Exploring the Ecosystem Service of Natural Pest Control in Australian Cotton Farming Systems

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Abstract: Over the last 10 years IPM (integrated pest management) research has encouraged the application of a variety of management practices to achieve effective pest control. One management option receiving increased research attention, especially in cotton production, is the use of natural enemies (predators and parasitoids) to control pest populations. Natural pest control is a valuable ecosystem service, which is largely lost from today's agriculture due to the nature of the farm environment and the management practices used. However, this service can be restored and/or enhanced by adopting alternative farm management practices, which stem from a better understanding of the system as a whole. I am employing a systems analysis approach to gain a better understanding of (1) the way natural pest control, and other IPM strategies used in cotton farming influence the cotton pest system, and (2) the status of current knowledge about the system. This paper outlines the purpose and aims of my research, gives a brief overview of the procedure and addresses the initial steps undertaken to characterise key components of the cotton insect pest damage and control system. The projects' conceptual framework is presented as well as an outline of further steps in the conceptual and simulation modelling procedure.

Keywords: Natural pest control; Cotton IPM

1. INTRODUCTION

1.1. Background

Agriculture is an ecological enterprise totally dependent on ecosystem process and functions [Saunders and West, 2000]. These process and functions provide services known as "ecosystem services", which have been defined as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life" [Daily, 1997]. However, to this definition I would add the services provided by agroecosystems, systems where agriculture is the dominant ecological component. In this context ecosystem services include; nutrient cycling, water cycling and filtration, maintenance of soil structure, pollination and natural pest control.

Modern pest control is achieved primarily through the use of pesticides. This reliance on pesticides has brought problems of natural enemy destruction and pest resurgence, pesticide resistance, destruction of other beneficial insects such as pollinators and honey bees, chemical contamination of soil and waterways as well as direct impacts on human health [Carson, 1962]. These problems have produced a growing impetus for the use of alternative pest control measures, such as natural pest control.

The Australian cotton industry is plagued with insect pests, a number of which have developed resistance to the major pesticide groups in use [Fitt, 1989; Herron et. al, 2000]. Pest resistance and the other factors mentioned above have prompted interest and research into alternative methods of pest control and biological insecticides.

The cotton-pest relationship is complex and dynamic. There are at least 6 herbivore pests of significant importance and a diverse array of associated predators and parasitoids [Gibb et. al, 2000]. Populations of herbivores and natural enemies fluctuate dramatically in both size and composition in response to a range of factors including; plant developmental stage, the farmers' actions (predominantly pesticide use) weather and the availability of essential resources.

1.2. Why Use Systems Analysis

As there are many components with multiple interactions in the cotton pest system, it is impossible to understand the way the system operates by looking at the components in isolation. A systems analysis approach is needed to consider the dynamics of the larger system. This approach is necessary when considering complex dynamic systems with highly connected variables and feedback loops. For further detail on this subject refer to Sterman [2000].

There is a considerable amount known about the cotton pest system, both in terms of the nature of the components themselves and the interactions between components. This knowledge provides much of the information needed to build an understanding of the system. Nevertheless, to date, research has been focused on single interactions or small parts of the system.

1.3. Conceptual Model & Research Purpose

The initial step in my research has been to develop a conceptual model, a simple diagram that captures the important variables and the influence links between them. This conceptual model was used to help define the cotton pest control system, identify the important questions and the level of detail needed to address these questions. The key questions are:

- What is the role of the natural pest control service?
- How do farm management practices, especially IPM, impact on the provision of this service?
- What is the role of the surrounding environment, especially in terms of resource provision and maintaining source populations of beneficial insects?
- These questions ultimately lead into the central question; can natural pest control be enhanced?

My modelling work is designed to produce a tool for researchers, to help understand what we know about the system. A powerful outcome will be the identification of important gaps in our current knowledge. It also provides a way of testing our current understanding. That is if this model is built on a sound understanding of our current knowledge, but does not reflect the same general trends as are found in the field, either the model has not captured the information or current knowledge does not adequately explain the key interactions. The model also provides a forum to evaluate combinations of IPM strategies and identify potential mechanisms for further IPM innovations.

1.4. Research Aims

There are four steps to my Research:

- Characterise natural pest control as an ecosystem service for cotton production in Australia using conceptual and simulation modelling.
- Identify the main variables that drive natural pest control in this system and simulate them using Vensim.
- Manipulate variables and identify management options cotton farmers could use to enhance natural pest control.
- Evaluate the potential effects of these options on pest and natural enemy populations, pest damage, yield and profit, as well as likely limitations to their effectiveness.

