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The regulation of host population growth by parasitic species

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SUMMARY

The nature of parasitism at the population level is defined in terms of the parasite's influence on the natural intrinsic growth rate of its host population. It is suggested that the influence on this rate is related to the average parasite burden/host and hence to the statistical distribution of parasites within the host population.

Theoretical models of host–parasite associations are used to assess the regulatory influence of parasitic species on host population growth. Model predictions suggest that three specific groups of population processes are of particular importance: over-dispersion of parasite numbers/host, density dependence in parasite mortality or reproduction and parasite-induced host mortality that increases faster than linearly with the parasite burden. Other population mechanisms are shown to have a destabilizing influence, namely: parasite-induced reduction in host reproductive potential, direct parasite reproduction within the host and time delays in the development of transmission stages of the parasite.

These regulatory and destabilizing processes are shown to be commonly observed features of natural host–parasite associations. It is argued that interactions in the real world are characterized by a degree of tension between these regulatory and destabilizing forces and that population rate parameter values in parasite life-cycles are very far from being a haphazard selection of all numerically possible values. It is suggested that evolutionary pressures in observed associations will tend to counteract a strong destabilizing force by an equally strong regulatory influence. Empirical evidence is shown to support this suggestion in, for example, associations between larval digeneans and molluscan hosts (parasite-induced reduction in host reproductive potential counteracted by tight density-dependent constraints on parasite population growth), and interactions between protozoan parasites and mammalian hosts (direct parasite reproduction counteracted by a well-developed immunological response by the host).

The type of laboratory and field data required to improve our understanding of the dynamical properties of host–parasite population associations is discussed and it is suggested that quantitative measurement of rates of parasite-induced host mortality, degrees of over-dispersion, transmission rates and reproductive and mortality rates of both host and parasite would provide an important first step. The value of laboratory work in this area is demonstrated by reference to studies which highlight the regulatory influence of parasitic species on host population growth.

INTRODUCTION

The combined effect of many factors, both physical and biotic, determine ... animal populations fluctuate in numbers. Some of these factors are importa... creating observed changes, while others act to reduce the scale of fluctua... around an average or equilibrium population level.

Predation and competition are generally regarded as two of the more imp... biotic factors which tend to suppress wide-scale population changes ... Krebs, 1972; Whittaker, 1975). Predation, for instance, may act in a d... dependent and thus regulatory manner if the attack rate of a predator increases ... prey density rises (Murdoch & Oaten, 1975; Hassell, Lawton & Beddington, 1... If a prey species 'escapes' the control of a predator (perhaps due to sat... effects), population growth will continue until other factors, such as intra-s... competition for finite resources, provide constraints.

Parasitic organisms are also thought to play an important role, either dir... or indirectly, in the regulation of the population growth of many, if not m... animal species. In contrast with other areas of population ecology, however, ... few studies have examined, either theoretically or experimentally, the dynam... properties of host–parasite associations. Our knowledge in this area of ecol... an area with important ramifications in medical and veterinary fields, is ... extremely limited.

The purpose of this paper is 2-fold. First, the paper aims to display the pro... ties of some simple population models which attempt to characterize the esse... biological features of host–parasite associations. The assumptions incorporated ... these models are based on empirical evidence documented in the parasitolog... literature.

The second, and most important aim is to focus attention on the biolog... features of host–parasite associations which determine the regulatory ... played by parasitic species in controlling host population growth. In particula... the paper attempts to consider such features within an evolutionary fram... work and in the light of classical parasitological notions of the 'successf... parasite'.

The paper is organized into four major sections. The first part considers th... nature of parasitism at the population level and compares the mode of action ... parasites with insect parasitoids, predators and symbionts. Past work in this are... by Crofton (1971*a*, *b*) is reviewed.

The second section documents the parasitological assumptions incorporated i... a basic population model and describes the modification of the model structur... to consider the regulatory effects of over-dispersion of parasite numbers/host ... density-dependent parasite reproduction and survival, and non-linear relationship... between host death rate and parasite burden.

The third section considers various aspects of host–parasite relations that tend ... to be destabilizing in influence: parasite-induced reduction in host reproduction, ... the effects of parasites reproducing directly inside the host and the effects of time ... delays in parasite reproduction and transmission.

... final part of the paper dis... ... parasites in natural populatio... ... mathematical developme... ... used in detail in two separa... ... 1978). In this present ... ... ly of the text but an App... ... parasitological framework ...

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In terms of their population dyna... ... tes at the two ends of this spectru... ... symbionts. Crofton (1971*a*, *b*) fi... ... these notions, and has suggested the ... ... the typical number of parasites, of a ... ... prehensive appraisal of Crofton's wo... ... ctions is given in May (1977)).

The concept of a 'lethal level', alt... ... rather crude and difficult to substantia...

The final part of the paper discusses, in general terms, the regulatory influence of parasites in natural populations of animals.

The mathematical development of the theories presented in this paper are described in detail in two separate publications (Anderson & May, 1978; May & Anderson, 1978). In this present paper mathematical details are omitted from the main body of the text but an Appendix is included to indicate the precise structure of the parasitological framework of the theory.

The nature of parasitism at the population level

In general, the terminology currently used for labelling animal associations appears rather imprecise when considered at the level of population rather than the individual organism (Starr, 1975).

This lack of precision is particularly apparent when considering the degree of damage or 'harm' caused by a parasitic species to the growth of its host population. Conceptual difficulties in this area do not always arise since, for example, insect parasitoids invariably kill their hosts as a developmental necessity; the parasitoid surviving the death it induced by the adoption of a free-living mode of life in the adult phase (Askew, 1971). Other eucaryotic organisms, such as various species of lice, fleas, ticks, protozoa and helminths, although commonly regarded as parasites (since they exhibit varying degrees of nutritional and habitat dependency on their hosts) do not kill their host as a pre-requisite for successful development. Such species invariably die if they cause the death of their host.

The conditions of nutritional and habitat dependency are widely accepted by parasitologists as necessary, but not sufficient conditions, for the classification of an organism as parasitic (see Dogiel, 1964; Noble & Noble, 1965; Smyth, 1976). Sufficiency is created if the organism in question induces 'harm' or damage to its host. Parasites exhibit a wide degree of variability in the degree of 'harm' they cause. At one extreme of the spectrum, parasites merge into the parasitoid type of association with its close affinities, in population terms, with predator–prey interactions (see Hassell, Lawton & Beddington, 1976). At this extreme, host death will invariably result from parasitic infection, but in contrast to parasitoids such deaths will kill the parasites contained within. At the other end of the spectrum lie the symbiotic forms of association in which the symbiont lives on, or in, the host and exhibits a degree of nutritional dependency akin to a 'permissive gastronomic hospitality' (Starr, 1975). Species at this end of the spectrum cause little, if any, harm to their host even when present in very large numbers.

In terms of their population dynamics, there will be differences between parasites at the two ends of this spectrum; between the parasitoid-like parasites and the symbionts. Crofton (1971*a*, *b*) first stressed the importance of quantifying these notions, and has suggested the definition of a 'lethal level' which measures the typical number of parasites, of a given species, required to kill a host (a comprehensive appraisal of Crofton's work on the dynamics of host–parasite interactions is given in May (1977)).

The concept of a 'lethal level', although a useful and important first step, is rather crude and difficult to substantiate from empirical evidence. It appears more

sensible to consider the degree of harm or damage caused by a parasite in terms of the natural intrinsic growth rate of its host population. A parasite can simply be regarded as an organism which, in addition to exhibiting a degree of habitat and nutritional dependency on the host, adversely influences the birth and/or mortality rates of its host. Furthermore, it appears intuitively obvious that the severity of the parasite's influence on these population parameters is likely to depend, for a case of an individual host, on the number of parasites harboured. The functional relationship between host birth and/or death rates and parasite burden provides a very precise way of quantifying the harmful effects of a parasitic species on the growth of its host population.

An important consequence of this concept is that the net growth rate of a host population will depend critically on the statistical distribution of parasites among hosts. In this context, the phrase 'statistical distribution' means the way in which variate values (hosts) are apportioned with different frequencies to the number of possible classes (the number of parasites they contain). No reference to spatial pattern is implied.

This conceptual view of the mode of action of parasites at the population level will be of little practical value unless it bears close relations to biological reality. The parasitological literature contains numerous accounts of the qualitative influence of parasites on host survival and reproduction. The majority of such accounts refer to experimental studies, based in the laboratory, where the survival or reproduction of infected and unaffected animals is compared. Some data drawn from such studies, concerning the survival and reproduction of molluscan hosts infected with larval digeneans, are portrayed in Fig. 1.

A more precise understanding of the influence of parasitic infection on the natural intrinsic growth rate of host populations can be obtained from information relating host reproduction or survival to the number of parasites harboured. We ideally need to consider not just two categories of hosts, infected and uninfected, but the whole range of classes contained within a frequency distribution of the numbers of parasites/host.

Some examples of the functional relationship between parasite burden and host mortality are shown in Fig. 2. The information presented in this figure can be portrayed in a more precise form highlighting functional tendency, by transformation into instantaneous rates of parasite-induced host mortality (Fig. 3).

The functional response between parasite burden and host death rate is sometimes linear, as shown by the effects of the parasitic mite *Hydryphantes lenuabilis* on its insect host *Hydrometra myrae* and the influence of *Fasciola hepatica* on laboratory mice (Fig. 3A and B). In contrast, more complex non-linear patterns may occur as illustrated by the power law relationship generated by the influence of *Heligmosomoides polygyrus* on the laboratory mouse and *Nippostrongylus muris* on the rat (Fig. 3C and D). It is worth noting that the lethal level concept envisaged by Crofton (1971*a*) is an extreme form of the patterns shown in this figure. Within the framework of the lethal level concept, the death rate would be zero up to a given burden and then immediately tend to infinity.

The examples documented in Fig. 3 simply portray the direct effects of parasitic

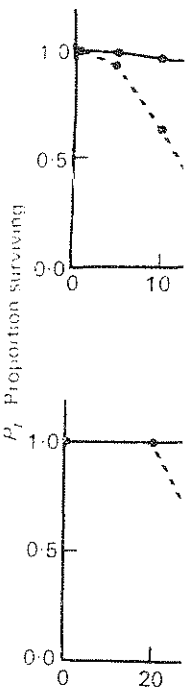

Fig. 1. The influence o
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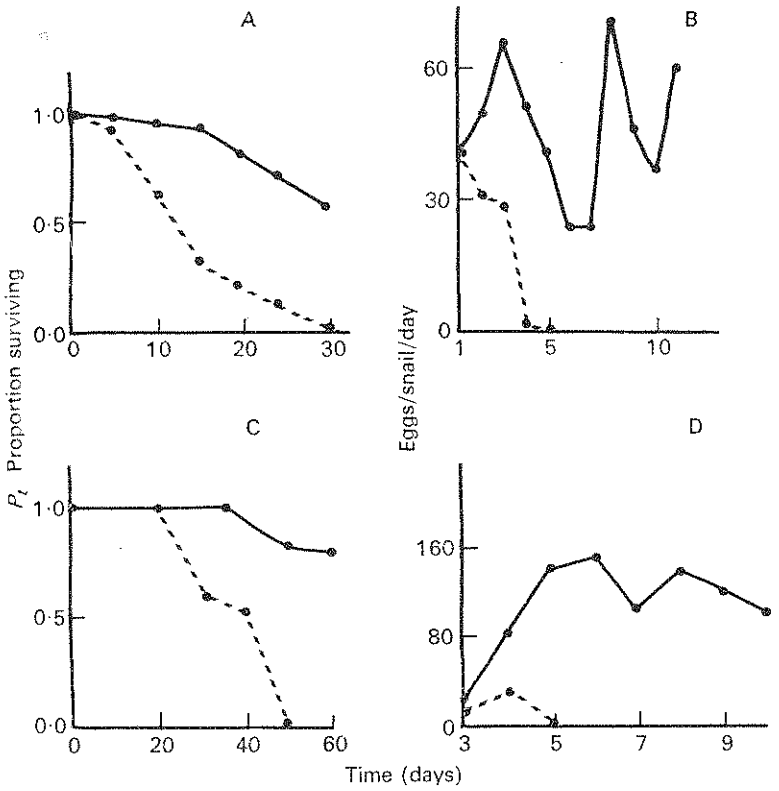

Fig. 1. The influence of larval digeneans on the survival and reproductive rates of their hosts. (●——●), Uninfected hosts; (●---●), infected hosts. (A) Survival of *Australorbis glabratus* infected with *Schistosoma mansoni*. (Data from Pan, 1965.) (B) Reproduction rate of *Australorbis glabratus* infected with *Schistosoma mansoni*. (Data from Pan, 1965.) (C) Survival of *Lymnaea gedrosiana* infected with *Ornithobilharzia turkestanicum*. (Data from Massoud, 1974.) (D) Reproductive rate of *Lymnaea truncatula* infected with *Fasciola hepatica*. (Data from Hodasi, 1972.)

infection on host survival. Laboratory-based studies of such phenomena invariably utilize experimental designs which exclude hosts from experiencing both the effects of intra- or inter-specific competition for finite resources and predation. Within natural animal populations parasite burdens will place a 'strain' on individual hosts, who as a result will become more susceptible to predation or more likely to fail to obtain sufficient of a resource to ensure survival within a competitive situation. The degree of 'strain' is again likely to be related to parasite burden. (Unfortunately such influences on host mortality are more difficult to measure either in the field or in the laboratory.)

