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Current Opinion in Insect Science

Game theory as a conceptual framework for managing insect pests

Joel S Brown[1,2] and Kateřina Staňková[3]

For over 100 years it has been recognized that insect pests evolve resistance to chemical pesticides. More recently, managers have advocated restrained use of pesticides, crop rotation, the use of multiple pesticides, and pesticide-free sanctuaries as resistance management practices. Game theory provides a conceptual framework for combining the resistance strategies of the insects and the control strategies of the pest manager into a unified conceptual and modelling framework. Game theory can contrast an ecologically enlightened application of pesticides with an evolutionarily enlightened one. In the former case the manager only considers ecological consequences whereas the latter anticipates the evolutionary response of the pests. Broader applications of this game theory approach include anti-biotic resistance, fisheries management and therapy resistance in cancer.

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Introduction

Game theory is the field of mathematics devoted to solving conflicts of interest between two or more players. It solves problems where your best action (strategy) depends upon the strategies of others. In nature, game theory is particularly suited for understanding adaptations emerging from evolution by natural selection [1•]. "The deer flees and the wolf pursues" [2] succinctly describes games between predators and prey. The evolution of pesticide resistance represents a special and economically crucial case of predator–prey games. Here, we illustrate how classical game theory and evolutionary game theory can be conjoined to produce bioeconomic games of pesticide resistance. Game theory and pest management thus become part of integrated pest management [3,4].

The evolution of biocide resistance marks the most dramatic, damaging and rapid manifestations of natural selection. Examples of rapid evolution in response to humans attempts to chemically control pests include herbicide resistance [5–8], anti-biotic resistance (*e.g.*, MRSA [9]), drug resistance by parasites (*e.g.*, malaria, [10,11]), and at the most personal level, the evolution of therapy resistance in human cancers [12,13]. Here we shall focus on the use of pesticides to control insect damage to agricultural crops, but the concepts and models can be extended to these other examples of disease and pest control.

We shall review the problem of pesticide resistance as a bio-economic game. The game has insect players that may evolve pesticide resistance, and the farmers in addition to the manufacturers and regulators represent players with economic and social interests. Such games can consider human health and environmental consequences of pesticides, and they can be added as costs and externalities. With the aim of sharing the contexts of pesticide games, we shall introduce a simple model for illustrating concepts. We shall emphasize the comparison between ecologically versus evolutionarily enlightened [14] approaches to pesticide applications [15•]. Throughout, we shall discuss parallels in such systems as fisheries management [16], anti-biotic resistance in infectious diseases [17•], and therapy resistance in cancer [18]. In conclusion, we advocate greater use of game theory in developing *resistance management practices* [19].

Pesticide management as a game

The interacting players in the game can be diverse and include society at large, regulators, biocide manufacturers, seed companies breeders, the birds or spiders that consume the pest, and of course, the farmers and the insect pest [20]. The insects and other species within the ecosystem find themselves in an *eco-evolutionary game* where ecological dynamics occur through changes in population size and evolutionary dynamics involve heritable changes in the species. In an evolutionary game the individuals (players come and go through births and deaths), their strategies are inherited, and their payoffs take the form of increased survivorship and breeding [21]. The solution to such games are often *evolutionarily stable strategies* (ESS) [22]. An ESS is a strategy (or coexisting set of strategies) that when common cannot be invaded by any rare alternative strategies.

The farmers or other human players engage in a more traditional, classical game. They choose rather than inherit their strategies, and payoffs take the form of monetary and/or utility rewards. Furthermore, the human players can anticipate and plan for the responses of other players [23]. Players in evolutionary games can never evolve a response to something that has not yet happened. The solution to classical games can be the *Nash Solution* [24]. This is a no regret strategy. When all players are at a Nash solution no individual player can benefit from unilaterally changing his/her strategy.

As humans we can anticipate the evolutionary consequence of our actions on nature. Yet in managing, we often do not anticipate but merely respond to the evolutionary changes we cause. And so it is with much of pest management. We respond to the ecological costs and benefits of our biocides without regard to their evolutionary consequences. We shall call this *ecologically enlightened management*. Game theory explains the temptation to simply be ecologically enlightened stewards. Game theory is also ideal for anticipating and incorporating the eco-evolutionary dynamics that we cause. When both the population and evolutionary dynamics of the species of interest are incorporated into human decision making we shall refer to this as *evolutionarily enlightened management* (sensu [25]).

