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Preserving Capital Returns under Increasing Pest Pressure

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Abstract

Pest management is an ongoing issue for producer's return on capital resources. The background pest mix and density is dependent upon both environmental factors and the producer's management actions. The concept of economic thresholds helps to understand pest management decisions. The economic threshold is described as the point where the benefit of control is equal to the cost of control, thus justifying management expenditure. As the density and/or damage caused by a pest increases management costs rise and ultimately capital return is reduced. This alters the comparative advantage of production. The aim of this paper is to examine the implications from producers reallocating capital between production choices under alternative pest dispersal rates through a defined landscape.

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Preserving Capital Returns under Increasing Pest Pressure

> *The return on capital owned and the return of capital owed are crucial factors in the fortunes of the farming business (Makeham & Malcolm 1981, p 49.)*

Introduction

Pest management economic relies on the difference between the concepts of economic injury (Stern et al. (1959) and Stern (1966)) and economic thresholds (Headley 1972) to justify management expenditure. Economic injury is the density at which a pest starts causing harm (reducing rent). While the economic threshold is when the density of a pest reaches a level when the costs of control are equal to the damage caused by that pest (i.e. the benefit of control). Consequently for a rational producer a residual base pest load will occur under active management. Pests reduce economic rent in a combination of one of three ways, increasing input costs, reduced yield and price reduction. A background pest level can be defined as a combination of individual pest species at alternative densities. By using a pay-off matrix, Carlson (1970) illustrated that a rational set of decision making responses existed to a known background pest level densities. This ultimately determines the comparative advantage of alternative production systems.

Individual pest species have non uniform impacts on alternative commodities. Thus if the background pest level permanently changes (e.g. a biosecurity event) the comparative advantage of production alters exposing capital already invested in the short run. In the long run, the economic success of an individual pest species can be then determined by the way in its distribution and density causes capital resource reallocation through time in a landscape. If economics analyses of pests fail to incorporate the ability for a producer to reallocate their capital resources between commodities (i.e. a passive management response), the true impact of the pest may be overstated. To test this premise, this paper models a theoretical pest invasion through a landscape and examines the opportunity cost from failing to reallocate capital. Complexity to this problem is added by modelling alterative patterns of spread through the defined landscape. By examining both the rate at which a pest invades a landscape and the difference in capital response we can provide information about why capital is reallocated between commodities in response to biosecurity events.

To achieve these goals an introduction to the economic importance of agricultural pests is presented in light of overall farm management decisions from an Australian perspective. Then an introduction into the economics of pest management is presented before the model is detailed. Then the parameters used to describe the economic importance of density and commodity return and the rate of spread through a landscape are presented. The results are outlined and then a wider ranging discussion about the implications from the model and its results are presented. Final comments including further scope for future analysis finally round out the paper.

Pest and Agriculture

For this paper the term an agricultural 'pest' is an all-encompassing phrase that refers to any species (*Animalia, Plantae, Fungi, Chromista, Protozoa and Bacteria*) that is in the wrong place at the wrong time that causes economic (economy, environment and human) harm or loss. No single

The economic impacts of pests within Australia have not been estimated but estimations of pest groups have been undertaken. For example, the annual cost to Australia from weeds is $4 billion (Sinden et al. 2004) and vertebrate pests $719.7 million (McLeod 2004). These estimations generally consist of management costs plus residual production losses and are used to help promote discussion. These evaluations ignore two correlated issues. Firstly the estimations are assuming a passive response by producers who are simple willing to accept a lower return. Secondly by treating each pest group as separate the opportunity cost of allocating resources remains elusive.

As pest management is a subset of the overall resource allocation problem for a farmer we need to know if it is considered important in the allocation process. In 2006-07 expenditure on chemicals in Australia was $1,545 million which equates to about 5% of total farm costs (ABARES 2010). As this expenditure is almost identical to the amount spent on fertilisers ($1,572 million), pest management still requires research. Note, as chemical expenditure only accounted for about 60 % of ABS's (2008) total pest management cost estimations ($2,342 million). Consequently by adding the application costs to the ABARE identified chemical costs, pest management probably accounts for about 7.5% of total farm costs. Logically depending upon the production systems, this figure alters.