Mechanisms of this kind, although different from the direct effects of parasitic infection displayed in Fig. 3, are still encompassed within a framework which relates the rate of parasite-induced mortality to parasite burden. We can therefore envisage this rate as being formed from a series of components measuring the direct influence of the parasite, increased susceptibility to predation and reduced competitive fitness. In natural populations it is probable that the last two components are of major significance.

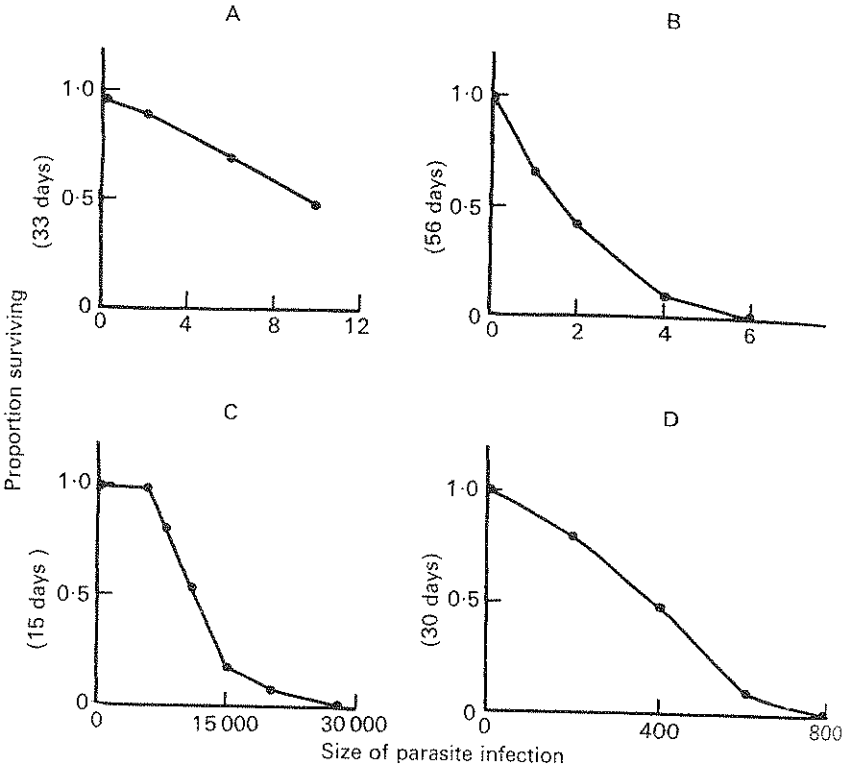

Fig. 2. Some examples of the influence of the size of a parasite infection on host survival. (A) The influence of the mite *Hydryphantes tenuabilis* on the survival of its host, the aquatic hemipteran *Hydrometra myrae* over a period of 33 days. (Data from Lancinani, 1975.) (B) The influence of the trematode *Fasciola hepatica* on the survival of the laboratory mouse over a period of 56 days. (Data from Hayes, Bailey & Mitrovic, 1973.) (C) The influence of the nematode *Nippostrongylus basiliensis* on the survival of male laboratory rats over a period of 15 days. (Data from Hunter & Leigh, 1961.) (D) The influence of the nematode *Heligmosomoides polygyrus* on the survival of the laboratory mouse over a period of 30 days. (Data from Forrester, 1971.)

The Basic Model

The conceptual definition, outlined above, of the mode of action of parasitic species at the population level can be captured within a set of formal mathematical statements. Representation in this form provides a scientific framework upon which various parasitological assumptions can be constructed in a precise and unambiguous manner. The influence of these assumptions on the dynamical properties of host–parasite associations can then be examined using a variety of mathematical techniques.

Before assembling such a model, however, it is important to delineate the main population components of a host–parasite interaction and to make certain assumptions concerning their precise form.

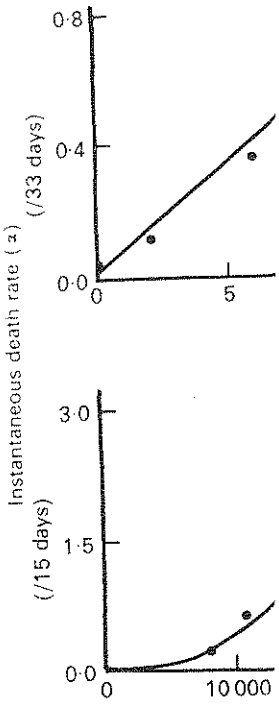

Fig. 3. The functional relatic induced host mortalities, estir parasitic infection. The specifi The lines indicate the best fit l values.

Biological assumptions

The vast majority of prot population growth with ove such patterns of population gr see May, 1976). The biologic structed from two differential and $P(t)$, representing the nu at time t.

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It is assumed that all paras tion of the host population an altered by the number of par associations it appears to be

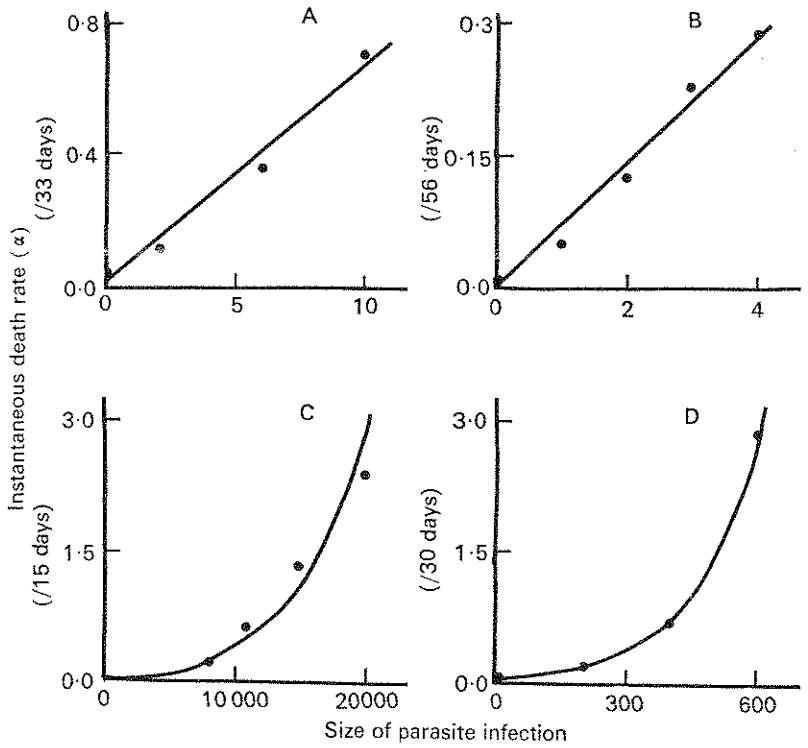

Fig. 3. The functional relationships between the instantaneous rates of parasite-induced host mortalities, estimated from the data shown in Fig. 2, and the size of a parasitic infection. The specific relationships shown in A–D are as defined for Fig. 2. The lines indicate the best fit linear or exponential models and the points are observed values.

Biological assumptions

The vast majority of protozoan and helminth parasites exhibit continuous population growth with overlapping generations. Mathematical description of such patterns of population growth should ideally be based on differential calculus (see May, 1976). The biological framework of the Basic Model is therefore constructed from two differential equations describing changes in the variables $H(t)$ and $P(t)$, representing the numerical sizes of the host and parasite populations at time t.

The template of the Basic Model characterizes the dynamics of parasitic species which do not reproduce directly within their definitive or final host, but produce transmission stages such as eggs, spores or cysts which pass out of the host as a developmental necessity. This template is modified at a later stage to encompass species which have a reproductive phase in the definitive host which directly contributes to the size of the parasite population contained within that host.

It is assumed that all parasite species are capable of multiply infecting a proportion of the host population and that the birth and death rates of infected hosts are altered by the number of parasites they harbour. In the majority of host–parasite associations it appears to be the death rate rather than the reproductive rate

Table 1. *Notation used to denote various population rate parameters*

Parameter	Description
a	Instantaneous birth rate of host (host/unit of time).
b	Instantaneous death rate of host due to natural causes (host/unit of time).
α	Instantaneous death rate of host due to influence of parasites (host ...
λ	Instantaneous birth rate of parasite transmission stages where birth ... the production of stages which pass out of the host (i.e. eggs, cysts, ... larvae) (parasite/unit of time).
μ	Instantaneous death rate of parasite within the host due to natural ... induced (immunological) causes (parasite/unit of time).
H_0	Transmission efficiency constant, varying inversely with the propor... transmission stages which successfully infect members of the host popula...
k	Parameter of the negative binomial distribution which measures inverse... degree of aggregation or contagion of the parasite within the host popula...
β	A constant measuring the severity of the parasite's influence on host repr... tion.
r	Instantaneous direct parasite birth rate. Reproduction directly increas... size of parasite population within a host (parasite/unit of time).

which is influenced by parasite infection. Exceptions to this statement, how... are particularly apparent in associations between larval digenean parasites ... their molluscan intermediate hosts (see Fig. 1). Many parasitic arthropods ... tend to decrease host reproductive power and in certain cases cause comple... parasitic castration (i.e. the influence of the crustacean *Sacculina gregaria* on ... crab *Eriocher japonicus*). The dynamical consequences of both increased mortal... and reduced reproductive potential are examined in this paper. As a first ste... however, attention is focused on the effects of parasite-induced host mortalities.

The components of population growth

The model framework is constructed from a series of components which represe... specific population processes. The notation used to portray the various populatio... parameters is summarized in Table 1.

Intrinsic growth rate of the host population

It is assumed that the rate of growth of the host population, in the absence of ... parasitic infection, is simply determined by constant birth and death rates denoted ... by a and b respectively. The death rate b is generated by natural mortalities, whic... are caused by factors other than parasitic infection, such as predation and senes... cence. The host population will grow exponentially provided a is greater than b. The omission of density-dependent constraints on the birth or death rates is deliberate. It is recognized that in the real world host population growth will be limited by the finite nature of resources in a given habitat. The aim of model formulation, however, is to provide qualitative insights into the mechanism by which parasites regulate host population growth and hence the concept of an environmental carrying capacity is excluded in order to clarify predictions of

Parasite-regulate

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... the Basic Model it is assumed th... ...s linearly proportional to the nu... ... The number of host deaths ... ...small interval of time δt, among ... δt, where α is a constant determi... ... In the examples shown in Fig. ... ...slope of the linear models fitted ... ...of loss of hosts in a population of

$$\alpha H(t$$

... term $p(i)$ represents the probabi... ...probability is conditional on i, a... ...site's distribution within the host ... mean number of parasites/host at

$$\sum_{i=0}^{\infty} ip(i) = E$$

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Parasite fecundity and transmission

The rate of production of transmis... ...parasite is defined as λ, leading to ... of

$$\lambda H(t) \sum_{i=0}^{\infty} i$$

The transmission stages will, in many ... external environment and survive in t... larvae awaiting contact with or ingesti... only a proportion of those produced will ... The magnitude of the proportion will d... physical parameters of the environmen... factor is of particular importance in d... density of such stages in the habitat i... In order to take into account losses of tr... of both populations, a transmission fact... tion of those stages produced by the a... which gain entry to the host populatio... is defined as $H(t)/(H_0+H(t))$, where H_0 ... the efficiency of transmission (MacDon...

parasitological interest. It is assumed that if the parasite fails to 'control' host population growth, exponential increase occurs until resource limitation leads to a gradual approach to the carrying capacity of the host's environment.

The rate of parasite-induced host mortalities

In the Basic Model it is assumed that the rate of parasite-induced host mortalities is linearly proportional to the number of parasites a host harbours (Fig. 3A and B). The number of host deaths (over and above the natural mortality rate) in a small interval of time δt, among hosts harbouring i parasites is represented as $\alpha i\ \delta t$, where α is a constant determining the pathogenicity of the parasite to the host. In the examples shown in Fig. 3A and B, the parameter α is equivalent to the slope of the linear models fitted through the observed death rates. The net rate of loss of hosts in a population of size $H(t)$ is therefore

$$\alpha H(t) \sum_{i=0}^{\infty} ip(i).$$

The term $p(i)$ represents the probability that a given host contains i parasites. This probability is conditional on i, and on various parameters characterizing the parasite's distribution within the host population. The above sum is by definition the mean number of parasites/host at time t

$$\sum_{i=0}^{\infty} ip(i) = E_t(i) = P(t)/H(t)$$

and hence the net rate of parasite-induced host mortalities reduces to

$$\alpha P(t). \tag{1}$$

Parasite fecundity and transmission

The rate of production of transmission stages (such as eggs, cysts or spores) per parasite is defined as λ, leading to a net rate for the total parasite population $P(t)$ of

$$\lambda H(t) \sum_{i=0}^{\infty} ip(i) = \lambda P(t). \tag{2}$$

The transmission stages will, in many life-cycles, pass out of the host into the external environment and survive in this habitat as resistant stages or free-living larvae awaiting contact with or ingestion by a host. While in the external habitat only a proportion of those produced will become adult parasites within or on a host. The magnitude of the proportion will depend on a variety of factors which include physical parameters of the environment such as temperature and humidity. One factor is of particular importance in determining transmission rates. This is the density of such stages in the habitat in relation to the density of hosts/unit area. In order to take into account losses of transmission stages and the relative densities of both populations, a transmission factor is defined which determines the proportion of those stages produced by the adult parasite population in the interval δt which gain entry to the host population. For the purpose of simplicity this factor is defined as $H(t)/(H_0+H(t))$, where H_0 is a constant which inversely determines the efficiency of transmission (MacDonald, 1961). The behaviour of this factor is

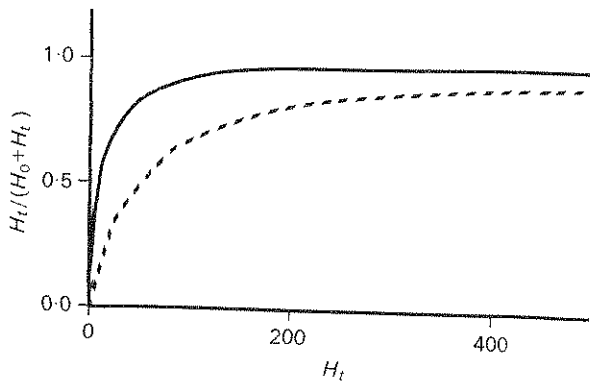

Fig. 4. The behaviour of the transmission factor, defined as $H_0/(H_t+H_0)$ in relation to host population density H_t. Solid line, $H_0 = 10$; dashed line, $H_0 = 50$.

demonstrated in Fig. 4. When $H(t)$ is large and H_0 small, the efficiency approaches unity, where all the transmission stages produced become adult parasites. Conversely when $H(t)$ is small and H_0 large only a small proportion are successful.