To keep things simple, we will view pesticides as a game of the farmers versus the insect pests. The game may take a general form of:

$$G(u,m,N) = F(u,N) - \mu(u,m) \quad (1)$$

$$\Pi(u,m,N) = Y(u,N) - cm \quad (2)$$

where G is the per capita growth rate of the insect pest and Π is the net profit to the farmers. The per capita growth rate of the insects is the difference between their growth rate in the absence of pesticides, F, and the mortality rate induced by the application of pesticides, μ. The farmers' net profit is the difference between the crop harvest, Y, and the cost of the pesticides. Each of these are functions of the resistance strategy of the insects, u, the rate at which pesticides are applied, m, and the density of insects, N.

We can assume that the insect's per capita growth rate, F, in the absence of pesticide declines with insect density, N, and with their resistance strategy, u: $\partial F/\partial N < 0$ and $\partial F/\partial u < 0$ represent negative density-dependence from competition and the cost of resistance, respectively. The insect's mortality rate from the pesticide declines with their resistance strategy ($\partial\mu/\partial u < 0$) and increases with the dosage of pesticide ($\partial\mu/\partial m > 0$). In this formulation the population growth rate of the insects is given by $\frac{dN}{dt} = NG(u,m,N)$. See Table 1 for more details regarding the model assumptions.

Crop yield will decline with the density of insects ($\partial Y/\partial N < 0$) and it may decline directly with the resistance strategy of the insects if this renders the insects less efficient foragers (an additional cost of resistance; $\partial Y/\partial u > 0$). The cost of pesticides is simply the product of their cost, c, and the rate at which pesticides are applied, m.

In the absence of pesticide, or under some critical level of pesticide, the optimal level of pesticide resistance for the insects will be $u^* = 0$. As applications of pesticide increase, the optimal level of resistance will also increase.

Table 1

Model basics

Pests' perspective			
Dynamics of pests' density N	$\dot{N} = \frac{dN}{dt} = NG(u,m,N)$		
Fitness generating function	$G(u,m,N) = r\frac{(1-u)K-N}{K} - \frac{m}{k+bu}$		
Optimal level of pesticide resistance u^*	$u^* = \mathbf{arg}\max_u G(u,m,N) = \sqrt{\frac{m}{rb}} - \frac{k}{b}$		
Equilibrium density of pests N^*	$N^* = K(1-u) - \frac{mK}{(k+bu)r}$		
Farmer's perspective			
Net profit of the farmer Π	$\Pi(m,N,Y) = Y\left(1-aN^2\right) - cm - \gamma$		
	Ecologically enlightened pest control	Evolutionarily enlightened pest control	Neither
$\frac{\partial\Pi}{\partial m}$	$-2aYN\frac{\partial N}{\partial m} - c$	$-2aYN\left[\frac{\partial N}{\partial m} + \frac{\partial N}{\partial u}\frac{\partial u}{\partial m}\right] - c$	$-2aYN - c$
$\frac{\partial N^*}{\partial m}$	$-\frac{K}{r(k+bu)}$	$-K\frac{\partial u}{\partial m} - \frac{rK(k+bu) - bmrK\frac{\partial u}{\partial m}}{r(k+bu)^2}$	n.a.

This can be represented as a best response curve in the state space of m versus u (Figure 1). The best response curve shows how the optimal resistance strategy of the insects, u^*, increases with the amount of pesticide applied. It can be thought of as the functional relationship between u^* and m: $u^*(m)$.

There may also be some equilibrium abundance of insects, N^*, where $G = 0$ when evaluated at N^*. For a fixed level of resistance, the equilibrium abundance of insects will decline with the pesticide ($\partial N^*/\partial m < 0$). The equilibrium will also be influenced by the insect's resistance strategy. The ESS level of resistance is a level of resistance which, if adopted by the insect population, cannot be invaded by any alternative level of resistance that is initially rare.

Ecologically enlightened management

Ecologically enlightened farmers anticipate the consequences of their actions on the population size of pests, N^*, but they do not consider the evolutionary consequences of their actions. They simply respond to the insects' current value of resistance. Hence, the farmers also have a best response curve. Given a certain resistance strategy among the insects, the farmers can select their optimal level of pesticides that maximizes their net profit. This m^* considers the effects of the pesticide on the residual abundance of insects, N^*. The farmer's optimal value for m^* becomes a function of the insect's resistance strategy: $m^*(u)$. The first order necessary condition for m^* requires that $\frac{\partial \Pi}{\partial m} = 0$ which yields:

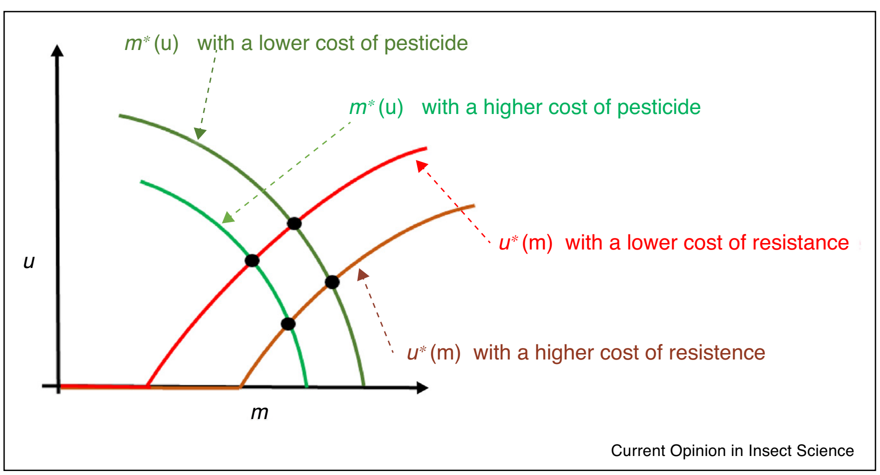
$$\frac{\partial Y \partial N}{\partial N \partial m} = c \tag{3}$$

The left hand side of the equality considers how reducing the density of pests will improve yields and this is multiplied by the marginal reduction in insects caused by a marginal increase in pesticides. The farmers are ecologically enlightened. They base their decision on the pesticide's effect on the insect's population, N^*. The right hand side of the expression gives the marginal costs of the pesticides. The value of m^* that satisfies Eq. (3) will vary with the resistance strategies of the insects, u. This function, $m^*(u)$ represents the best response curve of the farmers (Figure 1).

It can take on a variety of shapes. The value of m^* may continually increase with the level of resistance ($\partial m^*/\partial u > 0$) if greater amounts of pesticide can compensate for the higher levels of resistance. The relationship between m^* and u might be humped shaped. At first, more pesticide compensates for increased resistance, but beyond some point, the level of resistance renders the pesticide ineffective and so applying more is no longer worth the cost. For the model illustrated in Figure 1, m^* declines with u.

Possible solutions to this bioeconomic game occur at the intersection of the insects' and farmers' best response curves (Figure 1). This point is a Nash equilibrium for the farmers and an ESS for the insects. The farmers can do no

Figure 1



The ESS-Nash solution for ecologically enlightened management. The insect's best response curves $u^*(m)$ have positive slope and show the level of resistance that will evolve as a function of the amount of pesticide. The farmers' best response curves $m^*(u)$ have negative slope and show the optimal level of pesticide that should be used in response to a particular level of resistance by the insects. The intersection of the insect's and farmers' curves shows the ESS-Nash solution u^*, m^*. The different intersections show the consequence of changing the cost of resistance to the insects or changing the cost of the pesticide to the farmer. The model is shown in Table 1.

better given the strategy of the insects and the current resistance strategy of the insects cannot be invaded by an alternative rare mutant strategy.

Even in this general form several results emerge. Increasing the cost of resistance to the insects will shift their best response curve downwards resulting in a lower level of resistance, an increase in the application of pesticides, a large decrease in the population of insects, N^*, and an increase in profit to the farmers. Increasing the cost of pesticides to the famers shifts their best response curve towards the left resulting in a reduction of pesticide, a reduction in the resistance strategy of the insects, a large increase in their population size, and a reduction in net profit to the farmers.

But is this Nash equilibrium the best the farmers can do? Interestingly, if one fixes the resistance strategy of the insects to their Nash equilibrium, then the farmers maximize their net profit by using their Nash equilibrium of pesticide (Figure 2). So at first glance it seems the farmers can do no better. In fact, the farmers can do better if they anticipate the evolutionary response of the insects.

Evolutionarily enlightened management

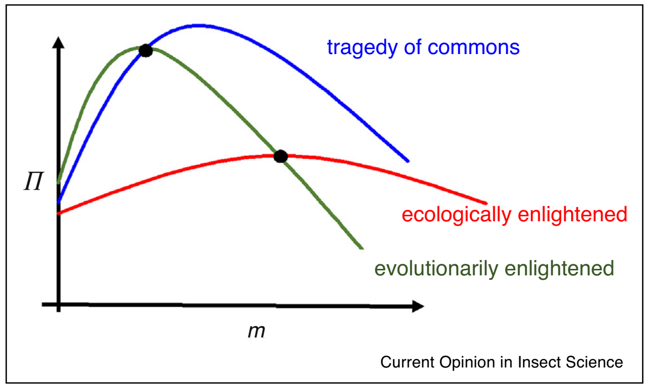
What if the farmers also anticipate their evolutionary consequences. An evolutionarily enlightened manager would incorporate both the ecological, $N^*(m)$, and the evolutionary, $u^*(m)$, components into their net profit function. The farmers know that in time the insects will evolve a resistance strategy that lies on their best response curve. It now behooves the farmers to select their m^{**} so as to find the value of m along $u^*(m)$ that maximizes their profits. The first order necessary condition for this m^{**} is:

$$\frac{\partial Y}{\partial N}\left(\frac{\partial N}{\partial m}+\frac{\partial N \partial u^*}{\partial u\, \partial m}\right)=c \qquad (4)$$