In a steady state, under active management, the combination of individual pest species success then defines a baseline pest level (or pest load) in temporal and spatial terms to which the economic cost of management options and residual impacts on production, both yield reduction and price paid, for alternative production systems can be estimated. These two factors (management costs and production loss) influence a regions comparative advantage for production. An invasive species can be described as a situation when the baseline pest load is altered, in such a way that some combination of: management costs increase; a reduction in yield occurs; and/or prices are negatively influenced. This change could alter the existing comparative advantage of production systems beyond the known distribution and ultimately may lead to a reallocation of capital.

Pests are either indigenous or introduced (deliberately, accidental or naturally migrate) but both can be invasive (Hone 1994). The success of an individual pest species, measured as density and distribution through time (Industries Assistance Comission 1985), is dependent upon the interrelated and interdependent characteristics of: spatial references (i.e. local, regional and interregional) (Mayer, Atzeni & Butler 1993); temporal aspects (Shea et al. 2002) (i.e. daily, weekly, seasonal and multi-annually); biological (i.e. thresholds (Økland, Skarpaas & Kausrud 2009); dispersal modes (Auld & Coote (1980) and Jeger (1999)); fecundity (Fitt 1990); the natural environment (i.e. topography (Brown 1984));

its ability to adapt and respond to the natural (Hoegh-Guldberg et al. 2008) and human influenced environment (Buckley, Bolker & Rees 2007); climatic induced responses (Drake 1994); predator-prey relationships (Harper 1991)) and the direct and indirect influence of private and public management strategies (Auld, B.A., Menz & Tisdell 1987). This is further complicated since, under alternative densities there may be a transition point in which a beneficial species becomes a pest (Skonhoft & Jon Olaf 2005).

A pest invading a new landscape can be represented with a cumulative distribution function. There are three phases of spread through a landscape where no, limited or unsuccessful management takes place. The initial establishment phase (lag) where a species gains a foot hold in an area, a rapid growth phase where colonisation can appear exponential and a maturity phase where the pest reaches its physical limits within a landscape. During the maturity phase natural contraction and expansion occurs as the pest species responds to environmental conditions.

The Foundations of Pest Management Literature

As mentioned in the introduction the seminal works by Stean and Headly provided the economic foundations for pest managements concept of economic thresholds. These foundations provided an understanding of the nature (economic and ecological) of the pest problem and the options available for its management in space and time (i.e. economics of pest management).

This paper uses the Norton & Mumford (1993) definition of economic thresholds of C = ØPDK.. Where C is the cost of management per unit in a given area dependent upon Ø the density of the pest attack at a given time of both the pests' life cycle and the development stage of the commodity at risk; P is price of the commodity at risk per unit; D is the damage coefficient associated with the corresponding levels of Ø; and K defines the success that control has on Ø. This definition then allows for the determination of optimal management by D or C, the evaluation of alternative management systems by Ø and/or K, and determination of threat alternatives species pose.

Headley's framework then allowed Hall and Norgaard (1973) to introduce bio-economic modelling to optimise both the timing and quantity of insecticide. Hueth and Regev (1974) examined the optimal control question as pest resistance developed. Gershon (1979) suggested how risk and uncertainty could be formulated into the economic threshold concept. These works in part provided the platform to introduce greater sophistication including: Hall & Moffit (1985) inclusion of inter-year economic thresholds; Lazarus & Swanson (1983) combined multiple management options; Lazarus & Dixon (1984) illustrating the benefits of area wide control versus individual management efforts; and Boggess, Cardelli & Barfield (1985) modelling of intergenerational age structure models of multiple species. Work in this area continues providing greater specification of how density and area under threat (i.e. distribution) impact on economic return on a range of emerging issues, for example Davis *et al.*(1992) work on public control for private benefits and Laxminarayan & Simpson (2002) work on refuge strategies for transgenic crops.