The net rate at which new parasites are acquired within the host population is therefore

$$\lambda P(t)H(t)/(H_0+H(t)).$$

This term contains the assumption that transmission proceeds without the occurrence of a time delay due to developmental processes. Such delays sometimes occur between the birth of a transmission stage and contact with a new host. In certain cases such stages are immediately infective to a new host, but in the majority of life-cycles specific biological processes have to occur, such as the hatching of a nematode egg and the development to the L_3 larval stage, before infection can proceed.

The assumptions incorporated in the models described in this paper are most closely linked to direct life-cycle parasitic species. The population dynamics of indirect life-cycle species can be interpreted in the light of the models' predictions if the population processes acting on the intermediate host, or hosts, and the parasite larval stages are subsumed into the transmission term (equation 3).

Parasite mortalities

Three distinct components contribute to the rate of parasite losses. Firstly losses occur due to natural host mortalities at the net rate of

$$bH(t)\sum_{i=0}^{\infty} ip(i) = bP(t). \qquad (4$$

Losses also result from parasite-induced host mortalities, where the death rate of a host harbouring i parasites was defined as αi (equation 1). The net parasite loss rate from the total host population due to such host deaths is therefore

$$\alpha H(t)\sum_{i=0}^{\infty} i^2 p(i). \qquad (5$$

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The third component of parasite loss is generated by natural parasite mortalities within individual hosts. The term natural parasite mortalities is used to encompass deaths due to host immunological attack and to parasite senescence. It is assumed that these occur at a constant rate/parasite, where the net loss from the total population is

$$\mu P(t). \tag{6}$$

Regulatory processes in the dynamics of host–parasite associations

The population components listed above (which contain specific biological assumptions) can be assembled to form a Basic Model consisting of two equations describing the trajectories of the host and parasite populations through time. The mathematical properties of this assemblage have been investigated in two previous publications (Anderson & May, 1978; May & Anderson, 1978). For the interested reader, an outline of the mathematical form of the Basic Model is given in an Appendix. This Appendix also contains brief comments on the procedure used to explore the behaviour of the model.

Investigations of the biological properties of theoretical models can proceed along a number of lines. The approach adopted in this paper is based on the ecological concepts of population regulation and stability (see May, 1975). More specifically we can use the theoretical framework to pose a simple question which highlights the importance of these concepts. What kinds of biological mechanisms lead to regulate growth to population equilibria and enhance the stability of host–parasite associations? (We can also pose the converse question concerning destabilizing influences.) If certain types of processes act in a stabilizing or regulatory manner we can then see if they occur in natural host–parasite associations in the real world.

Within a theoretical framework, a parasite is capable of regulating the growth of its host population if the model counterpart predicts population growth to a positive equilibrium or steady state. The stability of this equilibrium can be examined by monitoring the trajectories of the host and parasite population after the equilibrium state has been perturbed by small (neighbourhood stability analysis) or large (global stability analysis) displacements. If the system settles back to the equilibrium it can be regarded as stable. In contrast, if the population either grows exponentially or moves to extinction the association is regarded as unstable. For any given host–parasite association, certain numerical values of the population rate parameters (i.e. birth, death and transmission rates) will lead to regulated host and parasite population growth where an equilibrium state is achieved, while other values will generate unregulated growth. We can therefore delineate domains in the population parameter space (created by all the numerical values of the rates which can occur in the real world) which give rise to either regulated or unregulated growth patterns. In a similar manner, within the region of population parameter space which leads to regulated growth, we can define areas which lead to either stable or unstable population equilibria. The methods required to examine both local and global stability of population equilibria are documented by May (1975).

In the real world, populations are continually perturbed (i.e. by fire, climate or man's activities) and hence observed host–parasite associations should be characterized by population parameter values which generate stability if they are to persist on an evolutionary time scale.

There is an increasing body of evidence that suggests that the population parameter values which are observed in animal associations within natural communities are very far from being a haphazard selection of all numerically possible values (May, 1975; Southwood, 1976, 1977; Hassell, Lawton & May, 1976; Beddington, Free & Lawton, 1976).

The Basic Model of the dynamics of host–parasite associations (formed from the components defined in equations (1) to (6) and in the Appendix), in which it is assumed that the parasites are distributed randomly within the host population possesses the following dynamical properties.

The most important pattern to emerge, concerns the regulatory influence of the parasite on host population growth. Provided the host population intrinsic growth rate is positive ($a-b > 0$) the parasite is able to regulate growth if

$$\lambda > \mu+a+\alpha.$$

This condition requires the parasite 'birth' rate (λ) to be greater than the sum of the host birth rate (a), parasite natural mortalities (μ) and losses due to parasite-induced host mortality (α). If this condition is not satisfied the host population grows exponentially until finite resources limit growth or other factors such as predation or inter-specific competition come into play.

Empirical evidence and parasitological folk-lore strongly support the model prediction that the parasite should reproduce at a faster rate than its host if regulation is to be achieved. Theory further suggests, however, that the degree to which the parasite reproductive capabilities are in excess of its host depends on both the parasite death rate (μ) and the rate of parasite-induced host mortality (α). The order of magnitude of the difference between parasite and host should be high when μ is large, perhaps as a result of the immunological defences of the host. Similarly, if the parasite is very harmful to the host (α large) then λ must be high to compensate for parasite losses due to host mortality. In natural associations some of the widest margins between host and parasite reproductive potentials occur between mammalian hosts and their protozoan parasites (i.e. species of *Plasmodium*, *Eimeria* and *Trypanosoma*). These associations are often characterized by the highly developed, and often very efficient, immunological response of the host to parasitic infection (generating high parasite mortality rates (μ)). In certain cases, protozoan parasites may cause severe host mortality (high values of α) (Bruce-Chwatt & Bruce-Chwatt, 1974). Generally speaking, therefore, the theoretical predictions of the model appear to accord with certain observed patterns in the values of population parameters in natural host–parasite associations.

The Basic Model suggests that parasites can regulate host population growth (given certain combinations of population rate parameter values) giving rise to

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equilibrium states for both the host and parasite populations. However, are these steady states stable to environmental perturbation?

The model has structurally unstable properties, namely neutral stability (Anderson & May, 1978). Once perturbed from their equilibrium points, the host and parasite populations will oscillate with a period determined by the values of the rate parameters and an amplitude dictated forever after by the size of the initial displacement. The behaviour of a frictionless pendulum is analogous to this pattern. Neutrally stable models are structurally unstable since slight changes in the basic biological framework of the model will precipitate the system into either stable or unstable behaviours (see May (1975) for a fuller discussion of this point).

What types of biological mechanism shift the system from the knife edge of neutral stability into areas of stable dynamical behaviour? The following section of this paper considers three categories of biological processes commonly observed in natural host–parasite associations.

Over-dispersion of parasite numbers/host

The Basic Model contains the assumption that parasites are randomly distributed within their host populations. Empirical evidence does not support this assumption. The vast majority of observed frequency distributions in natural communities are over-dispersed where a relatively few members of the host population harbour the majority of the total parasite population (e.g. Williams, 1944; Cole, 1949; Frankland, 1954; Williams, 1963; Crofton, 1971*a*; Pennycuick, 1971; Schmid & Robinson, 1972; Anderson, 1974*a*; Boxshall, 1974; Randolph 1975).

The negative binomial probability model has proved to be a good empirical descriptor of such patterns and Fig. 5 portrays the adequacy of this model in describing the dispersion of helminth and arthropod parasites of vertebrate hosts. A large number of biological processes generate parasite contagion (Anderson, 1976*a*; Anderson, Whitfield, Dobson & Keymer, 1978), but the precise nature of the generative mechanisms is unimportant when considering the qualitative influence of over-dispersion on the dynamics of host–parasite associations.

Within the model framework, if the parasites are assumed to be over-dispersed within the host population, following a negative binomial pattern, globally stable population equilibria are produced by certain combinations of population rate parameters. More explicitly, the parasite is capable of regulating host population growth in a stable manner provided

$$\lambda > \mu + b + \alpha + (k+1)(a-b)/k, \tag{8}$$

where k is the parameter of the negative binomial which inversely measures the degree of aggregation or contagion of the parasites within the host population.

If this condition is satisfied, the trajectories of the host and parasite populations exhibit damped oscillations in time to globally stable equilibria (Fig. 6). In contrast, if the inequality (equation (8)) is not satisfied, the host population escapes the 'control' of the parasite and grows exponentially until finite resources, or other biotic factors, limit growth. Under these circumstances the parasite population

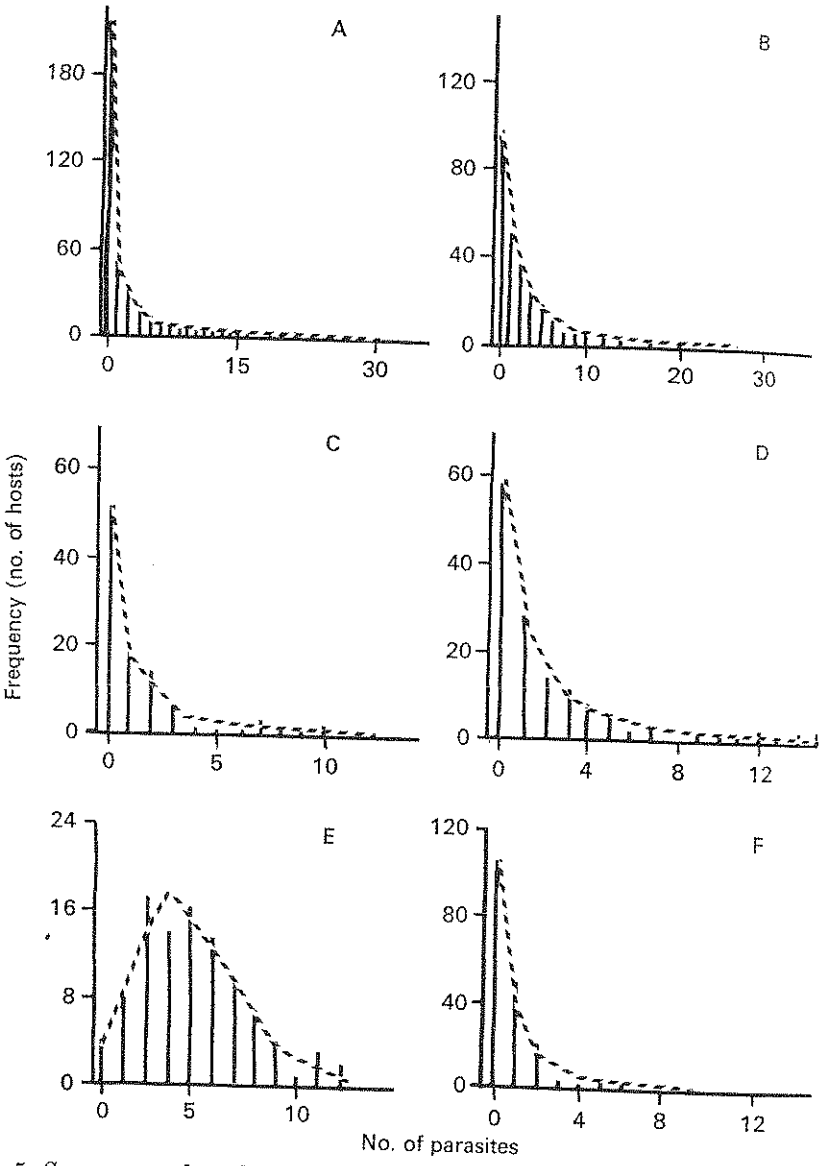

Fig. 5. Some examples of over-dispersed distributions of parasite numbers/host which are empirically described by the negative binomial model. The solid vertical bars represent the observed frequencies while the continuous dashed lines determine the expected frequencies predicted by the negative binomial. (A) The distribution of the tape-worm *Caryophyllaeus laticeps* within a population of the bream *Abramis brama*. (Data from Anderson, 1974*a*.) (B) The distribution of the monogenean *Diclodophora denticulatum* within a population of the marine fish *Gadus virens*. (Data from Frankland, 1955.) (C) The distribution of the acanthocephalan *Echinorhynchus clavula* within a population of sticklebacks *Gasterosteus aculeatus*. (Data from Pennycuick, 1971.) (D) The distribution of the nematode *Chandlerella quiscoli* in a population of the gnat *Culicoides crepuscularis*. (Data from Schmid & Robinson, 1972.) (E) The distribution of the copeopod *Lepeophtheirus pectoralis* on a population of the marine fish *Pleuronectes platessa*. (Data from Boxshall, 1974.) (F) The distribution of the tick *Ixodes trianguliceps* on a population of the field mouse *Apodemus sylvaticus*. (Data from Randolph, 1975.)