For most assumptions regarding the functional forms of these relationships, the value of m^{**} will be less than m^*. The evolutionarily enlightened managers will be more restrained in their use of pesticides than the ecologically enlightened ones.

Figure 2 illustrates both types of management strategies with curves of net profit as functions of pesticide use. The evolutionarily enlightened curve reaches a higher peak at a lower value of pesticide use than the ecologically enlightened curve. As it must, the evolutionarily enlightened curve intersects the ecologically enlightened from above and at the peak of the ecologically enlightened curve. While the solution of $(m^{**}, u^*(m^{**}))$ is unavailable to the ecologically enlightened farmers, the Nash solution $(m^*(u), u^*(m))$ of the ecologically enlightened farmers is available to the evolutionarily enlightened ones.

Figure 2



The effect on the farmers' profits, Π, of changing the level of pesticides, m. The profit curve for ecologically enlightened management has the farmer reacting to the level of pesticide resistance that evolves in the insects. It is constructed by fixing the resistance level of insects to their ESS value shown in Figure 1 from the intersection of the insect's and farmers' best response curves. The profit curve takes on a maximum with respect to m at the value m^* that is at that intersection. The evolutionarily enlightened manager anticipates the evolution of the insects. All along this profit curve the resistance strategy of the insects are changing according to their best response curve. The evolutionarily enlightened profit curve reaches a higher profit at a lower level of pesticides, m^{**}, than the ecologically enlightened one. The curve labelled 'tragedy of the commons' shows the profit that farmers could achieve in the short-term by changing their pesticide usage while the insects still have the resistance strategy based on m^{**}. While the peaks of the evolutionarily and ecologically enlightened profit curves are sustainable, the peak of the tragedy of the commons curve is not. At a pesticide use of $m > m^{**}$ the insects will over time evolve higher resistance. As the farmers react to these higher levels of resistance they will eventually drive the system to the lower peak of the ecologically enlightened profit curve.

When viewing pesticide resistance as games between the managers and the insect pest, the managers' best long-term strategy considers the consequences of their actions on the evolution of resistance. The application of pesticides will likely result in some resistance and the insects will evolve towards their ESS. But now, their ESS is no longer in response to the Nash equilibrium of the managers. Instead the mangers have changed to a *Stackelberg game* defined as a leader-follower game [26,27]. As leaders in the Stackelberg game, the farmers can steer the pest's evolution. As followers, the insects simply react along their best response curve. To maintain a less resistant pest population, the managers moderate their pesticide use below that which would maximize economic gain given the current level of resistance in the pest population. This may become a triple win. The manufacturer maintains a viable product, the farmers experience insect pests that can be managed at acceptable levels with less pesticide, and society has reduced exposure to negative externalities of toxic biocides. This line of reasoning has and is being applied within a game theoretic context to other systems.

Other systems

Pesticide resistance of problem plants and weeds represents a parallel scenario to pesticide resistance in insects [28]. Most of the ideas presented above also apply to herbicide resistant weeds, but the models might involve the competition between the weeds and the crop, or problems arising from the weeds contaminating the seed crop or the quality of say alfalfa or timothy grass hay. While these problems have not generally been approached as explicitly game theoretic, suggestions for reducing the spread of herbicide resistant weeds include reduced herbicide applications [29], crop rotation, and varied forms of weeding [19].

Fisheries management provides some of the earliest game theory models for managing evolving resources [30–32,33•]. While long debated, it is now known that size selective harvesting of fish selects for fish that evolve to mature and maintain a smaller size and fish that breed earlier in life [34]. The fishing industry and society lose twice. The fishing itself reduces fish stocks and the remaining fish stocks may be less profitable and valuable by virtue of their smaller size. Cod and herring represent two striking examples of evolving much smaller mature fish [35,36]. In Australia, New England (USA) and the Canadian maritime provinces, lobster fisheries have thrived under evolutionarily enlightened management [37] that involves, among other things, releasing the very small and the very large lobsters. Ecologically this maintains a stock of breeding individuals, and evolutionarily this reduces the evolution of smaller lobster.