By summarising the above material there are two conjunctive key drivers of pest management that determine the economic thresholds that change through time and they are: distribution and density; and density to damage relationships. Distribution (A) relates to the area where the pest was in the last time periods, where it is now (t = 0), where it could be in subsequent time periods. Pest distributions fluctuate depending upon the suitability of the location (i.e. can they survive there in the long run) the climate variability in the region (i.e. in good seasons distribution can quickly increase) and the nature of the private and public management strategies.

Density (Ø) relates to the number of pest individuals within a given area (∑a). The natural density (i.e. maximum possible carrying capacity of a given area (a)) is not uniform through a distribution (A) as the suitability of a given space is dependent upon pre-mentioned variable ecological factors that are influenced by time. The actual density is also dependent upon the successes of all management strategies in this and previous time periods, the population dynamics of pest species which includes the ability to spread from neighbouring and other areas of pest density. While density here could apply to a single pest, the management strategies are also impacting on non-target pest species thus lowering, but not always, the background pest load.

Once C exceeds the maximum possible return in t = 0 then a producer has two options either find a new management solution that either reduces costs C and or increases the benefits of management (PDK). Secondly they could transition to a new commodity which either lowers the base pest load; and or has different damage and economic thresholds. For simplicity in this paper we have assumed that as the pest enters an area, the background pest load is permanently changed and that the commodity selected for production does not speed up the rate of spread.

The abundance, distribution and frequency of naturalised pest attacks are dependent upon individual management response, area wide management strategies, population dynamics, resistance development, environmental conditions and the landscape. These factors then provide the absolute limit on naturalised pest ranges and density. If we accept the concept of Bayesian learning this implies for a known naturalised pests outbreaks the producer's response and expected management response lies between defined ranges providing a range of state experiences.

If we change the underlying parameters determining pest location and behaviour we then have to expect a response. If this response is significant in terms of pest location and abundance then we can no longer model the expected naturalised pest impacts and then we have to model the pest as an exotic. As in this case we have to expect producers' knowledge about the new pest states to be reflected as a new Bayesian learning experience. For this paper we have assumed that there is no lag in learning.

In considering naturalised to exotic pests the fundamental question of investment becomes critical. In a stable/naturalised pest environment with known management costs producers have factored this information into their investment decision making processes. However, an exotic species (or significant changes to a pest distribution and/or abundance) may radically alter the expected return on investment, especially in perennial horticulture, forcing changes to commodity selection causing industry wide impacts.

The complexity of spatial and dynamic interactions between distribution and density are critical in understanding the decision makers' choice in management decisions (including commodity choice). Nunn (1997) argues that the best way forward in understanding private and public decision making choices is the integration of disciplines. The lessons gained from working in this manner become especially important when trying to determine the impact of an exotic pest which has both known risks in its natural environment and uncertainties associated with colonisation of new areas. Auld & Coote (1980) provide one of the first Australian examples where of this approach to illustrate the economics of modelling spatial population dynamics.

The Model

This model is designed to be both simple and versatile in its depiction of a pest moving across a landscape. We abandon the rook-contiguity approach and adopts the strategy of Jones *et al*. (2000) where the pest has the ability to move in all directions within the landscape. We also abandon the movement limit imposed by previous models in order to allow the pest to move across variable ranges. An infested cell has a "radius" of *r* (*r* = 1 to 5) for which it can either create a new infestation or increase the severity of an existing infestation. The number of cells that can be affected ($n_{\emptyset}$) for a given *r* is defined by the following equation:

$$n_{\emptyset} = (2 + r)^2 \qquad (1)$$

The infestation process works as follows. Starting with a single infested cell, every cell within a radius of *r* (as specified previously) has a probability of becoming infested, or having an existing infestation worsened (notably, this range includes the cell itself). If we only have one infested cell, the probability is uniform across all cells within range of the infestation. The more infested cells a cell is in range of, the greater the probability of infestation.

