Biological control programmes — time to retrospect

R. Uma Shaanker and K. N. Ganeshaiah

Biological control is a tool free from the ill effects associated with chemical control. However, while the lack of documentation of the attempts that have failed has overestimated its potentiality, the euphoria of the success stories seems to have masked the repeated warnings about its other tangential disasters.

BIOLOGICAL control, where biological agents are used to control pests, began as an environmentally safe alternative to the chemical means of control. The Chinese are believed to be the pioneers in using this technique to control the stored grain pests by introducing the nests of the Pharoah's ants into their barns and bins[1]. Around 1200 AD, nests of *Oecophylla* ants were being sold in the markets of China to the farmers to release them in their citrus and litchi orchards to control the insect pests[2]. Some of the recorded instances in the most recent history are the introduction of mynah birds from India to control red locusts in Mauritius during 1762 (ref. 3) and mongooses from Calcutta to Trinidad to control rats during 1872 (ref. 1).

Perhaps the most celebrated example of biological control is the introduction of the Australian vedalia lady beetle to California to control the cottony-cushion scale insects of citrus orchards. The entire citrus industry of California threatened by the scale insect during the late 1880s was rescued following the introduction of the lady beetle during 1889 by Albert Koebele[4]. The success of this introduction triggered the interest world-over in the potentiality of biological control and initiates an extensive application of this technique to control the pests. In India, some of the well-known examples of biological control are the introduction of *Dactylopius opuntiae* from USA (via Australia) to control the prickly pear[5], *Opuntia elatior* and that of *Aphelinus mali* from Uruguay to control the woolly apple aphid in the apple orchards of Shillong[5].

Concern over the mass scale introduction of alien biological agents was expressed as early as 1899 by David Sharp when Albert Koebele introduced the vedalia beetle to America[6]. Referring to this as a 'huge biological experiment', Sharp warned about the possible disturbances to the native flora and fauna and called for a long-term monitoring and for meticulous recording of the consequences. Unfortunately, his warning went unheeded.

For most instances of biological control, there has been a lack of documentation and long-term monitoring of the native biota before and after the introduction of the alien species. Infact lack of such data *per se* has been used as an argument in favour of the safety of the biological control programme. But it should be realized that 'absence of evidence of negative environmental impact is not evidence of the absence of their impact'[6].

In a few situations where monitoring does exist, there is evidence to suggest the adverse environmental impacts caused by biological control programmes. *Bessa remota*, a tachinid fly was introduced to control the coconut moth, *Levuana iridescens* in Fiji Islands. But the fly has made the country poor by the targeted[7] and an other unrelated moth species[6]. Perhaps the most disastrous effect recorded was that due to the release of the predatory snail, *Euglandina rosea* to control the alien African Giant snail, *Achatina fulica*, in the Hawaiian islands[8]. *E. rosea* invaded the native forests and is believed to have annihilated several species of endemic tree snails[9]; today most of the 41 native species of snails are believed to be extinct while the African Giant snail still continues to be a pest[6]. Despite its failure in the Hawaiian islands, the predatory snail was introduced to the French Polynesian island, Moorea, during 1977 where it caused similar havoc to the endemic snails. Clarke *et al.*[10] reported that consequent to its introduction, seven endemic species of *Partula* became extinct. As they expressed, 'their loss is not merely a tragedy for students of genetics, *it is also a warning about the potentially devastating effects of some programs in "biological control"*'.

The effect of introduction on the native flora and fauna would often be complex, indirect and hence not immediately recognizable. For example, the introduction of *Myxoma* virus in Britain to control rabbits has been traced to have led to the extinction of the large

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R. Uma Shaanker is in the Department of Crop Physiology and K. N. Ganeshaiah is in the Department of Genetics and Plant Breeding, University of Agricultural Sciences, GKVK Campus, Bangalore 560 065, India

blue butterfly, *Maculina arion* due to loss of its original habitats[11]. While these are clear demonstrations of the ill-effects of the introduction of biological agents on the native biota, we could never be aware of the scores of species that are being slowly pushed to the verge of extinction.

The irony however is that even the experts accept these losses as inevitable; perhaps as a small cost to be paid for the manifold benefits to human betterment. There could also be other unintended but direct cost of biological control where the introduced species targeted to control a pest might itself turn out to be a pest. Such danger is especially high when the biological agent introduced to control a weed might end up as a pest on an economically important crop. For example the bug *Teleonemia scrupulosa* introduced to Uganda to control the weed *Lantana* was observed to switch over to the sesame crop[12]; fortunately, the problem was not serious since the bug could not reproduce on sesame[13].

Amusing though it may seem, there are instances where the introduced biological agents have necessitated the introduction of yet another biological agent to control them after they have turned out to be pests themselves. The monitor lizard, for instance, introduced by Japanese to Micronesian islands to control rats became pest, and toads were introduced to poison them. However, nature thought otherwise and today both lizard and toad live there happily as pests with unknown consequences to the native biota[14].

In the background of these examples it is probably time to critically re-evaluate the pros and cons believed to be associated with biological control. It is true that biological control as a programme has been frequently successful and instances of failure might not be all that important in the face of the huge benefits that could be accrued by a successful programme. It is also true that the ill-effects of the biological control programme have been at least partly foreseen and accordingly, regulatory policies have been formulated. But it is also likely that these policies have become obsolete since they were formulated at a time when our understanding of the functioning of the ecosystem was poor.