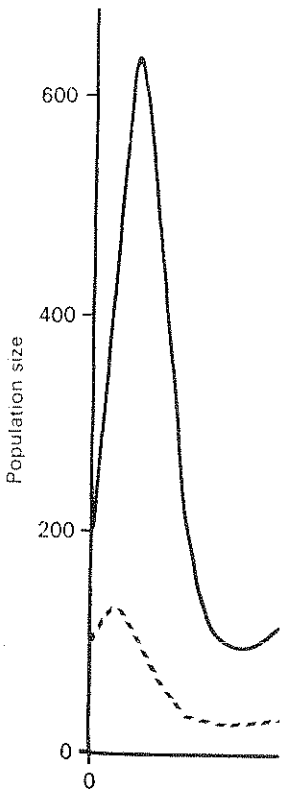

Fig. 6. The trajectories of popu
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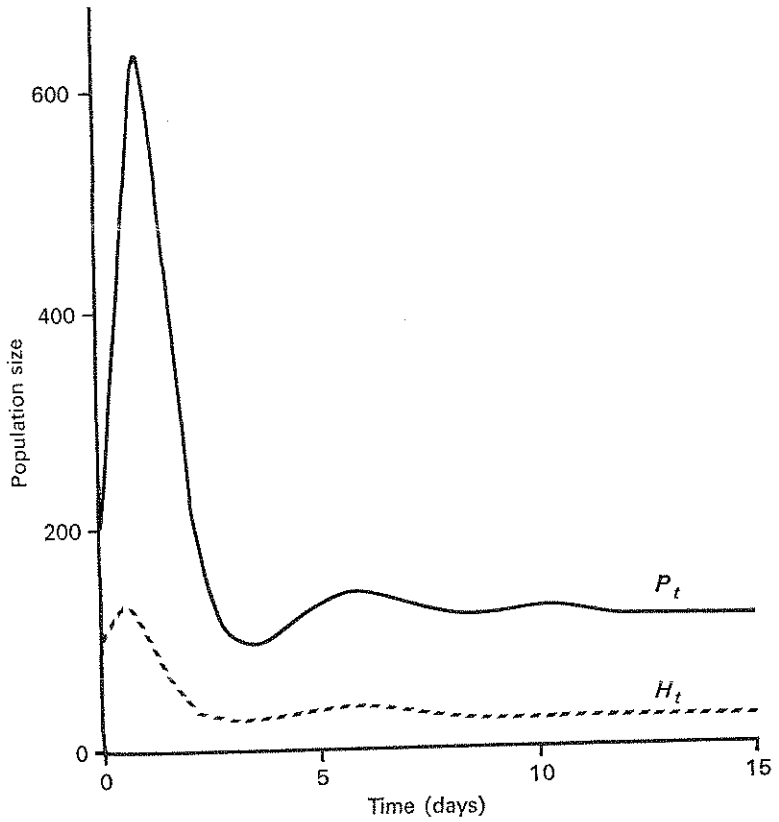

Fig. 6. The trajectories of populations of hosts (dashed line) and parasites (solid line) as predicted by the model in which it is assumed that the parasites are over-dispersed within the host population. The model exhibits damped oscillations to globally stable equilibria. The parameter values of the model are $a = 3{\cdot}0$, $b = 1{\cdot}0$, $\mu = 0{\cdot}1$, $H_0 = 10{\cdot}0$, $\alpha = 0{\cdot}5$, $\lambda = 6{\cdot}0$ and $k = 2{\cdot}0$.

will also grow exponentially but at a slower rate than the host and hence the mean parasite burden/host (P/H) will tend to zero.

To generate a parasite-regulated state, the parasite reproductive rate λ, must be larger than the host's intrinsic growth rate ($a-b$). In the case of over-dispersed distributions, however, the degree of aggregation of the parasites within the host population (measured inversely by k) plays an important role in determining whether the parasite can act in a regulatory capacity. If k is too small (parasites highly aggregated) equation (8) is difficult to satisfy for any value of λ, ($a-b$), α and μ, and hence the host population will tend to escape the control of the parasite. On the other hand, if k becomes large (dispersion tending to a random pattern) the condition is easy to satisfy and hence regulated population growth is more easily achieved. In such circumstances, however, the stability of the system breaks down due to the random pattern of dispersion and we revert to the state of neutral stability discussed previously. A moderate degree of over-dispersion is therefore desirable if regulation and stability are to be achieved. These points are more

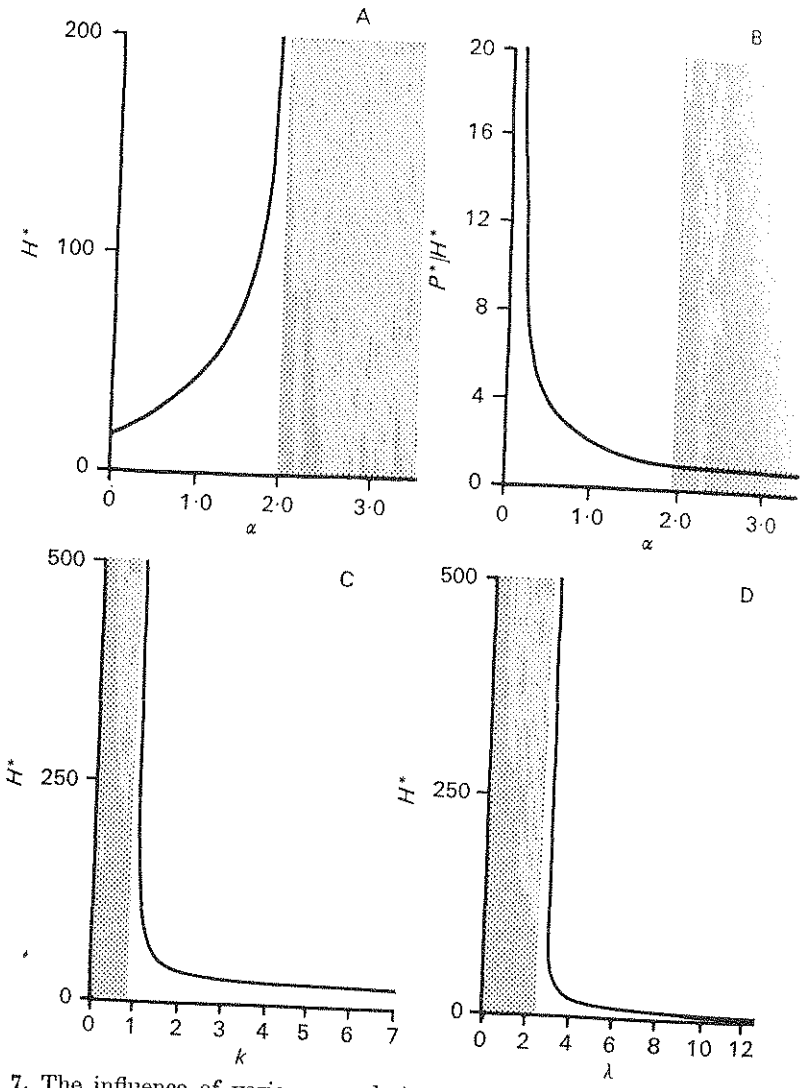

Fig. 7. The influence of various population parameters on the host equilibrium population size H^* and the equilibrium mean parasite burden P^*/H^*. The shaded regions denote areas in which parameter values do not lead to parasite regulated host population growth. The unshaded regions indicate areas of parameter values which generate locally stable equilibria. (A) The relationship between H^* and α, the rate of parasite-induced host mortalities ($\lambda = 6{\cdot}0$, $k = 2{\cdot}0$). (B) The relationship between P^*/H^* and α ($\lambda = 6{\cdot}0, k = 2{\cdot}0$). (C) The relationship between H^* and k, the parameter measuring inversely the degree of over-dispersion ($\lambda = 6{\cdot}0$, $\alpha = 0{\cdot}5$). (D) The relationship between H^* and λ, the rate of production of parasite transmission stages ($\alpha = 0{\cdot}5$, $k = 2{\cdot}0$). The general parameter values of the model are $H_0 = 10{\cdot}0$, $a = 3{\cdot}0$, $b = 1{\cdot}0$, $\mu = 0{\cdot}1$.

easily illustrated graphically by plotting the boundaries in population parameter space between values which give rise to either regulated or unregulated growth patterns. Fig. 7 A and B, for example, illustrates the effect of α, the rate of parasite-induced host mortality on the size of the host population equilibrium (H^*) and the steady-state mean parasite burden/host (P^*/H^*).

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As the parasite becomes more harmful to the host (α increases) the size of the host population rises; a pattern which appears counter-intuitive. This phenomenon is of major importance and is generated by a basic mechanism which is common to virtually all host–parasite associations. If a host dies due to the influence of parasitic infection, the parasites contained within are invariably killed. (There are two important exceptions to this general statement: larval parasites within intermediate hosts, where transmission results from a predator–prey association and certain species of ectoparasitic arthropods.) As α increases, many parasite-induced host deaths occur, and hence a large number of parasites are lost since those hosts which die contain more than the average burden of parasites. The total size of the parasite population therefore declines (as indicated by the mean burden (P^*/H^*) in Fig. 7B), and as a direct result, the regulatory influence of the parasites decreases. The host population is thus capable of increased growth to a higher equilibrium level. If α becomes too large, the resultant parasite population is too small to effectively regulate the growth of the host population.

The influence of the degree of contagion or aggregation of the parasites within the host population on the size of the host population equilibrium is interesting (Fig. 7C). When k is very small (parasites highly aggregated) the majority of the parasite population is centred on a few hosts. These few hosts suffer severe mortality rates due to their parasite burdens and hence the size of the total parasite population is drastically reduced. In such circumstances the host population may escape the controlling influence of the parasite. When k becomes large, the distribution approaches a random pattern and instabilities occur as discussed previously.

The effect of the rate of production of transmission stages (λ) on the equilibrium population sizes is illustrated in Fig. 7D. When λ is small the parasite fails to regulate host population growth and conversely, as λ increases in size the resultant host and parasite populations exhibit regulated growth patterns to stable equilibria.

The most interesting feature of the model predictions concerns the influence of the parameter α on the system. The model suggests that parasitic species which cause little harm or stress (small α) are the most effective regulators of host population growth. When parasites are extremely harmful they tend to fail to act in a regulatory manner since they cause the death of too many sub-populations of parasites within individual hosts. The commonly held notion of a 'successful parasite' being one which causes little harm to its host, gains support from these theoretical predictions. Low values of α appear to be very advantageous at the population level enhancing not only the regulatory role of the parasite but also the stability of the association.

The influence of the statistical distribution of parasite numbers/host on the dynamical properties of the model is also of importance. In natural populations of hosts, values of k are usually low, the parasites being highly over-dispersed where the majority are harboured by a relatively small proportion of the host population. The values of k listed in Table 2 represent observations covering a fairly wide cross-section of parasitic species. The majority of these values are less than 1 and therefore tend to suggest that parasites do not (in natural populations

Table 2. *Values of the negative binomial parameter* k *observed in natural population of hosts and parasites*

Taxonomic group of parasite	Parasite species	Host species	Range of k values	Author (s)
Platyhelminthes				
Monogenea	*Dicliidophora denticulata* (Olsson)	*Gadus virens* (L.)	0·684	Frankland (1954)
Digenea	*Diplostomum gasterostei* (Williams)	*Gasterosteus aculeatus** (L.)	0·097–0·705	Pennycuick (1971)
Cestoda	*Caryophyllaeus laticeps* (Pallas)	*Abramis brama* (L.)	0·115–0·478	Anderson (1974*a*)
	Schistocephalus solidus (Miller)	*Gasterosteus aculeatus** (L.)	0·740–2·380	Pennycuick (1971)
Nematoda	*Chandlerella quiscoli* (von Linstow)	*Culicoides crepusculariis** (Malloch)	0·488	Schmid & Robinson (1972)
	Toxocara canis (Werner)	*Vulpes vulpes* (L.)	0·469	Watkins & Harvey (1942)
	Ascaridia galli (Schrank)	*Gallus gallus* (L.)	0·696	Northam & Rocha (1958)
Acanthocephala	*Polymorphus minutus* (Goeze)	*Gammarus pulex* (L.)*	0·607–3·054	Crofton (1971*a*)
	Echinorhynchus clavula (Dujardin)	*Gasterosteus aculeatus* (L.)	0·067–0·474	Pennycuick (1971)
Arthropoda				
Copepoda	*Lepeophtheirus pectoralis* (Müller)	*Pleuronectes platessa* (L.)	0·280–9·800	Boxshall (1974)
	Chondracanthopis nodosus (Müller)	*Sebastes marinus* (L.)	0·607	Williams (1963)
	Chondracanthopis nodosus (Müller)	*Sebastes mentella* (L.)	0·223	Williams (1963)
Archnida	*Ixodes triangulíceps* (Birula)	*Apodemus sylvaticus* (L.)	0·0425–0·401	Randolph (1975)
	Liponysus bacoti (Hirst)	*Rattus sp.*	0·176	Cole (1949)
Insecta	*Pediculus humanis capitis* (L.)	*Homo sapiens* (L.)	0·144	Buxton (1940)

* Indicates intermediate host.

of hosts) play a major regulatory role. This prediction, however, must be accepted with considerable caution since the values of other population parameters such as x or λ are not known for the examples listed in Table 2. Unfortunately, estimates of such parameters are difficult to obtain from populations in the field.