Over-use of antibiotics in livestock and humans has been advocated as a means of forestalling the evolution of antibiotic resistant pathogens. A tragedy of the commons encourages each patient and physician to maximize success by using high doses of drugs. But, this action spread over literally millions of patients insures the rapid evolution and spread of resistant bacteria. Evolutionarily enlightened management suggests minimal short-term losses to individuals for ultimate long-term gains [38,39•].

Finally, clonal evolution by cancer cells [40] and therapy resistance in cancer is what makes cancers lethal [41]. Standard of care advocates maximum tolerable doses of drugs, radiation and/or immunotherapy. If the therapies kill all of the cancer cells, then success has been achieved. But, if residual populations of cancer cells survive they will evolve resistance, proliferate and ultimately result in patient death. Game theory models are being used to model cancer therapy [42] and how reduced doses of drugs can be used to maintain acceptably low populations of cancer cells that retain drug sensitivity (*e.g.*, adaptive therapy [43,44•]). If treating to kill results in the lethal evolution of resistance, then treating to contain becomes an attractive alternative.

Broader context of integrated pest management as a game

In principle a game theoretic approach to pest management seems straightforward. Yet, there are social, scientific and modeling challenges to achieving evolutionarily enlightened management. For instance, an ecologically enlightened approach may result because: (1) evolution is thought to be too slow or negligible, (2) insufficient data or knowledge exists to anticipate the resistance responses of the pest, (3) as a group the individuals may desire an evolutionary approach but some individuals may 'cheat' and create a tragedy of the commons [45,46], and (4) even best practice may result in pests that evolve high resistance resulting in unacceptable levels of crop damage. The optimal strategy for fighting the pest may require the joint and cooperative actions of many managers and farmers. But, in reality, a farmer's decision may be based on guidance from the commercial advisors, and perceptions of the immediate and local threat of the pest. In some cases, farmers may be tempted to over-use pesticides on their own farm while advocating restraint by all of the others, or if pesticides are proving effective over a large scale a famer may be tempted to forgo applying pesticides and free-load from the actions of others [47•].

Even an enlightened strategy may simply delay complete resistance rather than achieving a more or less static and sustainable equilibrium. In this case the dynamic path to equilibrium may be of the most interest, and such paths could be framed as evolutionary games. Such economic processes do not progress steadily toward some pre-determined and unique equilibrium [48]. The outcome of these path-dependent processes will not always converge on a unique equilibrium. There may even be several equilibria (sometimes known as absorbing states) [49]. With path dependence, both the starting point and accidental events (noise) can have irreversible consequences for the ongoing trajectory and outcomes [50].

The interplay between data, management options, and modelling become essential [51]. What are the resistance strategies and mechanisms of the pests? What are the available options? Who are the players, and what are the consequences of their actions [52]? In constructing the model, all of these need to be measured, estimated or assumed. More sophisticated management strategies may include the application of several pesticides, and temporal or spatial variability in their application [53•]. For instance, a double-bind strategy would be ideal if the resistance strategy of the pest to one chemical makes it more susceptible to another and vice-versa [54]. Depending upon the pest's life history and dispersal tendencies, leaving some fields or areas pesticide free may create temporal and spatial refugia that favor non-resistant pests. The opportunities for more realistic and sophisticated models are manifold.

Aside from the evolution of resistance, pests have other ways to escape control. They may undertake otherwise risky migrations to establish a population elsewhere [55] or they may move into a refuge, give up reproduction and enter a state of physiological dormancy [56,57]. Resistance may simply involve avoiding contact with or ingestion of the chemical agent. Life history strategies may adjust to create temporal avoidance. Hence, effective pesticide management may include the use of multiple chemicals, crop rotation, and other forms of deterrence in a highly dynamic manner that adapts to changing circumstances and that formulates the best sequence of pest control actions [58•,59]. Regardless of the simplicity or complexity of the system, the control of pests and the management of their resistance responses invites the application of game theory and game theoretic thinking. In the eco-evolutionary dynamics of crop pests and the countermeasures we take to maintain yields its game on!

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Brown JS: **Why Darwin would have loved evolutionary game theory**. *Proc. R. Soc. B* 2016, **283**:20160847.
• The author shares his enthusiasm for game theory as a conceptual tool for modeling natural selection and explaining the counter-intuitive adaptations that emerge from sex ratios, sexual selection, cooperation, and even macroevolution and cancer. The paper explains the structure of game theory, its applications and the diverse facets of evolutionary stability.

2. Bakker RT: **The deer flees, the wolf pursues: incongruencies in predator–prey coevolution**. In *Coevolution.* Edited by Futuyma DJ, Slatkin M. Sinauer; 1983:350-382.

