



The Agri-Environment

John Warren, Clare Lawson and Ken Belcher

CAMBRIDGE

CAMBRIDGE

www.cambridge.org/9780521849654

This page intentionally left blank

The Agri-Environment

The application of ecological theory and conservation biology to agricultural ecosystems has become an important and growing research field and undergraduate course component in recent years. This book is both an academic textbook and a practical guide to farm conservation, and has evolved from the authors' extensive teaching experience. It covers the ecology of farmed land, how agricultural practices influence the environment, how agriculture has changed over time and how the species that inhabit the agri-environment have adapted. It also covers the history of agricultural policy and subsidies and the development of agri-environment schemes. A number of different farming systems are discussed, as are the difficulties in determining their relative merits. Guidance is offered on how to produce a workable farm conservation plan, and the final chapters look to the future and the development of new greener farming systems.

JOHN WARREN has 20 years of research and teaching experience in agro ecology, at the University of Liverpool and the University of the West Indies. He spent 7 years at the Scottish Agricultural College as head of the Farmland Ecology Unit, and is currently Director of Education and Lecturer at the Institute of Rural Sciences, University of Wales, Aberystwyth.

CLARE LAWSON has 10 years of research experience in habitat restoration and ecosystem processes within the farmed landscape, working at the University of London, Cranfield University and latterly as a Research Fellow at the University of Reading in the Centre for Agri-Environmental Research (CAER). Her current research focuses on the impacts of management practices on farmland biodiversity and the importance of trophic interactions (plant-soil and plant-insect interactions) in grassland restoration.

KEN BELCHER is an Associate Professor in the Department of Agricultural Economics at the University of Saskatchewan, Canada. Prior to this, he was a waterfowl and wetland biologist and he maintains a strong interest in the interactions and potential conflicts between agricultural systems and wildlife conservation.

The Agri- Environment

JOHN WARREN

University of Wales, Aberystwyth, UK

CLARE LAWSON

University of Reading, UK

KENNETH BELCHER

University of Saskatchewan, Canada



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press

The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org

Information on this title: www.cambridge.org/9780521849654

© J. Warren, C. Lawson and K. Belcher 2008

This publication is in copyright. Subject to statutory exception and to the provision of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published in print format 2007

ISBN-13 978-0-511-46040-1 eBook (Adobe Reader)

ISBN-13 978-0-521-84965-4 hardback

ISBN-13 978-0-521-61488-7 paperback

Cambridge University Press has no responsibility for the persistence or accuracy of urls for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

Preface and Acknowledgements page vii

- 1 An introduction to agro-ecology 1**
- 2 Agricultural support and environmentalism 19**
- 3 Environmental impacts of agriculture 42**
- 4 Principles behind agri-environment schemes 64**
- 5 Farm conservation planning 83**
- 6 Habitat management 105**
- 7 The management of agricultural wastes 127**
- 8 Low-impact farming systems 143**
- 9 Landscape and farmscape ecology 162**
- 10 The future of agri-environmental systems 180**

Glossary 196

References 203

Index 215

Preface and Acknowledgements

Historically agriculture has been considered purely as the method by which humans produced most of their food, fibres and other natural products. This activity has dramatically altered the farmed environment, favouring some species and habitats and degrading or destroying others. Over time as the human population has grown and agricultural activity has intensified the magnitude of this effect has increased, resulting in recent rapid declines in the abundance of many species and in the conversion of semi-natural habitats to monocultures. Population crashes in many of the species associated with farmed land and reductions in the quality and quantity of ecological services delivered by farmed land have resulted in an awareness that agriculture produces much more than just food. This realisation combined with other pressures such as reducing and decoupling economic subsidies from food production and changes in consumer demands for ecological goods and services are driving a second truly green revolution within the agricultural industry. New understanding of the ecology of the impacts of agriculture at a range of levels is enabling multifunctional production systems to be designed that deliver quality food products while supporting biodiversity and maintaining ecological services. Everyone involved in the agricultural industry during the twenty-first century will need an understanding of how to balance these conflicting demands.