2. DEVELOPING A CONCEPTUAL MODEL OF THE COTTON PEST SYSTEM

2.1. Method

Information on cotton farming, pest problems and IPM was gathered through extensive reading and discussion with researchers in NSW (ACRI and UNE) and Queensland (DPI and UQ). Vensim (Ventana Systems Inc, 1998), a computer package for modelling dynamic systems, was then used to structure the relationship between the identified components and produce influence diagrams of the system.

2.2. Key Components of the Conceptual Model

The influence diagram (Figure 1) illustrates the main interactions between key components of the cotton insect pest system. The arrowhead points to the component (e.g. pest damage) that is influenced by the component the arrow originates from (e.g. herbivore populations). The diagram also indicates that temperature and rainfall/moisture influence all biotic components of the system. Rainfall also influences the farmers' management practices, such as when pesticides are applied.

The herbivore populations' component, in Figure 1, includes populations of pests (*Helicoverpa armiger* and *H. punctigera*, spider mites, thrips, mirids, aphids, tipworms and other infrequent pests) as well as herbivores that do not appear to cause significant damage (e.g. jassids). The pest species are responsible for pest damage, while all

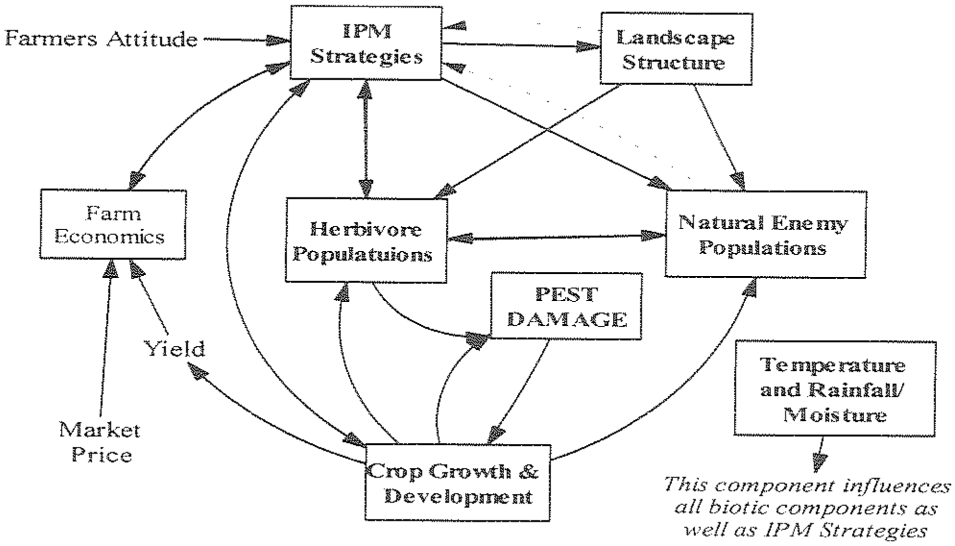

Figure 1. Influence diagram for the Australian cotton pest system. The key components are drawn in boxes and arrows indicate the direction of the influence between components, as described in section 4.2. Components in bold are considered in detail during further steps in my research.

species provide prey and/or hosts for natural enemies. The size, composition and activity of this complex is determined by the IPM strategies employed by the farmer, the surrounding landscape structure, the growth stage of the cotton crop (particularly how attractive it is as a resource for herbivores), temperature, moisture and the effect of mortality on the herbivores. Mortality factors explicitly dealt with in the model are natural enemies, climate/weather (i.e. temperature and rainfall) and the farmers' IPM strategies (eg pesticides and trap crops).

The natural enemy populations component in Figure 1 includes predatory beetles, bugs, lacewings, ants and spiders as well egg and larvae parasitoids. The size, composition and activity of this complex is determined by the structure of the landscape, the farmers' IPM strategies, the growth stage of the cotton crop, the herbivore population as well as temperature and rainfall. The landscape structure, cotton crop growth stage and herbivore population components are responsible for providing the natural enemies' food, shelter and other essential resources. If these components do not provide adequate resources natural enemies will not persist in the cotton crop. Like wise if the farmer is using pest management strategies that inflict high levels of mortality on natural enemies, populations will not persist in the crop, nor will they provide a pest control service.

The growth stage component of the cotton crop is extremely important in determining its susceptibility to herbivore pests. This is because some stages are relatively resilient to pest damage, while others are not. This concept is illustrated in Figure 1 by the arrow from crop growth and development to pest damage. For the purpose of this model cotton growth is predominantly a function of temperature, moisture, the farmers' management strategies (IPM strategies) and the effect of high pest damage. There are a number of assumptions made in using such a simple function and these are explained in section 4.3.

The landscape structure box in Figure 1 represents the role of the greater agroecosystem and surrounding natural ecosystems. This component acknowledges that the cotton crop, and its associated fauna, do not act in isolation of the surrounding landscape. The surrounding landscape provides the resources needed to maintain local populations of both natural enemies and pests, which can then enter the cotton crop. Farmers can influence the structure of this landscape through IPM strategies such as planting trap and refuge crops or areas of native revegetation.