3. Guedes RNC, Smagghe G, Stark JD, Desneux N: **Pesticide-induced stress in arthropod pests for optimized integrated pest management programs**. *Annu. Rev. Entomol.* 2016, **61**: 43-62.

4. Barzman M, Bàrberi P, Birch ANE, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, Hommel B, Jensen JE, Kiss J, Kudsk P, Lamichhane JR: **Eight principles of integrated pest management**. *Agron. Sustain. Dev.* 2015, **35**:1199-1215.

5. Harper JL: **The evolution of weeds in relation to resistance to herbicides**. In *Proceedings of the 1956 British Weed Control Conference*; *The British Crop Protection Council: UK: 1956: 179-188*.

6. Ryan GF: **Resistance of common groundsel to simazine and atrazine**. *Weed Sci.* 1970, **18**:614-616.

7. Bergelson J, Purrington CB: **Surveying patterns in the cost of resistance in plants**. *Am. Nat.* 1996, **148**:536-558.

8. Powles SB, Yu Q: **Evolution in action: plants resistant to herbicides**. *Annu. Rev. Plant Biol.* 2010, **61**:317-347.

9. Maple PAC, Hamilton-Miller JMT, Brumfitt W: **World-wide antibiotic resistance in methicillin-resistant *Staphylococcus aureus***. *Lancet* 1989, **333**:537-540.

10. Slatter MJ, Pettengell K, Taylor R: **Chloroquine-resistant malaria**. *S. Afr. Med. J.* 1983, **63**:838.

11. Wellems TE, Plowe CV: **Chloroquine-resistant malaria**. *J. Infect. Dis.* 2001, **184**:770-776.

12. Korolev KS, Xavier JB, Gore J: **Turning ecology and evolution against cancer**. *Nat. Rev. Cancer* 2014, **14**:371-380.

13. Lloyd MC, Cunningham JJ, Bui MM, Gillies RJ, Brown JS, Gatenby RA: **Darwinian dynamics of intratumoral heterogeneity: not solely random mutations but also variable environmental selection forces**. *Cancer Res.* 2016, **76**: 3136-3144.

14. Ashley MV, Willson MF, Pergams OR, O'Dowd DJ, Gende SM, Brown JS: **Evolutionarily enlightened management**. *Biol. Conserv.* 2003, **111**:115-123.

15. Liang J, Tang S, Cheke RA: **Beverton–Holt discrete pest management models with pulsed chemical control and evolution of pesticide resistance**. *Commun. Nonlin. Sci. Numer. Simulat.* 2016, **36**:327-341.
• The authors model both the ecological and evolutionary dynamics of an agricultural pest. In examining the optimal temporal strategy for pulsing pesticides to reduce resistance, the ecological dynamics of the pest can become highly unstable with limit cycles and phase shifts in the qualitative nature of pest outbreaks and control.

16. Zimmermann F, Jørgensen C: **Bioeconomic consequences of fishing-induced evolution: a model predicts limited impact on net present value**. *Can. J. Fish. Aquat. Sci.* 2015, **72**:612-624.

17. Nichol D, Jeavons P, Fletcher AG, Bonomo RA, Maini PK, Paul JL, Gatenby RA, Anderson AR, Scott JG: **Steering evolution with sequential therapy to prevent the emergence of bacterial antibiotic resistance**. *PLoS Comput. Biol.* 2015, **11**:1004493.
• The authors use a Markov chain model of binary mutations at four loci of an asexual bacteria to examine how various sequences of antibiotics influence evolution along an adaptive landscape of resistance. Some resistance becomes inevitable, but evolution can be directed towards lower, less resistant fitness peaks and away from higher, less desirable ones.

18. Hata AN, Niederst MJ, Archibald HL, Gomez-Caraballo M, Siddiqui FM, Mulvey HE, Maruvka YE, Ji F, Hyo-eun CB, Radhakrishna VK, Siravegna G: **Tumor cells can follow distinct evolutionary paths to become resistant to epidermal growth factor receptor inhibition**. *Nat. Med.* 2016, **22**:262-269.

19. Nalewaja JD: **Cultural practices for weed resistance management**. *Weed Technol.* 1999, **13**:643-646.

20. Carroll SP, Jørgensen PS, Kinnison MT, Bergstrom CT, Denison RF, Gluckman P, Smith TB, Strauss SY, Tabashnik BE: **Applying evolutionary biology to address global challenges**. *Science* 2014, **346**:1245993.

21. Vincent TL, Brown JS: *Evolutionary Game Theory, Natural Selection, and Darwinian Dynamics*. Cambridge University Press; 2005.

