Published in *A Love of Ideas* in 2014 by Future Leaders (www.futureleaders.com.au)

A tale of swarms, cannibals, ageing and human obesity

Stephen J. Simpson

At first sight these seem like very strange bedfellows. In this chapter, I will explain how seeking to understand swarming in locusts has led to new discoveries on the dietary causes of human obesity and ageing, as well as provided an understanding of locust swarming that links neurophysiological events within the brains of individual insects to continental scale mass migration. I hope the narrative, with its strange twists and turns, gives a feel for why pure academic enquiry is so important. Even if I had known at the outset that my research on locusts would lead to new understanding of obesity and metabolic disease in humans (which, of course, I didn't), no funding agency that required immediate practical outcomes would have granted funding for such an outlandish research program. Another pervading theme is that multidisciplinary approaches are required to begin to address complex problems in biology, health and environmental science. In my case, this has involved techniques from molecular biology, population genetics, neurophysiology, biochemistry, behaviour, biomathematics, statistical physics, computer science, engineering, robotics, evolutionary theory, economics and landscape ecology. But let us start the story at the beginning, with ravaging swarms of locusts.

Locust phase change

Locusts are devastating pests affecting the livelihoods of one in ten people on the planet. There are a dozen or so species of grasshopper that are called locusts, some of which live in Australia, which are defined by having one peculiar feature that distinguishes them from all other grasshoppers: they are essentially two animals packed within the same genome. When reared alone they develop into camouflaged grasshoppers that shun the company of others; but when crowded they become brightly coloured, attracted by other locusts, and form huge marching bands of juveniles and flying swarms of adults.

The process of changing from the solitary to the gregarious form is initiated by crowding and begins rapidly. This transition is the catalyst for locust swarming. We found that touch-sensitive receptors on the hind legs are key sense organs involved, which if stimulated by other locusts (or by an experimenter with a paintbrush) trigger the change from solitary to gregarious behaviour. This discovery focused the search for the neurochemical mechanisms underlying behavioural phase change, culminating in showing that a pulse of the chemical serotonin in the central nervous system, released from a small number of specialist cells in the central nervous system, is responsible for initiating the switch from solitary to gregarious behaviour. Serotonin is a ubiquitous chemical messenger in the brains of all animals, ourselves included, and is universally involved in controlling social behaviour, mood and arousal.

From serotonin to mass migration

The next major step from individuals to swarms is the transition from disordered aggregation by gregarious locusts to cohesive, mass movement. Suddenly, as if of one mind, an entire group of gregarious juvenile locusts becomes highly aligned and starts to march. To explain this phenomenon, we used simulation techniques from statistical physics called ‘self-propelled particles models', in which individual particles are programmed to behave according to local interaction rules with respect to neighbouring particles. Using these models in conjunction with laboratory experiments and experiments in the field involving tracking tagged locusts in Australia with robotic aircraft, we found that the collective decision to start marching emerges within a crowd from local interactions between locusts. Locusts follow a local rule: 'align with moving neighbours'. Once a critical density of locusts is reached, the march begins. But why do locusts align with their moving neighbours? The answer came from studies on the Mormon cricket, a large flightless insect from Northwest America that forms vast marching swarms, extending kilometres. We showed that Mormon crickets are on a forced march to find protein. Individuals have to keep moving because they need protein, which becomes deficient in their environment. If crickets don't keep moving they don't find more protein, but worse than that, if they stop moving they become somebody else's protein meal — as, it transpired, are locusts.

Protein leverage: from cannibalism to human obesity

Our experiments indicated that if Mormon crickets and locusts are protein satiated they stop cannibalising, and marching. We had earlier discovered that separate appetites exist for carbohydrate and protein in locusts and other insects and went on to show that a specific protein appetite is found in organisms as disparate as slime moulds, spiders and predatory beetles, ant colonies, birds, fish, rodents, mink, cats, monkeys — and in humans. In fact, protein intake is especially tightly regulated in many omnivores and herbivores, taking priority over intake of other nutrients when the diet forces a trade-off between regulation of protein and non-protein energy.