This probability is dependent upon the density of the infestation in our initial cell, where density is defined as one of four states: No Infestation, Low Infestation, Medium Infestation and Heavy Infestation. The probabilities associated with each level of density are specified by the user, depending upon the nature of the pest. For example, a sleeper weed might have a small probability of spread at a low infestation, which changes to a large probability at a heavy infestation.

As probability of spread increases the number of new infested cells (a) in subsequent time periods also increases. If the probability of spread is equal to 1, then all of the cells within the range of infestation will become infested. Conversely, if the probability of spread is 0, the infestation will never spread beyond its initial cell. While neither of these cases is necessarily realistic, they are illustrative as to how the model's spread process works.

This spread model uses a landscape is a matrix with n *n regions (n=30), providing a landscape with 900 unique cells total area (N). In order to increase the applicability of this model, exactly what one cell denotes is left ambiguous. For example, a cell could represent a square metre of land, a paddock, or an entire farm. The length of each time in period is similarly ambiguous and could be represented as hours, days, weeks, seasons or years. The ambiguity in cell size and time period then allows stories to be created about not only the different dispersal patterns with pest species (i.e. weeds spread by natural means including birds, versus transportation in drought feed, through to accidentally spread via road works) but between pest groups to highlight why management strategies differ.

The model incorporates four levels of density (Ø) described as no pest present, low, medium and heavy. For each density level a subsequent cost has been describes the known gross returns for each commodity (jk) using the concepts of economic thresholds. This allows the cost of alternative densities to increase.

Equation 1 describes the possibility of each individual cell's background pest level changing.

$$\pi_n = \left(1 - \sum_{\emptyset=0}^{3}(1 - p_\emptyset)^{n_\emptyset}\right) \tag{2}$$

Where:

πn = probability of spread for cell n

Ø indexes a set of four states: no infestation, low infestation, medium infestation and heavy infestation

$p_\emptyset$ = probability of spread associated with density j

$n_\emptyset$ = number of cells within infestation range

r = number of cells the pest could move (1 to 5).

The expected spread (S) then through the landscape can be described in equation 3. This then provides the number of cells infested in each period by density.

$$E(A_\emptyset) = \sum_{n=1}^{N} \pi_n$$

That equation then allows for the cost (C) of the infestation by period

$$C_i = \sum_{\emptyset=0}^{3} D_\emptyset \times A_\emptyset$$

Where:

C = total costs
i ∈ $(0, \text{termination})$= period
Ø ∈ $[0,4]$ = infestation density (0=none, 1=low, 2=medium, 3=heavy)
D = Damage associated with density Ø
A = Number of cells with infestation of density Ø j

The converse of this is a simple measure of the land value, which is measured by aggregating the value of each individual cell on the landscape.

Model Parameters & Simulation

This paper models the impact of a new pest into a landscape to highlight the differences in impacts on two commodities, where only one (designated j(1)) is impacted by the pest species. To achieve this representation the initial starting point of the model divides the landscape in half down the middle. Each N/2 area is dedicated to a single commodity. When a pest is present in a cell on Landscape 1 (the infestation landscape), the corresponding cell on Landscape 2 takes the appropriate value from Table 2, which outlines all the models parameters used in this analysis. As the model has been run to examine the difference between a passive and active producer in regards to commodity selection, a classic with versus without scenario is required. Here six runs of the model have been undertaken. Three runs where for each r, where if the producer grows commodity 1, they can only grow commodity 1 (i.e. passive response) and 3 runs, where for each r, where the producer who grows commodity 1 can switch to commodity 2 if in response to net returns (i.e. the active response).

Table 2: Parameter Values

Parameters				
		Density		
	Nil	Low	Medium	Heavy
Net Economic Return: Commodity 1 ($/Ha)	100	90	80	70
Net Economic Return: Commodity 2 ($/Ha)	80	80	80	80
Probability of Spread (%)		0.01	10	50
Probability of Appearance (%)	50			
N	900			
r	1,3,5			
Model simulations	300			

Due to the variable nature of when the pest enters the landscape and the multiple combinations it can spread through a landscape the model has been run 300 times for each r value. To examine the simulations the models the mean and statistical deviation of the data for each period was determined. The model assumes that the production choices are mutually exclusive and are produced in the same time periods. While there are no positive feedback loops on production choice for the pest population. For all runs it has been assumed that farmers have perfect information in regards to if a pest is present and the density of the infestation.