It has been shown theoretically that introducing a species in a stable ecosystem can have chaotic consequences before it can regain stability[15]. For this reason, any biological control programme involving the introduction of a species alien to the habitat needs to be *a priori* analysed as comprehensively as possible with respect to the disturbances it might cause to the local habitat. Further the regulations overseeing the introduction are restricted only to the political borders; but the borders for the organisms which are habitats and not political have not been considered in analysing the possible ill-effects of introduction. Such regulations based on the habitat boundaries are especially important in tropical countries such as India which have an intricately linked mosaic of diverse habitats vulnerable for such choatic perturbations. Sadly enough, it is these countries that are lacking in such regulations.

Consider, for instance, the recent programmes to control *Parthenium* in India. *Parthenium* itself being an introduced weed, two programmes were initiated by independent groups to control it. While one group introduced a beetle[16] (see box page 729, this issue) from Mexico, the other[17,18] resorted to the use of a plant *Cassia uniflora*, Mill., a leguminous weed that entered India from South America. Our regulatory norms with respect to the environmental safety being still at their infancy, it is difficult to ensure if these methods have been rigourously and comprehensively evaluated for sufficient period of time for being environmentally safe before they were executed. Further assuming that both groups had generated evidence in support of their method to control *Parthenium*, an important question would be—was there a necessity to use both the biological agents in view of the potential disasters of introducing them? The alarm about the possible ill-effects of the beetle has already been raised (see page 729, and accompanying box, this issue). We have no assurance that the intentionally accelerated spread of *Cassia* will have no ill-effects on the native flora and fauna especially because its allelopathic effect observed against *Parthenium* has not been comprehensively studied on other native flora. This is particularly appalling considering that 'interference (allelopathy and/or competition) is found to influence succession and vegetation patterning in many plant communities'[19,20].

To conclude, our purpose here has not been to witch-hunt biological control programmes, rather it has been an attempt to introspect the effects of what may be termed as mass-scale biological experiments. It would be grossly unjustified not to acknowledge the benefits of these experiments and at the same time to fail to recognize that these experiments could be disastrous interventions into the long process of biological evolution if executed without seriously analysing the consequences.

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RESEARCH ARTICLES

Direct numerical simulation of the initial evolution of a turbulent axisymmetric wake

A. J. Basu*, R. Narasimha*† and U. N. Sinha*

*National Aeronautical Laboratory, Bangalore 560 017, India
*†Jawaharlal Nehru Centre for Advanced Scientific Research, Indian Institute of Science Campus, Bangalore 560 012, India

The initial evolution of a turbulent axisymmetric wake at a macroscale Reynolds number of 1500 has been simulated by direct solution of the unsteady three-dimensional Navier–Stokes equations using a (temporal) spectral scheme on the Flosolver Mk3 parallel computer at NAL. A visualization of the flow is presented in terms of constant-vorticity surfaces. The simulation shows a complete sequence of events from formation of vortex rings through generation of azimuthal instability and appearance of streamwise structures to eventual breakdown into turbulent flow, and reveals explicitly certain interesting features of the development of streamwise vorticity.

TURBULENT flows continue to provide the greatest challenge in studies of fluid dynamics, in spite of more than a century of scientific effort that has resulted in the acquisition of enormous amounts of experimental data and the formulation of many theoretical approaches[1]. The chief reason for the lack of any satisfactory theory to-date is that the Navier–Stokes equations that govern turbulent flows are nonlinear, and no exact solutions are known that may be relevant to an understanding of turbulence for any geometry. Experimental studies have thrown considerable light on various aspects of turbulence phenomena, but not all physical variables of interest are accessible to available instrumentation. Among the most prominent of these is the vorticity vector, whose three components are difficult to measure, especially with the resolution required to acquire the finest viscous scales. Complete measurements of such vector fields over a three-dimensional domain are till today virtually impossible.

When feasible, direct solution of the full, unsteady, three-dimensional Navier–Stokes equations (which we shall abbreviate to DNS, often also standing for direct numerical simulation), can provide the kind of complete data that experiments cannot. In particular, such simulations yield instantaneous pictures of any flow variable over the whole computational domain, but are very demanding on computer power and memory because of the need to resolve the wide range of length and time-scales encountered in turbulent flows (see Reynolds[2] for a recent review: the ratio of scales to be resolved increases like the 3/4 power of the Reynolds number (Re) of the flow). At present, DNS is usually performed on 64^3 or 128^3 grids, although 256^3 and 512^3 grids have been occasionally attempted. If N is the number of grid points along any space direction, then the number of operations per time-step[3] is typically of the order of

$$75\, N^3 \log_2 N + 100\, N^3.$$

For a 100 MFLOPS computer with careful programming, the CPU time required per time-step for homogeneous turbulent flow simulation is about 3 minutes at a Reynolds number (based on the turbulent macroscale and velocity scale) of 100, and 9 hours at a Reynolds number of 400. A typical simulation of fully developed turbulent flow takes 5000 or more time-steps. It is thus clear that such simulations need substantial computing power, and have been attempted only where super-