This book has been written for agricultural and conservation students and researchers and for those actively involved in balancing food production with on-farm conservation. Its aims are to provide an understanding of the underpinning ecological science that regulates the plant and animal populations and communities that inhabit the agri-environment. Through these ecological processes the human activity of food production changes the environment in which we co-inhabit with the other species on the planet. It is therefore essential that we understand these mechanisms if we are to better manage them in future. But

agriculture is not purely an ecological science, it also has social and economic elements and this book covers the history of agricultural policy and subsidies and the development of agri-environment schemes. A number of different production systems (some more scientific than others) are available which, at least in part, attempt to balance agricultural production with sustainable environmental management. These alternative production systems are explored, as are the difficulties in determining their relative merits. For the moment the main policy mechanism used by western governments to encourage more ecological sustainable farming is the agri-environment scheme. The principles behind such agri-environment schemes are discussed and a guide is provided for how to produce a workable farm conservation plan. The final chapters cover recent developments in our understanding of the importance of scale and landscape complexity within the agri-environment. These concepts are becoming increasingly important in managing farmed landscapes, for example in locating habitat restoration projects and increasing habitat connectivity. Such factors will be important from the level of farm planning to designing national policy. It is always dangerous to predict the future, but balancing the partitioning of sunlight energy as food between an increasing human population and the other species that share our planet is a difficult problem and one that requires a great deal of scientific understanding.

We wish to thank many of our colleagues and friends for discussions on the various chapters, for commenting on parts of the text, or for simply enduring our trials and tribulations. Members of staff of the Institute of Rural Sciences at Aberystwyth University, Sue Fowler, Will Haresign, Graham Harris and Mike Rose have rendered valuable assistance, as have Chris Topping and Bryony Williams. To all who have contributed in any way we wish to express our deepest appreciation.

An introduction to agro-ecology

Introduction

Agriculture, the cultivation of plants and domestication of animals by humans, is approximately 10 000 years old. In evolutionary terms this should be an insignificantly short period of time, but it has not been. Human agricultural activity has changed the world completely; the genotypes of domesticated species have often changed beyond recognition. The relative abundances of species on earth have been altered dramatically, so that previously uncommon weedy grasses (cereals) now dominate vast areas. Even the habitats occupied by wild species have frequently been modified so they now support entirely novel communities of plants and animals. Natural communities from late in succession have been replaced by communities with ecologies more typical of early succession. The move from hunter-gathering to farming has allowed the human population to rise to more than six billion and therefore everything that humans do, every impact that we make on the planet, can be considered as an indirect environmental impact of agriculture. However, the scope of this book is less ambitious as it covers the more immediate direct interactions between agriculture and the environment. The function of agriculture is to direct energy from the sun (including fossil sunlight) into the human food chain. Little of this energy that is utilised by humans is then available for the other inhabitants of our planet. This process involves a great deal of effort to convert natural habitats into agricultural ones and replace wild species with domesticated ones, while natural ecological processes are exerting pressure on the system in the opposite direction. This movement away from the natural situation constitutes one of the direct environmental impacts of agriculture.

This book explores the nature of these impacts, how they can be managed, and whether they can be balanced by farmers and policy makers with our need

to produce food. To better understand the complexities of the environmental impacts of agriculture, this first chapter explores the origins and ecologies of species that inhabit farmed land. This understanding of the population ecology of single species is developed into looking at competitive interactions between species, which builds into community ecology theory. Finally an understanding of the management and exploitation of biodiversity within the agricultural context are introduced as key themes that are considered further throughout the rest of the book.

Species that inhabit farmed land

Farmed land has only existed for, at most, about 10 000 years, which is very little time for new species to have evolved which are adapted to this relatively new habitat. During this period, selection by humans has produced a range of domesticated crops and animals that are no longer able to survive without the assistance of humans outside the agro-ecosystem. They have been so genetically modified, by hybridisation and selection, that their origins were uncertain until the advent of modern molecular genetics (Hancock, 2005). Although less dramatic, the wild species that co-inhabit farmed land have also undergone sometimes substantial genetic changes. Many of the wild species of the arable agri-environment would have been rare or out of range before the advent of agricultural activity. These plants and animals had evolved in naturally disturbed habitats associated with early succession, such as sand-dunes, retreating glaciers or volcanic lava fields. Such species are known to ecologists as ruderals, they have life-histories characterised by short lifespans, the production of large numbers of small offspring, and they are highly mobile and invest few resources in defence mechanisms. These are the annual weeds of the plant world. Many agricultural invertebrate pests and diseases have similar life-history strategies. Alternatively these problem species can be seen as valuable biodiversity at the base of the food chain for the other larger more charismatic species of farmed land. Determining to what extent we tolerate these non-agricultural species diverting sunlight from the human food chain to the rest of nature is central to how we manage the agri-environment and this is a problem that we will return to again in Chapters 8 and 10 (Figure 1.1).