Understanding the way in which landscape structure influences the presence and abundance of pests and natural enemies, is essential for effective pest management which incorporates natural enemies into the IPM program. It empowers the farmer to influence the structure of his farm environment to increase resources available to natural enemy populations and reduce those available to pests. The landscape structure component also emphasises the importance of farm management practices on neighbouring farms and the role of area wide management, an emerging concept in cotton IPM [MacPherson and Coulter, 2000].

The IPM strategy component in Figure 1 accounts for the impact the farmer has on the system. Here the definition of IPM is broad and covers any action the farmer makes that impacts on pests and/or natural enemies, for example revegetation to enhance resource provision for natural enemies or crop rotation choice to reduce pest source populations. Farmers' IPM decisions are influenced predominantly by their attitude toward IPM, herbivore populations, the level of pest damage, the farm economics, and the crops growth/ developmental stage. Progressive farmers may also consider the landscape structure and natural enemy populations when designing their IPM program.

The farm economics component is included to calculate the net profitability of producing cotton under different scenarios of both IPM strategies and landscape structures (Figure 1). This also provides evidence that the crop is being managed effectively and efficiently. As shown in Figure 1 this component is calculated from a simple relationship between yield, market price and input costs from the IPM strategy as well as basic cropping costs. (Note the cropping costs, seed, cultivation etc are not shown in Figure 1)

2.3. System Definition: Assumptions, Restrictions and Opportunities

Before discussing the conceptual model in any more detail I need to acknowledge a number of assumptions and omissions that have been made in defining the cotton pest system for the purpose of this work. Firstly, only insect and arachnid pests are considered. Although weeds also hamper cotton farming, in the context of this model, they are an aspect of landscape structure and a potential resource for both pests and natural enemies. There are also invertebrates that attack the roots of cotton plants (eg nematodes) and various diseases that again are not the target pests of this model.

Secondly, disease (viruses, bacteria and fungi), and vertebrates that attack insect pests are not explicitly included as natural enemies. Research into natural enemies is a relatively new field in cotton research and therefore relatively data sparse. There is far more information and data currently available on insect natural enemies than diseases or vertebrates. Hence there is a greater capacity to use modelling to explore and understand the role of insects in cotton pest management. Although, the role of diseases and vertebrates is not explicitly included the effect of these factors is considered in the size of the herbivore population and the level of mortality implicit in determining this. Pesticide, predator and parasitoid induced mortality is explicit in the model. In addition, there are various diseases that attack the natural enemies of cotton pests. These mortality factors are again accounted for implicitly when determining the size of the natural enemy population, rather than explicitly.

Thirdly, for the purpose of this model and the simplicity needed to consider such a large and complex system, two restraints/assumptions are made about the growth of cotton. These are that the amount of water and nitrogen available are optimal for cotton plant growth and development. In order for these assumptions to be valid the model is restricted to irrigated cotton systems, where water management can maintain soil moisture at optimum levels. It is assumed that the level of nitrogen is optimal due to soil monitoring and fertiliser application prior to planting

It may also be possible to incorporate stress factors to account for the effect of water logging, following a large rainfall event, and excess nitrogen. Excessive soil nitrogen levels increase end of season vegetative growth and subsequently pest damage. This can have a dramatic effect on the amount of pesticide needed to control pests and on yield. Nitrogen management is an important IPM strategy, which can be incorporated simply into the model through a nitrogen level factor.

Other factors that influence plant growth could be included such as other soil nutrients and soil type etc. However, detailed modelling of cotton growth has shown that temperature is the dominant environmental factor affecting crop development and yield [Contable and Shaw, 1988]. IPM strategies and pest damage have been added in this model, as they are key components of the system in question.

Lastly, the variables herbivore populations and natural enemy populations are divided into population components. These population components can be assigned their own values and equations for future simulation modelling and will most likely be assigned on the basis of functional groups. Modelling sub-populations will allow for far more powerful simulations as many factors, e.g. landscape structure and pesticides affect species and groups of species differently. Sub-components will also be used for pest damage as different pests attack different parts of the cotton plant and affect growth and/or yield to varying extents.

3. FURTHER STEPS IN MODEL DEVELOPMENT

3.1. Large Scale Conceptual Model Structure: Four Modules

To construct a more detailed conceptual model, four key components, IPM strategy, herbivore populations, natural enemy populations and crop development, were selected as major modules of the model. The farm economic component was combined with the crop growth module as they interact closely and this further simplified the model structure. The remaining key components were then overlaid on this basic four-module structure. Figure 2 depicts the major interactions between the four modules. A brief description of the herbivore population, natural enemy population and IPM strategies' modules is given below. However, the detailed conceptual structure of the four modules is not covered in this paper and will be presented in a future paper. It must be briefly noted that the "modules" are not discrete subsections of the model. Rather they are logical sections or divisions in the model that can be made to facilitate description and understanding.