The consequences of having a dominant protein appetite are considerable. When there is a shift towards including more high-fat and high-carbohydrate foods in the diet, the powerful protein appetite causes us and other animals to eat excess energy to gain limiting protein, predisposing to obesity and metabolic disease. This 'protein leverage' effect is made worse when the requirement for non-protein energy diminishes as a result of doing less exercise. In contrast, if the diet shifts towards a higher percent protein, then there is under consumption, a negative energy balance, and the potential to lose weight. Our results indicate that protein has the power to drive obesity and, potentially, also to ameliorate it; a finding that has important public health implications.

The downside of eating too much protein — ageing

Why do humans and other animals possess such a strong protein regulatory response? It is easy to explain why eating too little protein is to be avoided: protein is the only source of dietary nitrogen for growth, tissue maintenance and reproduction. But why are we and many other animals so unwilling to eat excess protein (thereby promoting reduced calories intake and weight loss on high-protein diets)? The answer came from a study in which we mapped landscapes for lifespan and reproductive output onto detailed nutrient intake arrays in the fruit fly, *Drosophila*. Eating too much protein relative to carbohydrate caused an early death; which explains why regulatory responses have evolved limiting its excessive intake — in insects at least. This conclusion has since been confirmed in several other insect species, and recently also in a major study on mice, in which we undertook the largest analysis of the impact of macronutrient balance ever undertaken on a mammal.

Further lessons from locusts

Our work has helped show that there are fundamental links between dietary macronutrient balance and appetite regulation, obesity, ageing, metabolic health, immune function, autoimmune disease, the microbial ecology of our gut, and even mental health. We are now in a position to understand what it means to eat a balanced diet and the costs of failing to do so. We have combined nutrition and collective behaviour by studying nutrient balancing in ant societies and soil dwelling slime moulds, which play a critical role in decomposition and nutrient cycling. These experiments have implications that extend from solving multiple supply chain problems to understanding carbon sequestration in soils. We are currently extending the study of nutritional interactions beyond individuals and groups to model how nutritional interactions fashion species assemblages, food webs and the functioning of ecosystems. We are also working to optimise diet composition for companion animals, and in food animal production systems, including aquaculture and poultry production, and using nutritional modelling to aid in the conservation of endangered species — from the rare flightless kakapo parrot in New Zealand to free-ranging populations of primates in South America and Africa. All thanks to locusts.

The Charles Perkins Centre

From locusts to cannibals to human obesity to ageing to a new paradigm for the study of nutritional ecology is a strange journey, which provides a compelling example of the power of pure scientific discovery, and has been a great deal of fun. My next step is to take the lessons learned from locusts and write them even larger — at the University of Sydney's visionary new Charles Perkins Centre. The Centre has the mission to ease the burden of obesity, diabetes and cardiovascular disease and related conditions. These diseases are among the leading causes of mortality, disability and reduced quality of life in Australia. They account for half the deaths in this country and are increasing the financial burden on health systems worldwide. They are also extremely complex problems that require more than a conventional drug-based medical solution; rather, we need to reweave the fabric of society — not only helping individuals to change their lifestyles, but also considering the built environment, the food supply system, cultural, economic, commercial, political, ethical and cultural contexts. To this end, the Centre is bringing together researchers and practitioners from the medical, life, environmental, physical and mathematical sciences, along with researchers in the social sciences and humanities, along with representatives from industry, government, the not-for-profit sector, and civil society. The Centre is established to create the environment in which new research and teaching collaborations and opportunities emerge in a way that maximises innovation and creativity, makes new and original research and teaching links across disciplines, and has an impact, leading to practical solutions that improve health outcomes for individuals, communities, and the world.

Further reading

SJ Simpson & D Raubenheimer, *The nature of nutrition: a unifying framework from animal adaptation to human obesity*, Princeton University Press, Princeton, 2012.