Until recently pastoral agriculture was based on the grazing of native or semi-natural grasslands or dwarf-shrub communities, but the twentieth century saw an increasing reliance on more productive, agriculturally improved forage systems. These new artificial grass-dominated communities are species-poor. The species they contain are now amongst the commonest on Earth, but their natural ecologies and genetics have been completely changed by agriculture

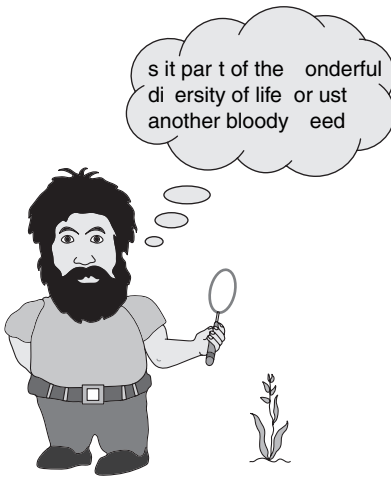


Figure 1.1 When should a species be considered an agricultural pest or be tolerated or even encouraged as valuable biodiversity? The answer to this question is central to how we think about and manage the agri-environment.

(Warren *et al.*, 1998). The plant species that form the basis of both improved and semi-natural pasture systems evolved in non-agricultural grasslands. In Western Europe most grasslands have previously been thought of as transitional vegetation communities, which form part of a succession that would naturally lead to climax woodland. Vegetation succession has been arrested at the grassland stage only because of agricultural grazing. This view has been challenged by Vera (2000) and many now think that the natural vegetation of Western Europe may have included much more grassland than was previously considered. This is significant because it might imply that agricultural habitats regarded as semi-natural may be more natural than previously thought and the species associated with them may have been coevolving for longer. Where the history of agricultural development is much shorter, such as North America and Australia, there is a better understanding of the make-up of the climax communities, whether forest or grassland. In fact remnant tracts of many natural vegetation communities, albeit very small in some cases, do still exist.

Population dynamics of single species

The science of ecology is about understanding why species live where they do and why sometimes they are abundant and sometimes rare. The practice of agriculture is about managing populations of species so that they can be exploited by humans. Therefore, by necessity agriculturalists need to know what species will live where and how well they will thrive. Agriculturalists

need to understand ecology and need to know what regulates populations. Understanding what processes regulate population sizes underpins selecting stocking rates of livestock, sowing rates of crops, what species can be successfully grown or kept together, plus the biological or chemical control of pests and diseases.

With a single species, in the simplest of all worlds, that is with no overlap of generations, no immigration or emigration from the population and all individuals being hermaphrodite, all of whom successfully reproduce, because resources (food, water, space, sex, etc.) are in excess and disease, predators and competitors are all absent, then:

$$N_{t+1} = N_t R.$$

The population in the next time period (N_{t+1}) = the population now (N_t) multiplied by the maximum number of offspring an individual can produce, R .

These restrictions might seem unrealistically crude; however, the population dynamics of many species of weed and pest of agriculture can at least spasmodically be regulated and mathematically predicted by such exponential explosions in numbers when they exploit a new resource, for example a newly ploughed field. These ruderal species tend to have populations that rapidly increase in numbers and then crash, with the episodic declines usually resulting from agricultural activity, such as ploughing or the application of chemical control.

In most species, the size of the population is regulated by density-dependent processes. That is, as the population size increases competition between individuals of the same species tends to reduce the growth rate of individuals, which affect the age or size at which individuals reproduce, decrease the birth-rate or increase the death-rate. Exactly what combination of these possible effects occurs differs between species, but the outcome of limiting population size always arises. This within species competition for resources, which reduces the size of individuals and over time increases the death-rate of smaller (less competitive) individuals, is responsible for a relationship known as self-thinning in plants (see Figure 1.2) and this effect is behind what determines optimal sowing rates for crops and planting densities for tree crops.

Even if agriculturalists are not consciously aware of the self-thinning rule, they select sowing rates for crops so that the plants are able to grow to a desirable size by keeping levels of intraspecific competition low enough to avoid crop plant mortality. This must be balanced by sowing enough of the crop to obtain an acceptable yield and for interspecific competition to be intense enough to help in suppressing the growth of non-crop plants.