Density-dependent constraints on parasite population growth

Population rate parameters, such as birth and death rates, are often functionally related to population density. The death rate of an organism, for example, may increase as population density rises due to intra-specific competition for finite resources.

The growth of a parasite sub-population within an individual host can also be influenced by density-dependent factors. Such mechanisms act on either the reproductive or death rates of the parasite and may be generated by either immunological attack mounted by the host, or intra-specific competition for finite resources such as space or nutrients. Some examples of density-dependent survival are shown in Fig. 8 where instantaneous parasite death rates (μ) are plotted against the number of parasites administered to a host.

Processes of this form are known to play an important regulatory role in the growth of free-living animal populations (Krebs, 1972). It is hardly surprising, therefore, that their inclusion in the host–parasite model results in regulated population growth to globally stable equilibria for a wide range of population rate parameter values (Anderson & May, 1978). What is surprising, however, is that density-dependent parasite survival can generate stable parasite-regulated host population equilibria even when the parasites are randomly distributed within the host population. This insight is of importance, since in the early stages of colonization of a host population, random distributions of parasite numbers/host are often observed (Fig. 9). Although these patterns may be of a transient nature, over-dispersion resulting with the passage of time, it is obviously important that such population associations are stable in their random phase. The presence of density-dependent processes enables stability to be achieved.

Density dependence is most commonly observed in survival processes (Fig. 8) but it may also operate on the reproductive rate of the parasite. Some examples of such responses are shown in Fig. 10, where the mean egg output/fluke of four helminth species is plotted against population density. Patterns of this form, as in the case of density-dependent survival, are generally created by either intra-specific competition or immunological attack. At the population level both types of density-dependent response act in an identical manner, promoting regulation and aiding stability.

The combined influences of over-dispersion and density dependence also lead to stable population equilibria. There is a tendency in such cases, however, for over-dispersion to limit the range of parameter values which lead to regulated population growth. This point is illustrated graphically in Fig. 11. High degrees of over-dispersion and severe density-dependent contraints on parasite survival create very heavy parasite losses. The net result is that the parasite population is too small to regulate host population growth. High rates of parasite-induced

Arthropoda	*Ixodes trianguliceps* (Birula)	0·176	Cole (1949)
Insecta	*Liponyssus bacoti* (Hirst)	0·144	Buxton (1940)
	Pediculus humanis capitis (L.)	*Rattus sp.*	
		Homo sapiens (L.)	

* Indicates intermediate host.

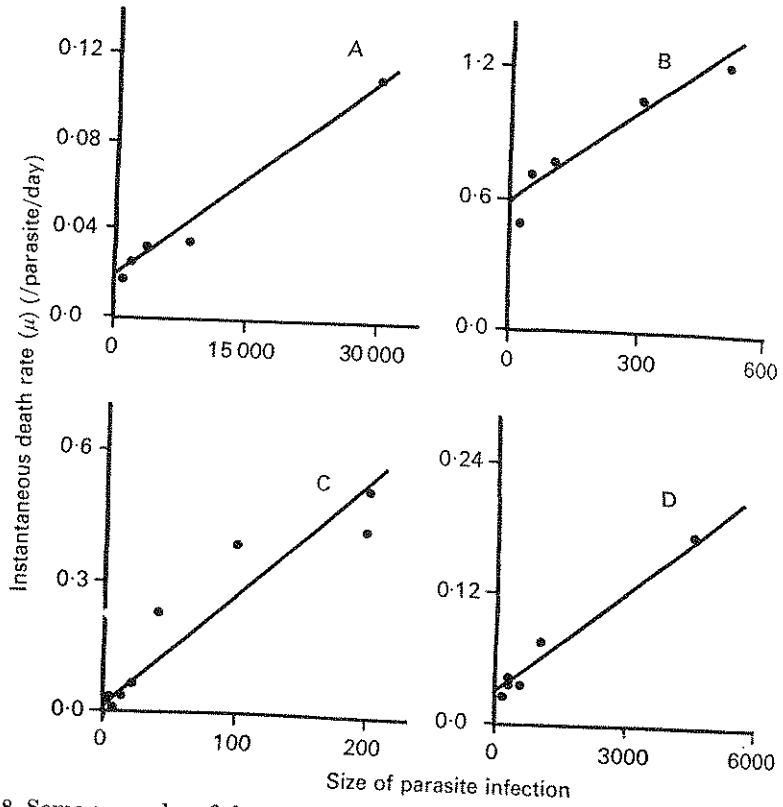

Fig. 8. Some examples of the relationships between the instantaneous natural death rate (μ) and parasite density (i) within individual hosts. The solid lines are the least squares best fit linear models of the form $\mu(i) = a+bi$, and the solid circles are observed points. (A) Calves infected with the gut nematode *Ostertagia ostertagi* ($a = 0{\cdot}0171$, $b = 0{\cdot}031 \times 10^{-5}$). (Data from Anderson & Michel, 1978.) (B) Chickens infected with the nematode *Ascaridea lineata* ($a = 0{\cdot}582$, $b = 0{\cdot}0014$). (Data from Achert, Graham, Nolf & Porter, 1931.) (C) Rats infected with tapeworm *Hymenolepis diminuta* ($a = 0{\cdot}0025$, $b = 0{\cdot}00254$). (Data from Hesselberg & Andreassen, 1975.) (D) Rats infected with nematode *Heterakis spumosa* ($a = 0{\cdot}0296$, $b = 0{\cdot}000032$). (Data from Winfield, 1932.)

host mortalities accentuate this problem leading to even heavier parasite losses (Fig. 12). Theory therefore suggests that, in natural animal populations, high values of parasite-induced host mortality, density-dependent parasite survival and severe degrees of over-dispersion should not be observed occurring together within a given parasite life-cycle. For example, if over-dispersion is severe, density-dependent contraints should in theory be weak. If all these rates are high within a specific life-cycle it would tend to suggest that factors other than parasitic infection regulate host population growth.

Non-linear parasite-induced host mortality

So far, model construction has been based on the assumption that the rate of parasite-induced host mortality (α) is linearly related to parasite burden (equation (1)). Often, however, as indicated in Fig. 3C and D, the relationship between host

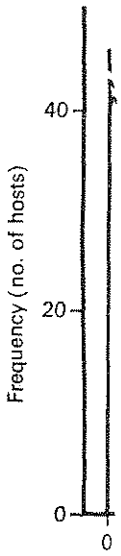

Fig. 9. Random distribution of
larval nematode *Cammallanus ox*
fish *Dorosoma cepedianum* samplec
Solid lines are observed frequencie
Poisson model.

death rate and parasite burden is
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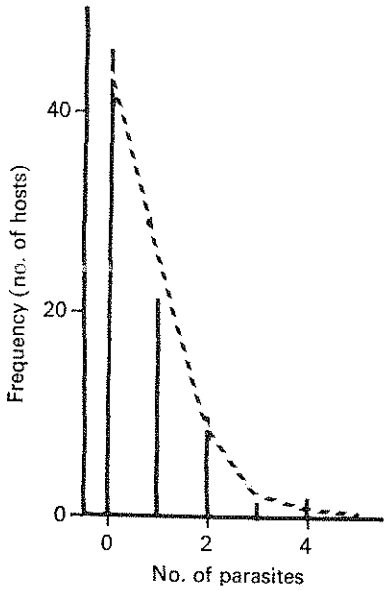

Fig. 9. Random distribution of parasite numbers/host. The distribution of the larval nematode *Cammallanus oxycephalus* in a population of young gizzard shad fish *Dorosoma cepedianum* sampled in August (data from Stromberg & Crites, 1974). Solid lines are observed frequencies and dashed lines are frequencies predicted by the Poisson model.

death rate and parasite burden is of a more severe form. In particular, such patterns often seem to follow a power law relationship.

Where parasites are randomly distributed within their host population, non-linear functional relationships of the power law type give rise to regulated population growth to stable equilibria even in the absence of density-dependent parasite survival or reproduction.

The model reveals a more complex pattern of behaviour in the case of under-dispersed patterns (the positive binomial distribution is an appropriate statistical model for such patterns; see Anderson, 1974*b*). Stable and unstable parasite-controlled host equilibria can arise depending on the numerical values of the various population rate parameters.

This point is portrayed in Fig. 13 where the relationship between the size of the host population equilibrium (H^*) and the value of the parameter α is plotted. Parasites which cause little damage to their hosts (low values of α) generate unstable equilibria while very harmful parasites fail to regulate the growth of the host population. Intermediary α values, however, generate stable equilibria.

The domains of parameter space giving rise to regulated population growth are always smaller when non-linear parasite-induced host mortality is present in comparison to the influence of relationships of a linear form. On the other hand, if regulated population growth occurs, the equilibria produced are extremely stable to perturbation. This feature can be explained intuitively since severe rates of parasite-induced host mortality tend to suppress the size of the parasite popula-

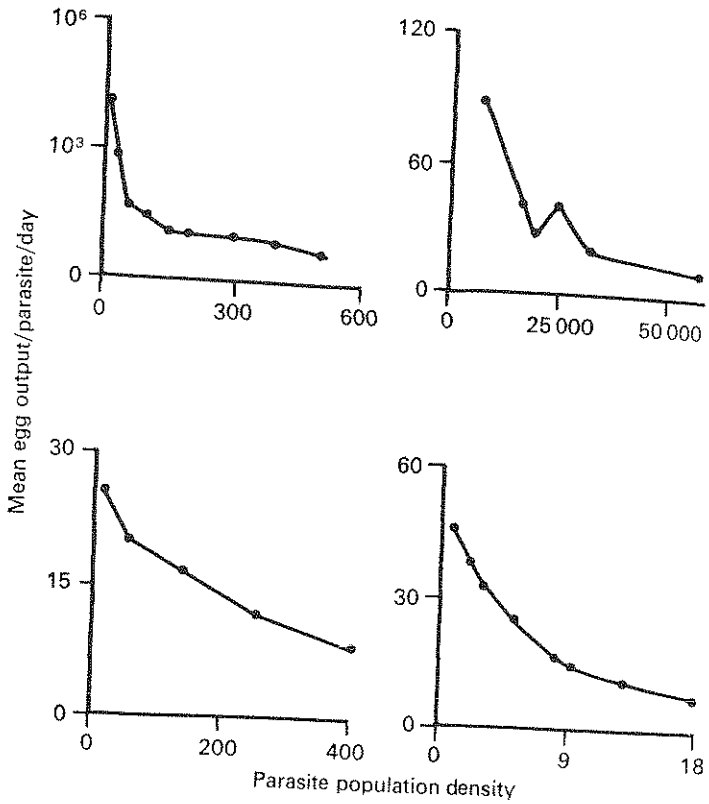

Fig. 10. Some examples of the influence of parasite population density within individual hosts on parasite reproduction rates. The relationships between the egg output of helminth parasites and population density. (A) Laboratory mice infected with the cestode *Hymenolepis nana*. (Data from Ghazal & Avery, 1974.) (B) Calves infected with the nematode *Ostertagia ostertagi*. (Data from Michel, 1969.) (C) Sheep infected with *Fasciola hepatica*. (Data from Boray, 1969.) (D) Mice infected with *Hymenolepis microstoma*. (Data from Jones & Tan, 1971.)

tion, particularly in the case of over-dispersed parasite distributions, and hence regulation of host population growth by the parasite is more difficult to achieve. If it is achieved, however, the additional non-linearities, which are in effect a type of density-dependent response, generate a high degree of stability.

In general, the model suggests, that if a parasite severely influences the survival rate of its host (more severely than a linear relationship between death rate and parasite burden) we should expect low degrees of over-dispersion if the parasite is a major influence in regulating host population growth.

Empirical evidence to support this prediction is not easy to come by. Certain helminth parasites, however, tend to exhibit patterns which loosely conform to this prediction. For example, many cestode and acanthocephalan species appear to be particularly harmful to their intermediate invertebrate hosts, only small numbers of parasites being able to infect a single host without causing extensive damage (i.e. *Polymorphus minutus* in the crustacean *Gammarus pulex*). These larval parasites although over-dispersed in their intermediate host populations

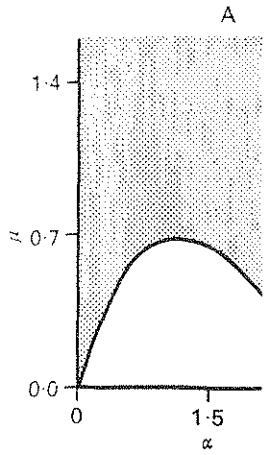

Fig. 11. Density-dependent e
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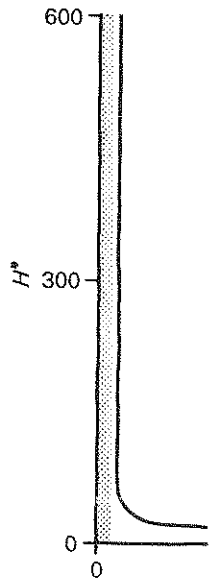

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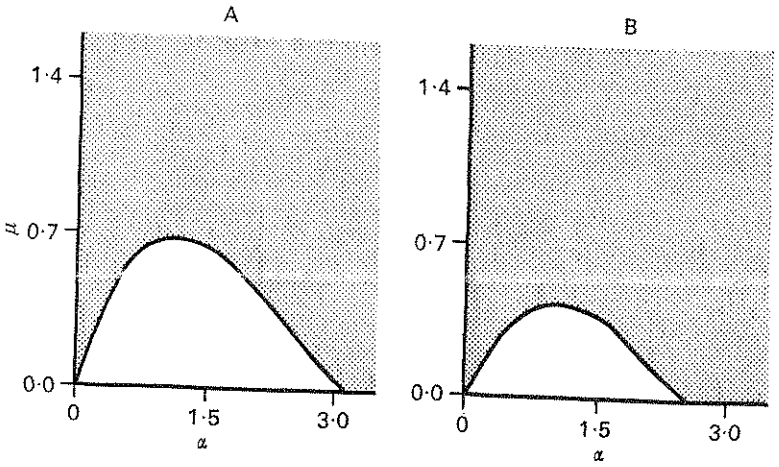

Fig. 11. Density-dependent constraints on parasite population growth. The solid lines enclose unshaded regions of parameter values, in the 2-dimensional space seated by the parameters μ and α, which lead to locally stable parasite-regulated equilibria. The shaded regions determine parameter values which lead to exponential growth where the parasite fails to regulate the host population. (A) Pattern predicted by the model in which parasites are randomly distributed (Poisson) within the host population ($H_0 = 10{\cdot}0, \lambda = 6{\cdot}0, a = 3{\cdot}0, b = 1{\cdot}0$). (B) Pattern predicted by the model in which parasites are over-dispersed (negative binomial) ($H_0 = 10{\cdot}0, \lambda = 6{\cdot}0, a = 3{\cdot}0, b = 1{\cdot}0, k = 4{\cdot}0$).