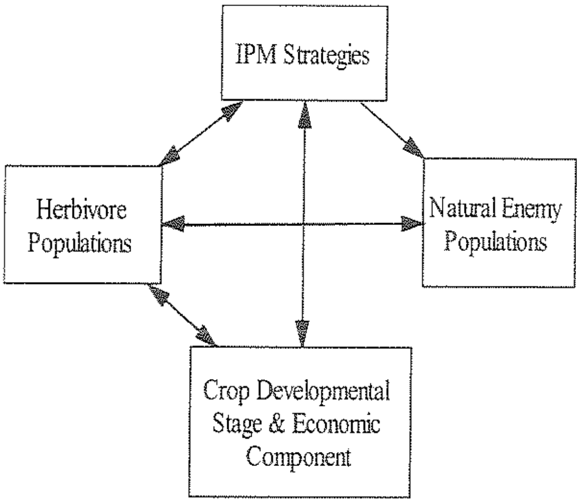

Figure 2. Large scale structure of the conceptual model identifying the four modules in boxes and their major interactions.

3.2. Herbivore Populations, Natural Enemy Populations and IPM Strategies Modules

The herbivore populations and natural enemy populations are determined as a level of infestation (for pests) or relative abundance level (for natural enemies, e.g. low, medium and high etc). The key components that influence these modules are used to determine the resource base, size of source populations, rate of emergence or arrival and the relative mortality level. It is these variables that are used to determine the size and composition of the populations. The activity of the population (kill rate for natural enemies and damage rate for pests) is determined from the size of the population, temperature and rainfall. This is because temperature and rainfall dramatically affect the searching and foraging behaviour of insects.

IPM strategies affect natural enemy and herbivore populations by altering their resources base, source populations build up, emergence and arrival behaviour or directly through mortality and/or fecundity. There are many IPM strategies a cotton farmer can employ and they are used to varying extents throughout the industry. The suite of IPM strategies to be applied will be entered into the model as a set of decision rules. For example, IF pest infestation level above 80% plants infected THEN spray x pesticide. Other IPM strategies, such as planting lucerne as a mirid trap crop and a natural enemy refuge, will be reflected predominantly in components other than the IPM decision rules, e.g. the landscape structure component. Different decision rules can be entered for consecutive simulations as a means of testing and comparing different IPM scenarios.

3.3. Landscape Structure, Temperature and Moisture Components

A few notes are needed at this point to explain the way these components will operate in the model, particularly for simulation. The landscape structure component is made up of a number of sub-components (Table 1.) It is these sub-components that interact with other components in the model. The landscape structures component has been used in this paper to prevent the higher level of detail from complicating the conceptual model. For simulation, the value of the landscape structure sub-component will be taken in an appropriate form, e.g. area, presence, absence etc. This will then be transformed into a ranking, for each component it interacts with, depending on the way it effects the component (i.e. high medium low or high, fair, poor etc). Effectively the sub-components are used to determine the suitability of the environment for supporting herbivores and natural enemies.

This ranking can be hypothetical reflecting an environment scenario or taken from a real environment within a set radius of the cotton field. The radius needs to represent the average distance most natural enemies and herbivores are thought to operate over.

Table 1. List of landscapes structure sub-components used in the model.

Landscape Structure Sub-Components
Crop Diversity (spatial and temporal diversity)
Size of Patches (patches of native vegetation, weeds, crops etc)
Connectivity of Patches
Native Vegetation (quality and quantity)
Weeds
Herbivore Overwintering Sites
Natural Enemy Overwintering Sites
Obstacles to Movement

Temperature (maximum and minimum values) and moisture (rainfall) values will be included in the model as either real or hypothetical data. Temperature and moisture thresholds will be defined for each interaction in the form of a decision rule. For example, the temperature decision rule for herbivores to emerge from diapause (hence increase the herbivore population) will be in the form, IF temperature > emergence threshold THEN emerge, ELSE stay dormant (i.e. not part of the population in the crop).

3.4. Further Development of the Conceptual and Simulation Modelling Using Vensim

The basic conceptual model (Figure 1 and 2) is being used to build 4 detailed modules. These modules were initially in the form of box and arrow influence diagrams. As the conceptual model is developed further the box and arrow configuration will be transformed into a stock and flow diagram. The stock and flow model structure can then be simulated by adding equations. Graphical functions and ranking systems are also being developed and will provide many of the values used in the equations for simulation. The ranking system is being used to define suitability indices, e.g. how suitable is the available resource base. Experimental data and expert opinion are being used to develop these ranking systems and graphical functions. The results of this process will also be presented in subsequent papers.

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