In managed agricultural populations extra resources are used to counter the effects of density dependence to artificially increase birth-rates. Death in

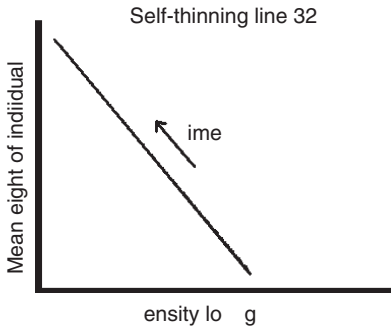


Figure 1.2 As individuals grow over time competition becomes more intense. This results in the death of the weaker/smaller individuals, which reduces the density of the surviving population, which eases competition and allows the surviving individuals to grow larger. Thus both size and population density are interrelated and change over time in accordance with the self-thinning rule. The gradient of the self-thinning relationship $-3/2$ arises from the fact that density (log) is area based and changes as a square whereas weight/volume changes as a cube.

domesticated species tends to escape density dependence by being regulated by harvesting/slaughtering rather than competition. However, the natural processes illustrated in Figure 1.3 do regulate the populations of the wild species that inhabit the agri-environment.

Mathematically, density dependence can be incorporated in population equations, with similar assumptions as before, those of: no overlap of generations, no immigration or emigration from the population and all individuals being hermaphrodite; although competition within a species is represented, the effects of disease, predators and other competitors are again all absent. Under these conditions:

$$N_{t+1} = \frac{N_t R}{(1 + aN_t)^b}$$

As before N_{t+1} represents the population size in the next time period, N_t is the population now and R is the maximum number of offspring an individual can produce. The only new parameters in the density dependence equation are a , which is described by some plant ecologists as ‘the area of isolation’ (that is the area which a plant needs to be able to produce R seeds and beyond which no extra seeds are produced) and b , ‘the coefficient of resources use efficiency’. However, both these values are probably best thought of as simply constants, which just happen to be useful in predicting the size of the population next year. The effect of variation in the value of parameter b on the population size in the following time period can be seen in Figure 1.4. Species with low b and R values and hence relatively stable populations are associated with late succession, such

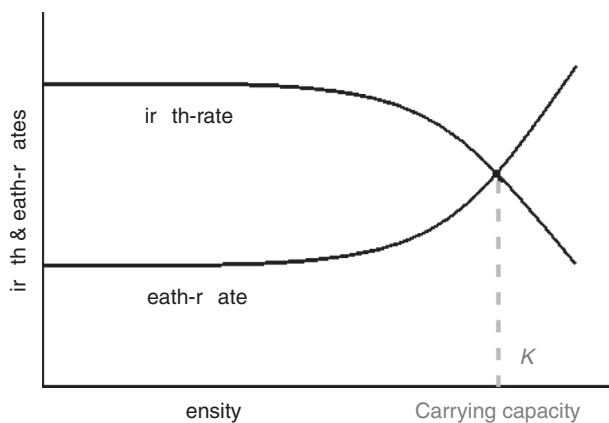


Figure 1.3 In the wild as population density increases, birth-rate decreases and death-rate increases. At the point at which the birth-rate and death-rates are equal, recruitment and death are equal and the population size may reach a stable equilibrium size. This is known as K, the carrying capacity.

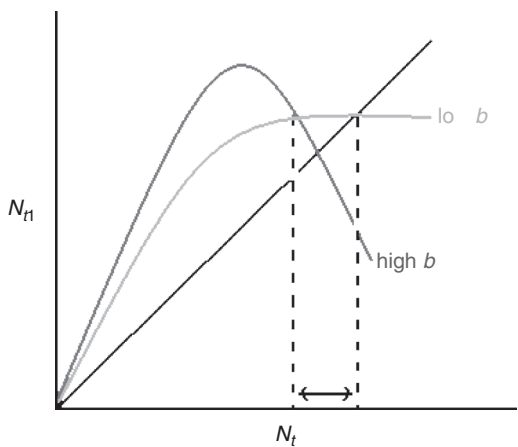


Figure 1.4 Variation in the value of parameter b affects the robustness of the predicted population size in the next time period (N_{t+1}). When b is low the predicted population curve cuts the 45° line close to the horizontal, so that a small amount of variation in the current population (N_t) has very little effect on the prediction of the subsequent population. However, when the value of b is large the predicted population curve cuts the 45° line in such a way that a small level of variation in the estimated population now makes a great difference to the predicted size of the next (future?) generation.

as oak trees or large mammals; those with high values of b and R , which are prone to dramatic changes in population size, are more likely to be associated with agriculture, such as locusts.