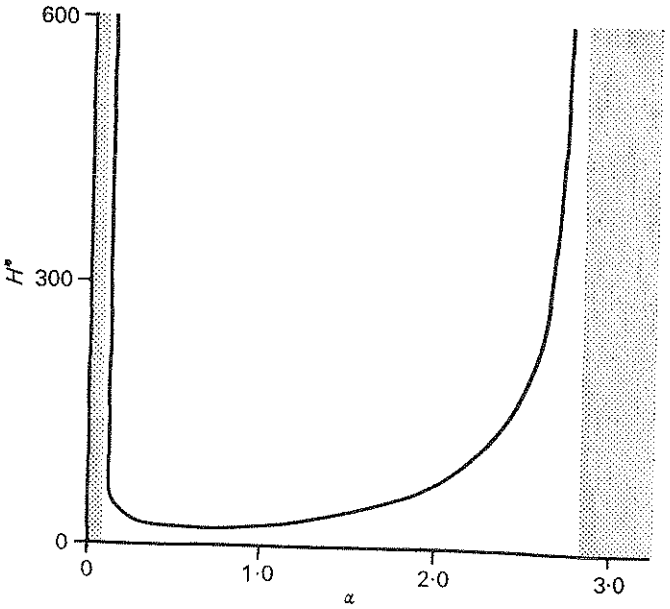

Fig. 12. Density-dependent constraints on parasite population growth. The influence of the parameter α on the numerical size of the host population equilibrium H^* (parasites randomly distributed within the host population). The shaded region defines parameter values which lead to unregulated growth, while the unshaded region denotes parameter values which lead to locally stable equilibria (solid line) ($\mu = 0{\cdot}1, H_0 = 10{\cdot}0, \lambda = 6{\cdot}0, a = 3{\cdot}0, b = 1{\cdot}0$).

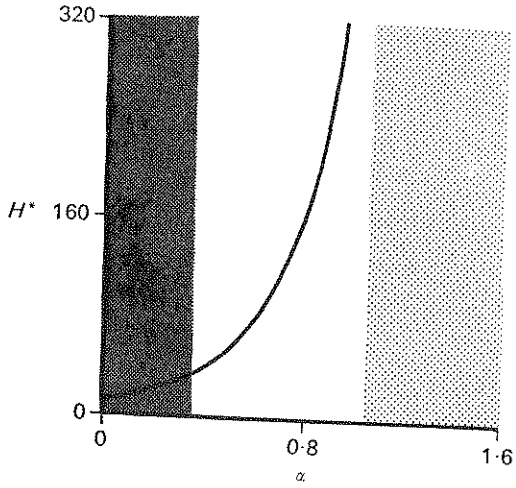

Fig. 13. Non-linear functional relationships between the rate of parasite-induced host mortalities and parasite burden. The influence of the parameter α on the size of the host population equilibrium H^* (solid line), when the parasites are under-dispersed within the host population (positive binomial). Darkly shaded regions: parameter values which give rise to locally unstable equilibria; unshaded regions: locally stable equilibria and lightly shaded regions, no equilibria at all (host exhibits exponential growth) ($H_0 = 10{\cdot}0, \lambda = 6{\cdot}0, a = 3{\cdot}0, b = 1{\cdot}0, k = 20{\cdot}0, \mu = 0{\cdot}1$).

do not tend to exhibit the same degrees of aggregate as shown by their adult forms in the vertebrate definitive host. In the adult form the parasites are highly aggregated and furthermore do not appear to markedly influence host survival unless present in very large numbers. These observations, however, are of a rather qualitative and subjective nature. Support for, or disproof of the hypothesis outlined above must await more detailed studies of the population parameter values occurring in various types of parasite life-cycle.

Destabilizing processes in the dynamics of host–parasite associations

In the previous section of this paper, three categories of population processes were shown to be of particular significance in stabilizing the growth of host and parasite populations. This section, in contrast, considers biological mechanisms which tend to disrupt the stability of host–parasite associations.

Parasite-induced reduction in host reproductive potential

Changes in host reproduction, as a result of parasitic infection, are commonly associated with helminth infections in vertebrate or invertebrate intermediate hosts (the influence of larval digeneans on molluscan hosts and larval cestodes on fish species), and crustacean infections in arthropods (the influence of parasitic cirripedes on various species of crab).

In some cases, the degree of reduction in fecundity is dependent on the burden of parasites harboured by a host. For example, reduction in egg-laying by *Biomphalaria truncatus* infected with *Schistosoma haematobium* is related to the number of miracidia that have invaded the mollusc (Chu, Sabbaghian & Massoud, 1966).

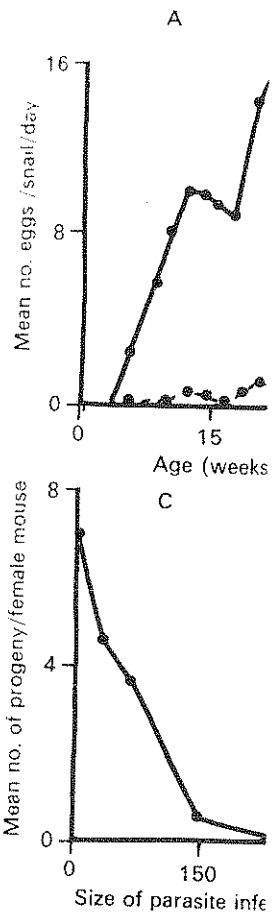

Fig. 14. Some examples of the rates of infected hosts. (A) *Bion* (Data from Sturrock, 1966.) (B with a Brachylaemid digenean tory mice infected with the larv from Weatherly, 1971.) (D) *Lyn* (Data from McClelland & Boun

Sometimes, molluscan hosts ma tion is lost (Berrie, 1970) but m 1971).

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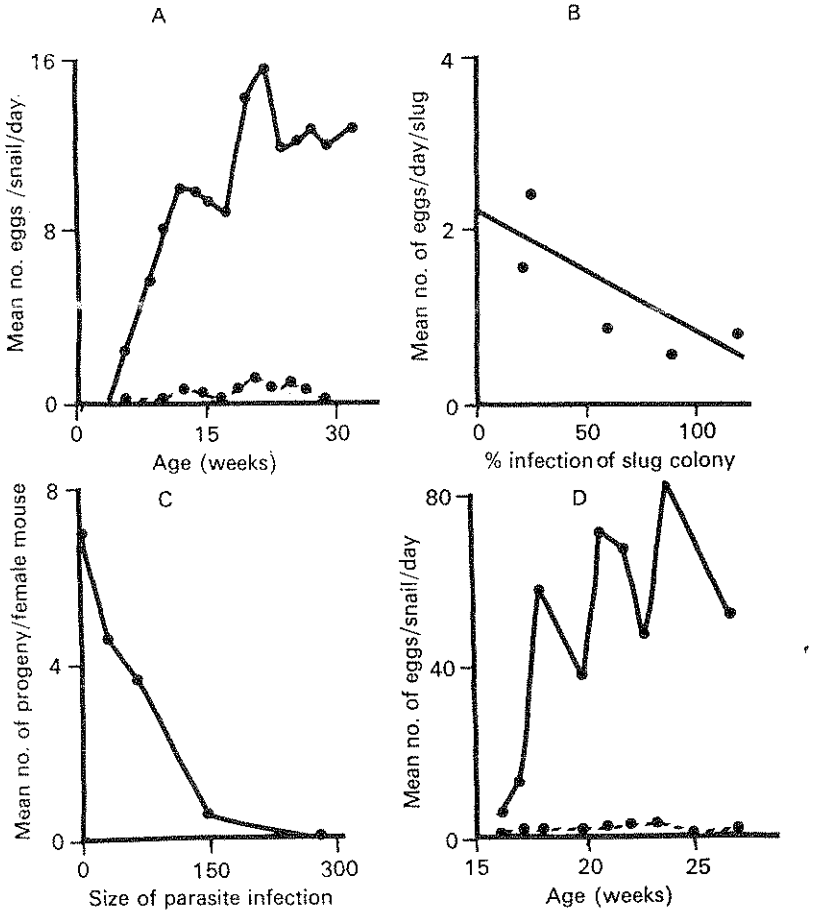

Fig. 14. Some examples of the influence of helminth parasites on the reproductive rates of infected hosts. (A) *Biomphalaria pfeifferi* infected with *Schistosoma mansoni*. (Data from Sturrock, 1966.) (B) Colonies of the slug *Agriolimax reticulatus* infected with a Brachylaemid digenean metacercaria. (Data from Foster, 1958.) (C) Laboratory mice infected with the larval stages of the nematode *Trichinella spiralis*. (Data from Weatherly, 1971.) (D) *Lymnaea stagnalis* infected with *Trichobilharzia ocellata*. (Data from McClelland & Bourns, 1969.)

Sometimes, molluscan hosts may resume normal egg-laying if the digenean infection is lost (Berrie, 1970) but more usually permanent damage is created (Wright, 1971).

Total loss of reproductive ability is relatively uncommon and usually associated with crustacean infections in crustacean hosts (i.e. *Sacculina gregaria* in the crab *Eriocher japonicus*). In general, parasites tend to diminish but not completely eliminate host reproduction. A number of quantitative examples of parasite-induced changes in host reproduction are shown in Fig. 14.

When parasites are over-dispersed within the host population certain combinations of population rate parameter values lead to regulated patterns of population growth. Parasite-induced reduction in host reproductive potential, however, tends

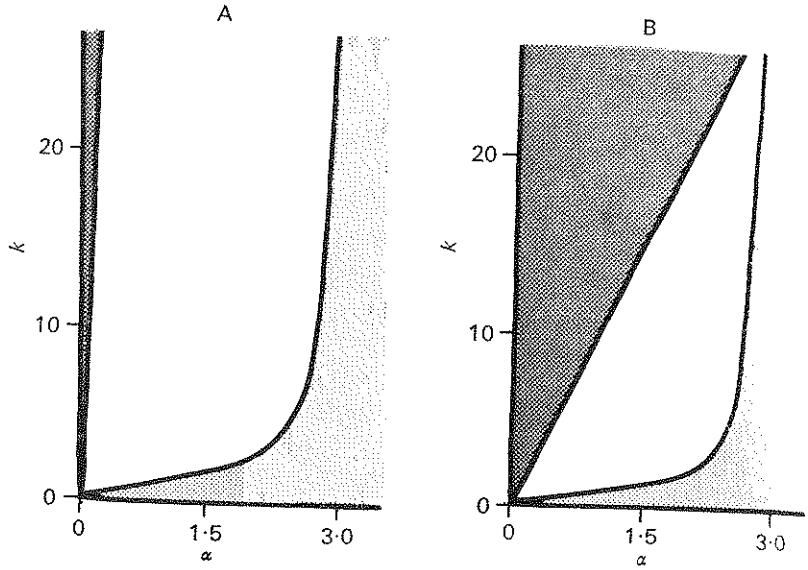

Fig. 15. Parasite-induced reduction in host reproductive potential (parasites are assumed to be over-dispersed within the host population, following the negative binomial pattern). The influence of the parameters k, and α, on the dynamical properties of the model. The solid lines enclose unshaded regions in the $k-\alpha$ parameter space in which globally stable parasite-regulated host population equilibria occur. These boundaries are shown for two different values of β, which determines the severity of the parasite's influence on host reproduction. (A) $\beta = 0{\cdot}01$, (B) $\beta = 0{\cdot}1$. The lightly shaded regions denote parameter values which lead to unregulated host population growth while the darkly shaded areas indicate parameter values which give rise to globally unstable equilibria. The parameter values of the model are: $a = 3{\cdot}0, b = 1{\cdot}0, \mu = 0{\cdot}1, H_0 = 10{\cdot}0, \lambda = 6{\cdot}0$.

to limit the range of values, within this domain of parameter space, which lead to stable equilibria.