Results & Discussion

Once the 300 runs for each simulation were completed the mean and standard deviation for each period were calculated. This approach smoothed out of the variance to illustrate the expected impact in each time period for ease of analysis. The critical aspect of analysis is the speed in which the landscape reaches the new equilibrium, as illustrated in Table 3. As discussed pest invasion follows a cumulative function therefore the impacts of the adjustment depends upon the speed at which the pest species move. If the new invasive species can only move to the neighbouring cell then it takes 172 periods, if the invasive species can move up to 3 cells per move then it drops to 50 periods and if the species can move by 5 cells then this contracts to only 29 periods.   In a wider since this suggests that a slow moving species may not recognised as a problem until the exponential growth phase commences.

If a producer acts rationally and alters commodity in response to the pest there is a net benefit of $4,500 per period once the equilibrium has been reached for all runs. This is compounded when we consider the total benefits from switching commodities over time. Although the gross value is greatest in pest that slowly invades a landscape, the use of discount rates in evaluation would favour research allocation towards species with a high rate of dispersal. This is compounded when considering that the initial costs of a slow moving species are likely to be lost in the natural variation of output caused by environmental factors, other pests and price signals. Thus producers may switch commodities without realising that a new background level of pests has forced the change.

By treating producers as having only a passive response to pests by only increasing management costs, the total impact a pest has to economic growth is then overstated. If then research funding is allocated purely on the speed at which a species invades a misallocation of funding will occur if the true background pest level is not understood.

Table 3: Simulation Results

	Jump		
	1	3	5
Period fully infested	172	50	29
Max Difference	$4,500	$4,500	$4,500
TOTAL Benefits of Switching ($'000)	$567.4	$345.2	$70.6
Max Difference in Annual Loss	$1,652	$1,336	$1,424

Many examinations of pests specify the changes in costs before and after pest invasion as either an increase in inputs, a decrease in outputs or both. This information is generally gleaned from changes to gross margins. This number is then used to describe the economic impact a species can have. In reality, producers have a number of options once a pest is present. One notable example, and the main one examined by this model, is the ability to switch commodities to one less affected by the pest. This means that the question for economic analysis is one of opportunity cost, rather than a simple calculation of accounting loss. By ignoring the possibility that, if possible, producers may alter production systems to respond to a pest, economic evaluations of pests may be overestimating the importance of that pest problem, see Chart 1. If producers are passive to a pest then their net return through time is lower than an active response of changing commodities.