Species that are pests of agricultural systems tend to have the capacity to produce large numbers of offspring (they have large values of R) and therefore

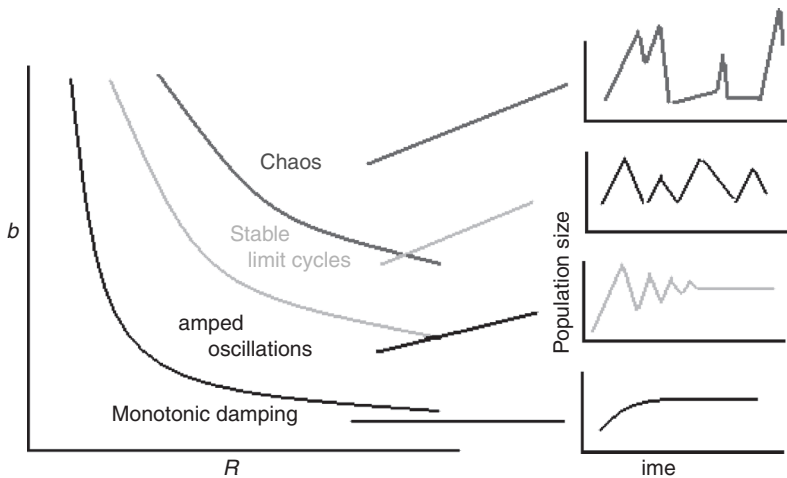


Figure 1.5 Knowing the parameters R and b allows long-term predictions to be made about the stability of population size. Species that are pests of agricultural systems tend to have populations that have chaotic dynamics and are prone to rapid increases and decreases that are difficult to predict.

their populations have the ability to increase very rapidly. When this is combined with high values of b , which make it difficult to make reliable predictions of the population from generation to generation, then the long-term population dynamics of agricultural pest species can be difficult to predict (see Figure 1.5). However, the chaotic population dynamics of many agricultural pests does not mean that their populations cannot be predicted, just that increasing amounts of data are required to successfully predict over reduced periods of time. Plus, given that many of the apparently random population crashes result from agricultural control measures, it is not true to say they are genuinely chaotic.

Two species interactions in agriculture

Much of the above discussion of the population dynamics of single species considered pest species, but of course these do not live as single species, and although intensive agriculture is often regarded as the management of monocultures, the reality is rarely so simple. In many farming systems managing different species together in the same space at the same time is the norm; therefore, if we are to successfully control pests or optimise yields over several species, we need to develop our understanding of the population ecology to more complex systems.

Two different experimental approaches have been developed by crop-ecologists to investigate the competitive interactions between two species. The two methods

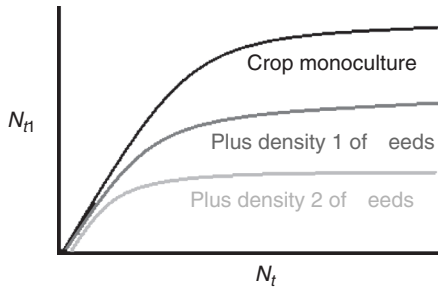


Figure 1.6 Additive experimental designs are useful for investigating the impact of the addition of different infestation rates of weeds on the yield of crops sown at a fixed density. Alternatively the experiment can be reversed and used to quantify the potential of the crop to reduce known weed populations. A similar experimental approach can be used to look at the suppression of weeds resulting from chemical control measures.

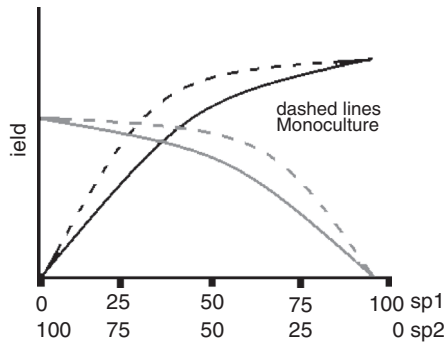


Figure 1.7 Replacement experimental designs have a fixed sowing density, but within a plot the ratio of two species varies from monoculture of one species through to the monoculture of the second.

relate to different applications. Firstly, additive experiments (see Figure 1.6) involve the addition of different levels of a second species to a fixed population of the first species. This can be used to represent the occurrence of a population of weeds or a second crop species in a fixed sown population of a crop. Secondly, there are replacement series experiments (sometimes called De Wit replacement experiments in honour of the Dutch ecologist who developed the approach), in which individuals of one species are replaced by individuals of a second, but with the overall population being kept constant (see Figure 1.7). This second approach is useful when trying to establish the optimal ratio of two species to use when bi-cropping.