22. Maynard Smith J, Price GR: **The logic of animal conflict**. *Nature* 1973, **246**:15-18.

23. Apaloo J, Brown JS, McNickle GG, Vincent TL, Vincent TL: **ESS versus Nash: solving evolutionary games**. *Evol. Ecol. Res.* 2014, **16**:293-314.

24. Nash J: **Non-cooperative games**. *Ann. Math.* 1951, **54**:286-295.

25. Brown JS, Parman AO: **Consequences of size-selective harvesting as an evolutionary game**. In *The Exploitation of Evolving Resources.* Edited by Stokes TK, McGlade JM, Law R. Berlin, Heidelberg: Springer; 1993:248-261.

26. von Stackelberg H: *The Theory of the Market Economy*. Oxford: Oxford University Press; 1952.

27. Simaan M, Cruz JB Jr: **On the Stackelberg strategy in nonzero-sum games**. *J. Optim. Theory Appl.* 1973, **11**:533-555.

28. Heap I: *The International Survey of Herbicide Resistant Weeds*. 2009. Available at: http://www.weedscience.com.

29. Neve P, Vila-Aiub M, Roux F: **Evolutionary-thinking in agricultural weed management**. *New Phytol.* 2009, **184**: 783-793.

30. Law R, Grey DR: **Evolution of yields from populations with age-specific cropping**. *Evol. Ecol.* 1989, **3**:343-359.

31. Miethe T, Dytham C, Dieckmann U, Pitchford JW: **Marine reserves and the evolutionary effects of fishing on size at maturation**. *ICES J. Mar. Sci.* 2009, **67**:412-425.

32. Heino M, Baulier L, Boukal DS, Ernande B, Johnston FD, Mollet FM, Pardoe H, Therkildsen NO, Uusi-Heikkilä S, Vainikka A *et al.*: **Can fisheries-induced evolution shift reference points for fisheries management?** *ICES J. Mar. Sci.* 2013, **70**:707-721.

33. • Landi P, Hui C, Dieckmann U: **Fisheries-induced disruptive selection**. *J. Theor. Biol.* 2015, **365**:204-216.

The authors use adaptive dynamics, a widely used approach to evolutionary games, to consider whether the bioeconomic game between fisherman and the fish stock could result in an ESS with two types instead of one type of fish. Standard fishing policies may inadvertently be causing such disruptive selection that ultimately will reduce maximum sustainable yields over what is possible if the fish remain one type.

34. Jorgensen C, Enberg K, Dunlop ES, Arlinghaus R, Boukal DS, Brander K, Ernande B, Gardmark A, Johnston F, Matsumura S, Pardoe H: **Ecology-managing evolving fish stocks**. *Science* 2007, **318**:1247-1248.

35. Olsen EM, Heino M, Lilly GR, Morgan MJ, Brattey J, Ernande B, Dieckmann U: **Maturation trends indicative of rapid evolution preceded the collapse of northern cod**. *Nature* 2004, **428**:932-935.

36. Östma Ö, Karlsson O, Pönn J, Kaljuste O, Aho T, Gårdmark A: **Relative contributions of evolutionary and ecological dynamics to body size and life-history changes of herring (*Clupea harengus*) in the Bothnian Sea**. *Evol. Ecol. Res.* 2014, **16**:417-433.

37. Acheson J, Gardner R: **Fishing failure and success in the Gulf of Maine: lobster and groundfish management**. *Marit. Stud.* 2014, **13**:8.

38. Vander Wal E, Garant D, Calmé S, Chapman CA, Festa-Bianchet M, Millien V, Rioux-Paquette S, Pelletier F: **Applying evolutionary concepts to wildlife disease ecology and management**. *Evol. Appl.* 2014, **7**:856-868.

39. • Tasman H: **An optimal control strategy to reduce the spread of malaria resistance**. *Math. Biosci.* 2015, **262**:73-79.

The author considers the fascinating conundrum of how best to coordinate the use of anti-malarial drugs on patients and the use of insecticides on mosquitoes in a manner that controls the disease when both the malaria can evolve drug resistance and the mosquitoes insecticide resistance. As a dynamic optimization problem (time dependent strategies), the application of drugs and insecticides influences the ecological dynamics, the stability of the malaria-mosquito system, and the dynamics and frequency of the disease in the humans.

40. Greaves M, Maley CC: **Clonal evolution in cancer**. *Nature* 2012, **481**:306-313.

41. Nowell PC: **The clonal evolution of tumor cell populations**. *Science* 1976, **194**:23-28.

42. Cunningham JJ, Gatenby RA, Brown JS: **Evolutionary dynamics in cancer therapy**. *Mol. Pharm.* 2011, **8**:2094-2100.