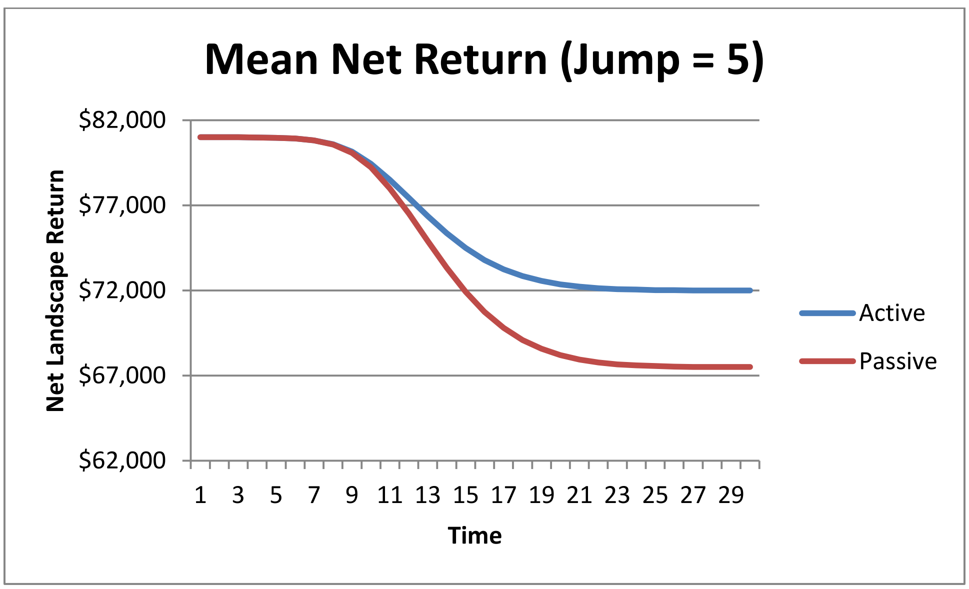

Chart 1: Mean Net Return between Active and Passive Producer Response

As producers switch commodities in response to pests we introduce inflexibility and rigour into the production systems that leaves producers exposed to other external shocks. For production systems with extensive inter-annual capital requirements (e.g. perennials, livestock) the modelling of pest impacts for in situ investments provides greater complexity in the management response. In landscapes, like rangelands, where monoculture production systems exist, and/or the impact on all production systems is uniform then traditional ways of determining pest economic costs hold true.

Adamson (1996) and Adamson *et al.*(2000) demonstrated the suitability of the landscape to invasion from specific species based on using CLIMEX software. CLIMEX matches the suitability of a given geological areas climatic parameters to the pests climatic thresholds. By understanding the heterogeneity of landscape risk to pests we provide greater understanding to how natural boundaries could be incorporated into control optimisation solutions.

While the description of the landscape suitability to a given pest is made, at the same time the description of each cells return for a range of commodities would further illustrate not only the issues of comparative advantage but also individual farmers attitudes to pest management. For example, in areas of low return the incentives for pest management are low could well be described in an agent based approach where the individual response to both the pest and the impact on their commodity could be described.

The combination of the above two points would then help describe area management solutions to exotic outbreaks not only in terms of the benefits of protecting capital investment but the areas at high risk from described pests via a stochastic representation of impacts. Hesitancy to control pests can be explained, in part, by economic thresholds and the number of commodities a producer can choose between. In areas of low economic return per unit area with few commodity options (e.g. beef in semi-arid rangelands), spending money to control low infestations of pests provides negative returns.

The distribution and density of a pest through a landscape is not uniform and this has implications for monitoring and optimal management decisions. If optimal management decisions are based on monitoring models using a uniform spread patterns then there will be cases where the monitoring system will fail.   Secondly the adoption of economic thresholds illustrates that producers can actively respond to pests by altering inputs and/or switching commodities. If decisions are made on a discrete density to damage relationship then two critical outcomes will occur. Firstly the true impact for a producer will be overestimated and secondly limited research funding to deal with pests could be misallocated.

These findings then place a query on the models used by Epanchin-Niell & Wilen (2010) and Chalak, Pannell & Ployakov (2011) who address the issue of optimal control of an invasive species. Like this paper they model a landscape in a cell matrix but they limit spread by using a rook contiguity pattern (i.e. the pest cannot move diagonally within a landscape) and only the neighbouring cell is at risk. It would be interesting to see these types of evaluations introduce both the concepts of active management response and species to move rapidly as if the spread jumps through a landscape the optimal control would then require a monitoring boundary for eradication scenarios.

Concluding Comments

In light of what we have discussed, we can now redefine biosecurity events as follows. A biosecurity event for an individual producer is when the base pest load alters and costs are incurred either through increased inputs or lost income beyond the expected natural variation. Input changes occur from altering farming systems to negate the possibility of biosecurity incursion or a new management event takes place that is consistent with concept of economic thresholds. As discussed income is a combination of yield and price. A severe biosecurity incursion is one where the return on capital alters investment choices. By incorporating the ability of individuals to actively respond by changing commodity choice we preserve return on capital but we also illustrate the reduction in production choices. It is perhaps this inflexibility into the area wide comparative advantage that pests pose that should be the future work in this model.

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