Replacement experiments typically demonstrate a phenomenon of fundamental significance to agro-ecology. Competition between species is usually less intense than is competition within a species. This is because individuals of the

same species have the same environmental requirements, they compete for exactly the same resources. In contrast, different species will have different resource requirements, they will need different nutrients, or may root at different depths or grow at different times of the year, etc. Two very important facts result from this:

1. Overall yields (in terms of biomass production) tend to be higher with two species than in monoculture.
2. Such species have the ability to coexist by competing for different resources and so diversity is assembled.

Of course reality is more complex than this simple assertion, but it is an important factor that operates behind many agricultural processes. The first complication arises from the experiment's simple assumption of a fixed ratio of species. Just because two species are sown at a fixed ratio does not mean that they remain at that ratio; this is particularly true where there is differential growth or spread, such as with vegetative species. Secondly, in the artificial situation of a replacement experiment both species are usually established at exactly the same time. In the field, however, species may establish at different times or over a period of time. This can be important in further promoting diversity, because species that are competitively inferior (and over time would be lost due to competition) may not be excluded by competition if they have the opportunity to establish before the normally competitively dominant species. In addition, from an agricultural point of view the simple statement that overall yields are higher with two species than one may have little value, because the yield of total biomass may be less useable and there can be many practical problems in the management and harvesting of more than one species. Certain varieties of cereals and legumes can successfully be combined together and their grains separated mechanically, but other combinations with different maturation times can be more difficult to process.

An additional complication in the agricultural application of replacement experiments is that the outcome is often density dependent and such experiments are typically carried out at a single fixed sowing density. When a replacement experiment is performed at low density there is plenty of opportunity for the two species to exploit different resources (and therefore have higher yield in comparison to monoculture). However, when the same experiment is repeated at a higher overall sowing rate, the level of competition between individuals is more intense and the subtleties of between species differences are reduced as individuals struggle to survive, so that the increased yield potential of bi-cropping is reduced. Therefore, if replacement experiments are to be used to

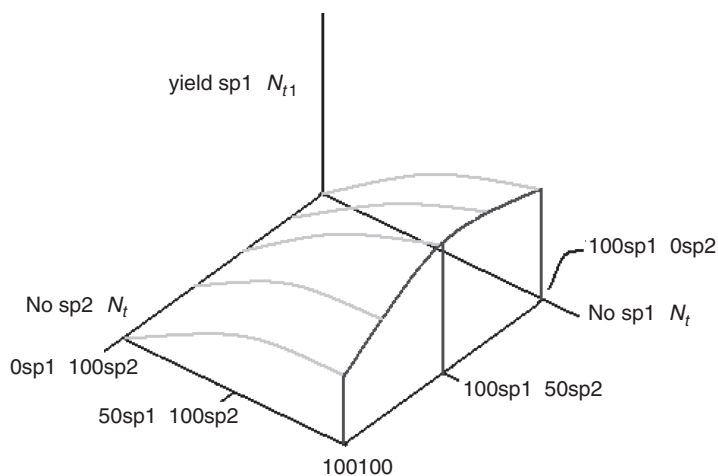


Figure 1.8 Response surface analysis of competition between two species over a range of ratios and overall sowing densities can be used to optimise bi-cropping systems or to identify optimal stocking rates and ratios of different livestock species such as cattle and sheep. In this figure the x and y axes are N_t and N_{t+1} as in Figure 1.4 while the z axis (N_{t2}) represents the size of the sown population of the second species at the time 0.

optimise ratios and sowing densities in bi-cropping systems, a series of experiments is needed, over a range of sowing densities (see Figure 1.8).

Parasites, pests and diseases

So far we have been considering the population dynamics of two competing species within agricultural systems such as weeds and crops, two species of grazing animals or combining two crops. This situation is different when one of the species is a domesticated species and the second is a direct predator, parasite or disease. Above we saw that many pests and diseases have the ability to rapidly increase in numbers to exploit available agricultural resources; their large reproductive potential allows them to generate lots of viable offspring, which are the raw material upon which natural selection acts in adaptive evolution. The rate of evolution of agricultural pests can be rapid for two reasons: firstly the large numbers of individuals involved, this does not just reflect the large numbers of progeny produced but also the vast areas of agricultural production over which they are produced; secondly the intensity of the selection applied by chemical, biological, genetic or physical means can be intense. It is no surprise, therefore, that when agriculturalists try to produce enough food to feed a global human population of six billion plus, other species adapt to exploit this vast potential food resource. Whatever control measures are applied, pests seem to

evolve mechanisms of resistance, be they insecticide, herbicide or fungicide resistance in crops, or antibiotic or anthelmintic resistance in livestock, plus the ability to break down genetic resistance in both.