Where β defines the magnitude of the parasite's influence on host reproduction, May & Anderson (1978) have demonstrated that equilibria are only stable provided

$$\alpha > \beta k. \tag{9}$$

This statement implies that the parasite's influence on host reproduction (β) must not be too severe in relation to its influence on host survival (α). If β is large, then k, the parameter measuring the degree of over-dispersion of parasites within the host population, must be small (parasites highly aggregated).

Further insights into the meaning of these conditions for stability can be obtained by plotting the boundaries between regions in parameter space which give rise to unregulated, stable and unstable states. These areas are shown for the parameters α and k in Fig. 15. As the severity of the parasite's influence on host reproduction increases (β becomes large), it becomes more difficult to achieve a parasite-regulated host equilibrium. This is especially true if the parasites do not exhibit a marked degree of over-dispersion (k large) and fail to severely restrict host survival (α small).

When parasites are randomly distributed within their host population, it was

demonstrated in the previous section that regulated growth could be achieved provided density-dependent processes placed constraints on the parasite population. The presence of parasite-induced reduction in host reproduction, in association with these characteristics, tends to have a destabilizing influence.

Population equilibria are only stable provided

$$\mu > \beta. \tag{10}$$

In other words, stability only occurs when the severity of density-dependent parasite survival (μ) is greater than the effects of the parasite on host reproduction.

These predictions are of some biological interest since they suggest that the stability of a host–parasite association can be seriously impaired when the parasite decreases host reproductive potential. Stable interactions are possible provided over-dispersion is present or density-dependent constraints operate on parasite survival or reproduction.

Many natural associations persist despite the parasite substantially altering host reproductive capabilities. Theory suggests that such interactions should be characterized by either over-dispersion or density dependence. Empirical evidence lends some support to this prediction. For example, parasitic crustacea often influence host reproduction but are invariably highly over-dispersed within their host populations (see Boxshall, 1974; Williams, 1963). Furthermore, larval digeneans, which have a pronounced influence on the reproduction of their molluscan hosts, often exhibit density-dependent population growth within individual snails (Lim & Lie, 1969).

Parasite reproduction within the host

A number of parasites, particularly protozoan species, reproduce within their final host, directly contributing to population growth. In population terms, reproduction of this form is distinct from the production of transmission stages which either pass to the exterior in the faeces or into a blood-sucking vector. For clarity, the two types of birth processes are termed transmission (λ) and direct reproduction (r).

The coccidian and amoeboid parasitic protozoa exhibit both forms of reproduction within a direct life-cycle. *Entamoeba hystolytica*, for example, lives in the alimentary tract of man and multiplies by monotomic fission to directly increase its population size within the host. Periodically, small pre-cystic individuals are formed which give rise to a resistant cyst, which is discharged with the faeces into the external environment. If such a cyst is ingested by a suitable host, the protozoan excysts and resumes growth and reproduction (Dogiel, 1965).

Intuition suggests that the occurrence of both direct and transmission reproduction within a life-cycle will tend to create more complex dynamical patterns of population growth. These patterns will undoubtedly differ from those produced by cycles in which transmission births are the only reproductive phase (i.e. helminths such as *Trichuris trichuria*, the nematode parasite of man).

Intuitive feelings in this matter are borne out by theoretical studies. The in-

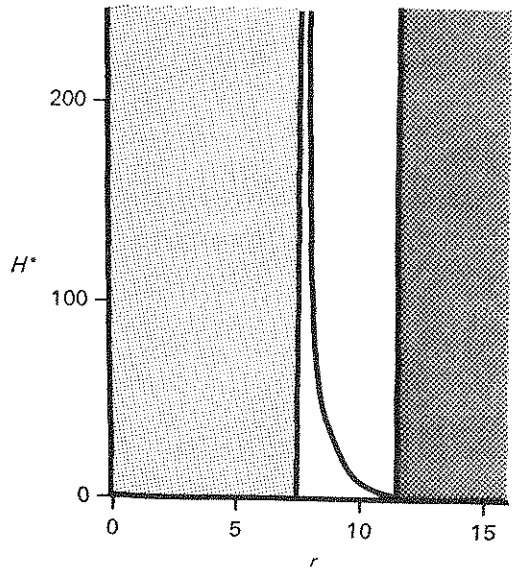

Fig. 16. Parasites which exhibit both transmission and direct reproduction (parasites are assumed to be over-dispersed within the host population following the negative binomial pattern). The relationship between the size of the host population equilibrium H^* and the rate of direct reproduction r. In the unshaded regions the equilibria are stable, in the darkly shaded regions both host and parasite populations become extinct and in the lightly shaded regions the parasite fails to regulate host population growth. The parameter values of the model are, $a = 3{\cdot}0$, $b = 1{\cdot}0$, $\mu = 0{\cdot}1$, $H_0 = 10{\cdot}0, \lambda = 4{\cdot}0, k = 0{\cdot}2, \alpha = 0{\cdot}5$.

clusion of direct reproduction with the host–parasite models results in the occurrence of three distinct patterns of population growth (May & Anderson, 197[illegible]. Parasite regulated host equilibria only occur provided

$$\lambda + r > d > r, \tag{11}$$

where

$$d = \mu + \alpha + b + (a-b)(k+1)/k. \tag{12}$$

The parameter r measures the rate of direct parasite reproduction. When the rate of direct reproduction is very high, extensive host mortalities occur due to explosive growth of the parasite within individual hosts ($r > d$). Under such circumstances both host and parasite are likely to become extinct. On the other hand if the transmission and direct reproduction rates are too low in comparison to the host's intrinsic growth rate, the parasite fails to regulate host population growth ($\lambda + r < d$). The three patterns of behaviour are, therefore, regulated growth to stable equilibria, extinction of both host and parasite or unregulated exponential growth of the host population (Fig. 16).

The domains in the λ (transmission reproduction), r (direct reproduction) and α (rate of parasite-induced host mortalities) parameter space, which lead to the various patterns of population growth are portrayed in Fig. 17. Too large values of r lead to extinction, while too small values generate unregulated population growth. Over-dispersion tends to suppress the destabilizing influence of direct

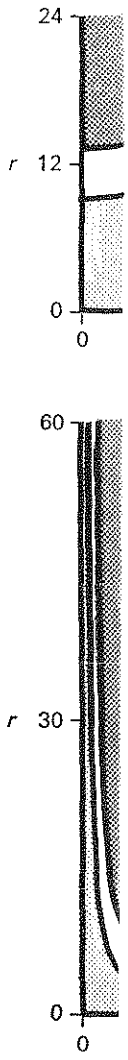

Fig. 17. Parasites which exhibi[illegible] are assumed to be over-dispers[illegible] binomial pattern). The unsha[illegible] defined for Fig. 15. (A) The in[illegible] tion rate) and α (rate of para[illegible] model. (B) The influence of th[illegible] of aggregation of the parasite[illegible] model. Both graphs demonstra[illegible] to stable parasite-regulated ho[illegible] and some to unregulated popu[illegible] model are: $a = 3{\cdot}0$, $b = 1{\cdot}0$, μ[illegible] $\alpha = 0{\cdot}1$.

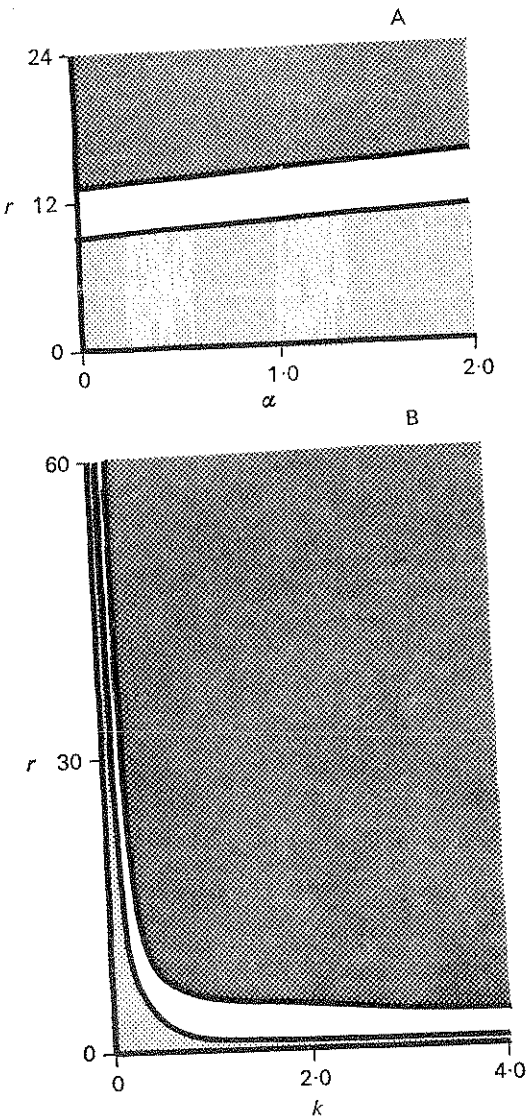

Fig. 17. Parasites which exhibit both transmission and direct reproduction (parasites are assumed to be over-dispersed within the host population following the negative binomial pattern). The unshaded, lightly shaded and darkly shaded regions are as defined for Fig. 15. (A) The influence of the parameters r (direct parasite reproduction rate) and α (rate of parasite-induced host mortalities) on the stability of the model. (B) The influence of the parameters r and k (inversely measuring the degree of aggregation of the parasites within the host population) on the stability of the model. Both graphs demonstrate that certain combinations of parameter values lead to stable parasite-regulated host population equilibria, others to unstable equilibria and some to unregulated population growth. The remaining parameter values of the model are: $a = 3{\cdot}0$, $b = 1{\cdot}0$, $\mu = 0{\cdot}1$, $H_0 = 10{\cdot}0$, $\lambda = 4{\cdot}0$. In A, $k = 0{\cdot}2$ and in B, $\alpha = 0{\cdot}1$.

parasite reproduction. For example, Fig. 17 demonstrates that small values of k (high degree of over-dispersion) help to reduce the chances of extinction of density-regulated population growth even when r is large.

In the real world, values of r tend to be extremely large when compared with host reproductive capabilities. Many parasitic protozoa possess enormous asexual reproductive capacities in the nutrient-rich environments (such as the liver or blood system) within vertebrate hosts. *Plasmodium falciparum*, for instance, can produce in excess of 30000 merozoites by mitotic divisions from one schizont during the exo-erythrocytic stage of its life-cycle (Baker, 1968). The merozoites can be produced within the space of 5 days, and hence if it is assumed that 5 mortalities occur during this period, the value of r for *P. falciparum* would be approximately 10·0/5-day period. A reproductive rate of this size is obviously very many orders of magnitude greater than that of its mammalian host. The model suggests that the danger of extinction of host and parasite populations created by such high r values can be decreased if parasite numbers/host are over-dispersed. Empirical evidence for the patterns of dispersion of protozoa within vertebrate hosts is unfortunately not available at present due to the enormous practical difficulties encountered in measuring the number of parasites/host.

Theoretical considerations, however, concerning the nature of exponential growth of a parasite population within an infected host, plus the chance nature of infection within a population of hosts suggest that parasites with direct reproductive capabilities should be over-dispersed. For example, it is interesting to note that a stochastic model of a pure birth process (a process shown by many protozoa during the early phases of population growth within a host), where the likelihood of a birth (or cell division) is subject to chance mechanisms, predicts a negative binomial distribution of parasite population size within a homogeneous host population (see Bailey, 1964). Any heterogeneity within the host population due to differing prior experiences of infections, would tend to increase the degree of over-dispersion of the parasites.

In addition to over-dispersion, other biological mechanisms help to diminish the chances of extinction caused by explosive parasite population growth (high r values). In particular, density-dependent mechanisms can act to restrain population growth within individual hosts. Such constraints may be caused by intra-specific competition or, more commonly, by immunological attack mounted by the host in response to the presence of the parasite.

The inclusion of density dependence in the host–parasite model reveals an interesting pattern of population behaviour (May & Anderson, 1978). Density-dependent constraints or either parasite survival (μ) or transmission reproduction (λ) allow high values of r to exist without causing host or parasite population extinction. This result holds even when the parasites are randomly distributed within the host population.

Some of the best documented accounts of immunological responses to parasitic invasion concern the reaction of mammalian hosts to protozoan infection. Many of these parasites such as species of *Plasmodium* and *Trypanosoma* have extremely high rates of direct reproduction and in certain cases show distinct patterns of

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density-dependent population growth within individual hosts (Viens, Targett, Leuchars & Davies, 1974; Targett & Viens, 1975).

Many protozoan–mammalian host associations have persisted through evolutionary time, despite the parasite possessing high direct reproductive potential. Theory and biological observation suggest that other population parameters, like density-dependent survival (μ) or degree of contagion (k) must have co-evolved in a compensatory manner to enhance population stability.

The influence of time delays

Time delays in parasite life-cycles can be generated by a variety of biological mechanisms. For example, a lag may occur between the production of a transmission stage (such as a nematode egg) and the point when this stage is infective to a new host. This type of delay is generally called a developmental lag and its length may often be functionally related to climatic factors such as temperature or humidity (Rose, 1956; Anderson, 1976*b*). Time delays can also be generated by density-dependent responses. High densities of a helminth parasite within a host at one instant in time may decrease egg production (λ) by individual parasites at some future point, due to the detrimental effects of intra-specific competition for finite food resources during early adult life. Alternatively, lags may be created by time-delayed immunological responses. The severity of an immune response at one point in time is often linked with the degree of antigenic stimulation (parasite population density) experienced at a preceding point in time.

