-term population studies of both parasites and their intermediate hosts cannot be overemphasized in this context.

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