The rapid evolution of agricultural pests and diseases is an example of an evolutionary phenomenon known as the Red Queen Effect (Van Valen, 1973). What is occurring in these situations is an evolutionary arms race between the breeder or chemist and the pest or disease. Each time a breeder produces a new variety or breed with a resistance gene or a chemist produces a new agrochemical or veterinary medicine it imposes a selection pressure on the pest to evolve a mechanism to avoid the method of control. Once the pest has evolved its own resistance, then the new variety or chemical control becomes ineffective and the breeder and chemist are ensured of employment as they are required to develop a new form of control. Some agrochemicals or resistance genes may be more difficult than others for pests to evolve resistance to, but given time they will. This coevolutionary process occurs in nature, driving arms races of defence mechanisms and counter-mechanisms in pests and diseases and their hosts. For this reason abundant species are unlikely to reproduce vegetatively for too long before they become too badly infested with pests and disease. Similarly, all agricultural crop varieties and agrochemicals will have relatively short periods of effectiveness. The more widely used they are, the stronger the selection pressure they will produce, and the shorter their shelf-life is likely to be.

From a profitability perspective, an ideal new pesticide is one in which resistance naturally evolves in the pest population at around the time the patent on the product runs out. This strategy prevents commercial competitors from being able to exploit an innovative company's research and development costs. While this might make good economic sense in the market economy, it is not a sustainable way to manage resistance genes, antibiotics or agrochemicals. Away from market economics, there is a method to escape from this evolutionary treadmill in the managed agricultural environment. Red Queen evolutionary arms races are linear in nature. Evolution in agricultural pests tracks genetic changes that occur in their host or is driven by a new control method until such a point that resistance genes spread throughout the pest population. However, if the selection pressure applied by the new crop resistance gene or chemical control agent was varied in space or better still in time, then the strength of the selection pressure would be reduced or completely altered in direction. Utilising different resistance genes in different locations is part of the rationale for growing different cultivars in adjacent fields or more rarely as multi-lines mixed within a single field. This has the advantage that the crop is less likely to be devastated by a particularly virulent strain of pathogen or pest. However, this method of managing the evolutionary arms race that occurs between

agricultural hosts and their pests merely slows down the pace of genetic change. Exploiting different resistance genes or varying chemical control methods over time, rather than space, totally changes the nature of evolution. Instead of tracking the evolution of its host the pest species is required to evolve in a different direction every time the cultivar or agrochemical etc. is changed. This of course requires large-scale coordination of the industry and requires companies to take their products or varieties off the market for a number of years, and therefore it is unlikely to be compatible with free market economics, but it would enable a more sustainable way to manage pest control in the agri-environment. This approach has been successfully applied in nature. Two very different groups of species have effectively evolved this method of avoiding their pests, by synchronising their life-cycles and being unavailable as a food source for several years. A further refinement to this strategy is the use of prime numbers, so that when the food resources become available, it is difficult to predict exactly when they will appear. The species involved are cicadas and bamboos. Certain species of cicadas emerge as adults after 7, 13 or 17 years as larvae. In the intervening years no adults emerge, so this food source is unavailable for their pest and disease species to attack. Similarly, bamboos synchronise their life-cycles, with all individuals within a species flowering and setting seeds in the same year before dying. When this mass production of seed occurs a huge food source is produced, but potential consumers are unable to predict the timing of the event, as in some species it occurs only every 120 years. Such a long-term removal of a resource is not practical within agriculture, but crop rotations (which also tend to be based around prime numbers) have similar if less dramatic effects. However, if a particular crop could be removed from cultivation for more than a hundred years, it would probably be freed from many of its pest species by the process. Similarly, if a pesticide or antibiotic could be withdrawn for such a long period, there would be few resistant individuals left to pass on their resistance genes when usage was resumed.