A very simple way of introducing lags into population models, consisting of a set of differential equations, is to increase the number of equations in the set. The dynamics of a particular variable (such as parasite population size $P(t)$) can be delayed by having to 'move via' an extra equation. In host–parasite models where two equations are involved, describing changes in the host and parasite populations, delays can be incorporated by adding a third equation describing, for example, the dynamics of a pool of infective stages in the free-living environment population variable $w(t)$).

May & Anderson (1978) have shown that the inclusion of time delays in models of host–parasite interactions tends to have a destabilizing influence. Certain combinations of parameter values still lead to regulated growth to equilibrium states, but many of these states are unstable. Since time delays are commonly observed in natural host–parasite associations, it is to be expected that evolutionary pressures will have selected certain population rate parameter values to compensate for these destabilizing influences. May & Anderson (1978) have shown that one such compensatory mechanism is over-dispersion of parasite numbers/host.

Other ecological studies also suggest that time delays in the population dynamics of interacting and single species situations can have a destabilizing influence (May, Conway, Hassell & Southwood, 1974). Invariably, the degree of instability created by the introduction of a time delay depends on its length in relation to the natural generation time of the organism (i.e. time from egg to sexually mature adult). A similar relationship appears to exist in model host–parasite associations (May & Anderson, 1978).

CONCLUSIONS

The theoretical studies of host–parasite associations described in this paper are characterized by the central assumption that parasites influence, in a density-dependent manner, the natural intrinsic growth rate of their host population. It is argued that the net influence on this rate is related to the average parasite burden of the members of a host population, and hence to the statistical distribution of parasite numbers/host. The inducement of host mortalities and/or reductions in host reproductive potential is regarded as a necessary, but not sufficient, condition for the classification of an organism as parasitic. Sufficiency is created by a degree of habitat and nutritional dependence on the host.

It is apparent from the work described in this paper that parasites may, in certain circumstances, play an important role in regulating the growth of their host population. In this respect parasites will play an analogous role to predators who suppress the growth of their prey populations. Three specific groups of population processes appear to be of particular importance in stabilizing the dynamics of host–parasite associations. These are over-dispersion of the parasites within the host population, density dependence in parasite mortality or reproduction and parasite-induced host mortality that increases faster than linearly with the parasite burden.

Other biological features of host–parasite interactions tend to have a destabilizing influence, namely: parasite-induced reduction in host reproductive potential, direct reproduction of the parasites within individual hosts and time delays in the development of transmission stages of the parasite.

Host–parasite associations in the real world exhibit all the above effects to a greater or lesser extent. Theory therefore suggests that such population interactions are in tension between stabilizing and destabilizing elements. Evolutionary pressures will have acted to ensure that the balance between such forces is fairly robust to perturbations caused by environmental change. A reasonable inference is that the persistence of quasi-stable host–parasite associations, which we observe in real ecological communities, demand parameter values in their model counterparts which lead to stable population equilibria.

As pointed out at the beginning of this paper, an increasing number of ecological studies suggest that population rate parameter values which typify animal interactions in the real world are very far from being a haphazard selection of all numerically possible values. Unfortunately there are very few studies which provide quantitative estimates of all the population parameters involved in specific parasite life-cycles. The work described in this paper, however, tends to suggest the existence of certain relationships between the values of different parameters within host–parasite associations. Such predictions should in theory be testable against field or laboratory observations.

In the first place, theory suggests that parasites should reproduce at a much faster rate than their hosts. This observation is certainly supported by empirical evidence. Of more interest, however, is the magnitude of the difference between the two rates since this will indicate, in part, the regulatory potential of the

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parasite to constrain host population growth. Other rate parameters, such as the rate of parasite-induced host mortality (α) and natural parasite mortality rate (μ) also influence the regulatory potential of parasitic species. Parasite death rates can be measured by laboratory studies (Fig. 8) but the rate α is more difficult to determine. Conceptually, the difference in size between a host population equilibrium generated by parasitic regulation, and the carrying capacity of the host's environment (which would be reached in the absence of the parasite) will indicate the magnitude of the regulatory role played by a parasite. The rate α plays a large part in determining this difference within the model host–parasite associations. The equations of the model suggest that in natural populations of hosts an indication of the severity of the parasite's influence may be gained by measurement of the mean parasite load provided the association is in a steady-state situation (see equation A 12 in the Appendix). The smaller the mean, the greater the influence of the parasite on host mortality. This measure is rather crude, however, and should be used with a degree of caution.

The host–parasite models suggest that only certain values of the parameter α will lead to regulated host population growth. If the parasite is too harmful, too many parasites are killed by the deaths they induce and hence the host escapes the 'control' of the parasite. As mentioned earlier, the parasitological folk-lore notion that a 'successful' parasite is one that does little harm to its host gains some support from this observation. Care must be taken, however, in the blanket application of this concept. For example, high values of α can lead to stable regulated host and parasite population equilibria provided other parameter values, such as the parasite death rate (perhaps influenced by the immunological response of the host), act in a compensatory manner. Furthermore, within certain parasite life-cycles, where adjacent links in a predator food chain are traversed, certain advantages accrue from causing severe damage to the host. Many larval helminths, for example, gain access to the definitive host via the consumption of their intermediate host which is an attractive prey item. As mentioned earlier, one component of the rate of parasite-induced host mortality is the degree to which a parasite increases host morbidity and hence susceptibility to predation. In other segments of such life-cycles, in the definitive host for instance, low values of α would appear to be advantageous since the production of transmission stages occurs in these hosts. Provided immunological attack is not too severe, the longer the host lives the greater the output of parasite eggs.

Dispersion patterns of parasite numbers/host also play a major role in determining the dynamical properties of host–parasite associations. All types of pattern can lead to regulated host population growth given certain constraints on other population rate parameters. For example, random distributions create stable regulated host population equilibria provided density-dependent constraints operate on parasite mortality or reproduction. Similarly, under-dispersed patterns can occur, if the rate of parasite-induced host mortality increases faster than linearly with parasite burden. Over-dispersion is undoubtedly the most commonly observed pattern in natural host–parasite interactions and theory suggests that this feature is strongly regulatory in nature. Very severe patterns of

over-dispersion, however, may lead to the host escaping the regulatory influence of the parasite. Many observed patterns seem to be highly over-dispersed (Table 1). In such cases parasites will only act as regulatory agents provided density-dependent constraints act on parasite survival and reproduction. Such constraints could be generated by immunological processes produced by the host in response to parastic invasion.

Further theoretical predictions of interest concern the destabilizing influences of parasite-induced reduction in host reproductive potential and direct parasite reproduction within the host. These destabilizing effects may be counteracted by either high degrees of over-dispersion of parasite numbers/host or density-dependent constraints on parasite population growth. Some empirical evidence is available to support these predictions but in general, however, detailed support for or falsification of such ideas must await the acquisition of large numbers of quantitative parameter estimates for a wide variety of parasite life-cycles.

It is hoped that the preceding discussion emphasizes one of the principal uses of theoretical study in biology. Obviously such models do not correspond in detail to any single real parasite life-cycle, but they aim to provide a conceptual framework for the discussion of broad classes of phenomena. Such a framework serves a useful purpose in indicating areas or questions for the field or experimental parasitologist. The host–parasite models discussed in this paper indicate a variety of areas in which measurement of key population parameters would help to provide information on not only the stability of host–parasite associations and the regulatory potential of a parasite, but also the relationship between structure and dynamics of complex parasite life-cycles.

Theoretical population studies ultimately aim to explain observed fluctuations in animal numbers within natural or managed communities. Laboratory studies, however, provide the initial template against which predictions can be tested. Two particular experimental studies throw some light on the regulatory potential of parasitic species.

Park (1948) in a classical study of intra-specific competition between two species of flour beetle, *Tribolium confusum* and *Tribolium casteneum*, found that his laboratory cultures were infected with species of the sporozoan parasite *Adelina*. The author observed that the growth of populations of *T. casteneum* was drastically reduced by the protozoan. Park (1948) demonstrated that the mean density of beetles in cultures with the parasite was approximately 50 % less than the density in cultures without the parasite. Furthermore, the parasite, under certain environmental conditions, reversed the competitive advantage between the two beetle species.

An experimental population study by Lancinani (1975) of the mite *Hydryphantes tenuabilis* parasitic on the aquatic hemipteran *Hydrometra myrae* provides further evidence of the regulatory influence of parasites. This author demonstrated that the instantaneous rate of increase of uninfected hosts was approximately double that of hosts carrying an average of ten parasites. Some results from this study are shown in Figs 2 and 3.

The work of Park (1948) and Lancinani (1975) elegantly demonstrates the

potential (in the laboratory) of parasites to act in a regulatory role. Whether this suggested potential is frequently realized in natural communities is difficult to assess at present due to the many practical difficulties encountered in field studies of host–parasite associations.

Our knowledge in this area, however, would be greatly enlarged by further experimental work in the laboratory. For example, we need to have precise estimates of all the population rate parameters involved in a given host–parasite association, before realistic assessments of dynamical behaviour can be made. The literature contains relatively few studies along these lines (i.e. Park, 1948; Lancinani, 1975; Anderson & Whitfield, 1975; Anderson, Whitfield & Mills, 1977; Anderson *et al.* 1978). Such work is likely to provide indications of the range of population parameter values that can occur in natural host–parasite associations and hence form a platform on which theoretical predictions can be examined.

Studies of this nature are of particular relevance in the case of parasites of economic importance. The parameter boundaries, predicted by the host–parasite models, between a parasite-regulated state and exponential growth of both host and parasite populations, suggest that control measures designed to eradicate a particular parasite may alter the dynamics of its host population, releasing the latter from the regulatory constraints of the parasites. For example, the parameter boundary represented in equation (8) may be crossed if the death rate μ of the parasite is suddenly increased by the application of chemotherapeutic agents within the host population. Such a change would result in exponential growth of both host and parasite populations until other factors limited growth. The control measures would therefore have resulted in an increase in both host and parasite population size and may not even have reduced the mean parasite burden/host. Attempts to eradicate the parasite may thus result in the further protection of the parasite population from extinction due to its increased population size.

Such theoretical predictions underline the urgent necessity for further studies to acquire quantitative information on the many population parameters which determine the dynamical properties of host–parasite associations.

APPENDIX

The construction of the equations of the Basic Model is outlined in this Appendix. The mathematical details of the stability properties of the model are documented in Anderson & May (1978).

The biological ingredients discussed in the main text, relating to the rates of change which control the dynamics of the host and parasite populations, can be put together to form two differential equations; one describing the rate of change of the host population with respect to time,

$$dH/dt = (a-b)H - \alpha H \sum_{i=0}^{\infty} ip(i) \qquad \text{(A 1)}$$

and the other describing the rate of change of the parasite population,

$$dP/dt = (\lambda PH/(H_0+H)) - (b+\mu)P - \alpha H \sum_{i=0}^{\infty} i^2 p(i). \qquad \text{(A 2)}$$

By definition, for all discrete probability distributions

$$\sum_{i=0}^{\infty} ip(i) = E(i) \quad \text{where at time } t \quad E_t(i) = P(t)/H(t),$$

the mean parasite burden/host.
Also by definition

$$\sum_{i=0}^{\infty} i^2 p(i) = E(i^2).$$

This term represents the mean square number of parasites/host, the [illegible] value of which depends on the underlying form of the probability distribution [illegible] parasite numbers within the host population.

Using equations (A 3) and (A 4), equations (A 1) and (A 2) can be rewritten [illegible] give

$$dH/dt = (a-b)H - \alpha P,$$
$$dP/dt = \lambda PH/(H_0+H) - (\mu+b)P - \alpha H E(i^2).$$

For random distributions of parasite numbers/host, of the Poisson form [illegible] single parameter the mean parasite burden ($m = P/H$) defines the properties [illegible] the distribution.

For the Poisson model

$$E(i^2) = m + m^2,$$

or in terms of the host and parasite population variables,

$$E_t(i^2) = P(t)/H(t) + P(t)^2/H(t)^2.$$

Equation (16) thus becomes

$$dP/dt = P(\lambda H/(H_0+H) - (b+\mu+\alpha) - \alpha P/H).$$

Equations (A 5) and (A 8) form the Basic Model discussed in the main body [illegible] the text.

The negative binomial probability distribution is defined by two parameters, [illegible] the mean m and k an inverse measure of the degree of parasite over-dispersion or [illegible] aggregation within the host population.

The expectation of i^2 for this distribution model is of the form

$$E(i^2) = m^2(k+1)/k + m,$$

or in terms of the population variables

$$E_t(i^2) = P(t)^2(k+1)/(kH(t)^2) + P(t)/H(t).$$

Substituting this result into the Basic Model (equations (A 5) and (A 6)) gives

$$dH/dt = (a-b)H - \alpha P,$$
$$dP/dt = P(\lambda H/(H_0+H) - (\mu+b+\alpha) - \alpha(k+1)P/(kH)).$$

The stability properties of this model are detailed in Anderson & May (1978).

The equilibrium population sizes (H^* and P^*) can be obtained from the models by setting dH/dt and dP/dt equal to zero and solving the resultant simultaneous equations for H^* and P^*.

For example, the Basic Model represented by equations (A 5) and (A 8) yields the population equilibria

$$P^*/H^* = (a-b)/\alpha \tag{A 12}$$

and

$$H^* = H_0[a+\alpha+\mu]/[\lambda-(\mu+\alpha+a)]. \tag{A 13}$$

Positive and thus realistic values of H^* occur only if

$$\lambda > \mu+\alpha+a. \tag{A 14}$$

The parasite regulates host population growth if this condition is satisfied. If the equation is not satisfied, however, the host and parasite populations exhibit exponential growth until other factors, such as resource limitation, provide constraints.

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