43. Gatenby RA, Silva AS, Gillies RJ, Frieden BR: **Adaptive therapy**. *Cancer Res.* 2009, **69**:4894-4903.

44. • Enriquez-Navas PM, Wojtkowiak JW, Gatenby RA: **Application of evolutionary principles to cancer therapy**. *Cancer Res.* 2015, **75**:4675-4680.

Adaptive therapy represents the cancer equivalent of the evolutionarily enlightened management of pesticide resistance in agricultural pests. The authors, using mice injected with cancer, show that standard of care therapy is relatively ineffective, whereas alternately applying and ceasing therapy based on the dynamics of tumor size can produce prolonged control of the cancer at non-lethal levels.

45. Miranowski JA, Carlson GA: **Economic issues in public and private approaches to preserving pest susceptibility**. In *Pesticide Resistance: Strategies and Tactics for Management.* Edited by Board on Agriculture. Washington, DC: National Academy Press; 1986.

46. Anten NP, Vermeulen PJ: **Tragedies and crops: understanding natural selection to improve cropping systems**. *Trends Ecol. Evol.* 2016, **31**:429-439.

47. • Milne AE, Bell JR, Hutchison WD, van den Bosch F, Mitchell PD, Crowder D, Parnell S, Whitmore AP: **The Effect of farmers' decisions on pest control with *Bt* crops**. *PLoS Comput. Biol.* 2015, **11**:1-18.

The authors find a coordinated response for pest control from the farmers in the same region that is effective at a landscape scale. In a game theoretic model akin to the snow-drift game, they model the corn borer in response to famers using a resistant or non-resistant form of corn.

48. Toma L, Barnes AP, Sutherland LA, Thomson S, Burnett F, Mathews K: **Impact of information transfer on farmers' uptake of innovative crop technologies: a structural equation model applied to survey data**. *J. Technol. Trans.* 2016:1-18 http://dx.doi.org/10.1007/s10961-016-9520-5.

49. David PA: **Path dependence: putting the past into the future of economics**. *The Economic Series Technical Report 533*. California: Institute for Mathematical Studies in the Social Sciences, Stanford University; 1988.

50. David PA: **Path dependence and predictability**. In *Dynamic Systems with Local Network Externalities: A Paradigm for Historical Economics.* Edited by Foray D, Freeman C. London: Technology and the Wealth of Nations; 1993.

51. Tabashnik BE, Mota-Sanchez D, Whalon ME, Hollingworth RM, Carrière Y: **Defining terms for proactive management of resistance to Bt crops and pesticides**. *J. Econ. Entomol.* 2014, **107**:496-507.

52. Horowitz AR, Ishaaya I: *Advances in Insect Control and Resistance Management*. Springer International Publishing; 2016.

53. • Le Cointe R, Simon TE, Delarue P, Hervé M, Leclerc M, Poggi S: **Reducing the use of pesticides with site-specific application: the chemical control of *Rhizoctonia solani* as a case of study for the management of soil-borne diseases**. *PLoS One* 2016, **11**:0163221.

The authors consider conceptually and empirically the ecological (though not evolutionary) application of a fungicide to control outbreaks of a crop pathogen. They show how spatial considerations of both infected and non-infected plants can permit precise and limited applications of fungicide to be effective.

54. Gatenby RA, Brown JS, Vincent TL: **Lessons from applied ecology: cancer control using an evolutionary double bind**. *Cancer Res.* 2009, **69**:7499-7502.

55. Lima EAB, Godoy WAC, Ferreira CP: **Integrated pest management and spatial structure**. In *Insecticides-Advances in Integrated Pest Management.* Edited by Perveen F. InTech; 2012:3-16.

56. Staňková K, Abate A, Sabelis MW: **Irreversible prey diapause as an optimal strategy of a physiologically extended Lotka–Volterra model**. *J. Math. Biol.* 2013, **66**:767-794.

57. Staňková K, Abate A, Sabelis MW, Bua J, You L: **Joining or opting out of a Lotka–Volterra game between predators and prey: does the best strategy depend on modeling energy lost and gained?** *Interface Focus* 2013, **6**:20130034.

58. • Guiver C, Edholm C, Jin Y, Mueller M, Powell J, Rebarber R, Tenhumberg B, Townley S: **Simple adaptive control for positive linear systems with applications to pest management**. *SIAM J. Appl. Math.* 2016, **76**:238-275.

The authors propose a switching adaptive control approach for optimizing pest control. They show how adaptively cycling through several pest management strategies provides a robust and durable reduction or elimination of the pest.

59. Wu KM, Guo YY: **The evolution of cotton pest management practices in China**. *Annu. Rev. Entomol.* 2005, **50**:31-52.