It is well known that in natural systems predators and prey or diseases/parasites and their hosts tend to regulate the size of each other's population via a mechanism known as predator-prey cycles. As predators or disease-causing species increase in abundance they reduce the population of their prey or host species, reducing their own food supply until the population of predators declines to such a point that the prey population is able to recover. Such natural regulation of populations is often spoken about by organic agriculturists, but it is difficult to find predator-prey cycles operating in most agricultural systems for three reasons. Firstly, pests of agricultural systems tend to be generalist species; because their ecological interactions are young in evolutionary terms, pest species typically have the ability to attack a range of

hosts so that when the host population declines, rather than track this decline, the pest species moves over to an alternative host. Secondly, the large-scale production of agricultural species enables pest species to potentially attain very high numbers, because if their host population declines in one area, the pest species is likely to have the ability to relocate to a neighbouring farm. Under these outbreak conditions the third process is likely to operate, and human intervention via chemical or mechanical control is likely to be applied to the pest species. In small-scale organic systems predator–prey cycles can be effective, because the second of these processes does not apply, and it may function further up the non-agricultural food chain. Crop rotations can be highly effective in regulating pest populations, but when production is scaled up to the industrial level of modern production farming pest populations can quickly move from host to host (see Chapter 9). Separating production into small blocks may alleviate this difficulty, but large-scale agricultural production will always produce a large potential food source for pest species to exploit. Fighting this never-ending ecological and evolutionary battle, while still allowing sufficient photosynthate to enter the non-human food chain, is the main challenge that faces modern agriculture.

Biological control and chemical control

The biological control of agricultural pests in its simplest form is the use of one species to control a second species, and as such it depends on the two species population dynamics described above. Classically, predators or diseases have been released to reduce the numbers of agricultural pests. Biological control has often been regarded as an alternative to the use of chemicals, but there is no reason that the two methods cannot be complementary. Although the use of chemicals to control pests in agriculture can be traced to 4500 BP when the Sumerians used sulphur compounds to control insects, and later the ancient Chinese used plant-derived complex organic insecticides, their intensive use was a twentieth-century invention. The widespread use of chemical pesticides in agriculture has tended to be characterised in the literature as being environmentally damaging; in contrast, biological control has been seen as being natural and environmentally benign. However, conservation ecologists are slowly starting to realise the damage that has been inflicted by poorly considered attempts to use biological control (Hamilton, 2000). In fact there are many parallels between the development and environmental impacts of these two different control methods.

The first generation of synthetic pesticides that were widely used were developed during the Second World War in an attempt to eradicate malaria

mosquitoes. The insecticides, DDT, chlorinated hydrocarbons, organophosphates, carbamates, and herbicides, 2,4-D, DNOC, MCPA, were broad-acting and toxic to a wide range of different species (see Chapter 3). These chemicals are now known to have had several undesirable environmental effects including bio-magnification, killing non-target species and having long half-lives. Subsequent generations of pesticides have tended to be better targeted both in their chemical specificity and by refinements in the designs of spraying equipment. Many agrochemicals are now highly complex organic molecules, which are applied in low doses and rapidly break down in the environment. Their direct environmental impacts in terms of poisoning of wildlife are considerably less than those of the first generation of pesticides. However, any efficient method of pest control is likely to have significant impacts for species further up the food chain.

The first attempts to use biological control were also unrefined and resulted in unexpected ecological impacts. Classical biological control involves the release of predators or diseases, typically to control an introduced alien agricultural pest. The problems with this approach have been that the introduced control species frequently fails to establish, and when it does it may unexpectedly attack native species, driving them to extinction. Furthermore, classical biological control that affects non-target species has been associated with the ‘genie out of a bottle’ problem that has been levelled at the release of genetically modified organisms, in that once a biological control agent has been released into the wild, it can itself be difficult to control, if it starts to behave in an unexpected way. Perhaps the best known example of this is *Bufo marinus*, the cane toad that was introduced into Queensland in 1935 in an attempt to control cane beetles. Since then it has spread west and south across Australia, eating or poisoning much of the native wildlife. There are many such examples mostly involving insects, but arguably the most significant in terms of causing extinctions has been the introduction of the predatory snail *Euglandina rosea* from the United States with the intention of controlling the giant African snail *Achatina falica* that was widely introduced across Asia and the Pacific as food. Unfortunately this introduction has resulted in the decline and extinction of many endemic snails of the genera *Achatinella* and *Partula*. Over time biological control measures have also become more refined. A whole range of techniques are now covered by the term biological control, including the augmentation of wild populations of natural enemies, or enhancing these natural populations by habitat management (e.g. using beetle-banks) or inoculation of these naturally occurring populations by the periodic or one-off releases of individuals. All of these techniques are more targeted than classical biological control and since they all avoid introducing alien species, they are free from the ‘genie out of a bottle’ problem.