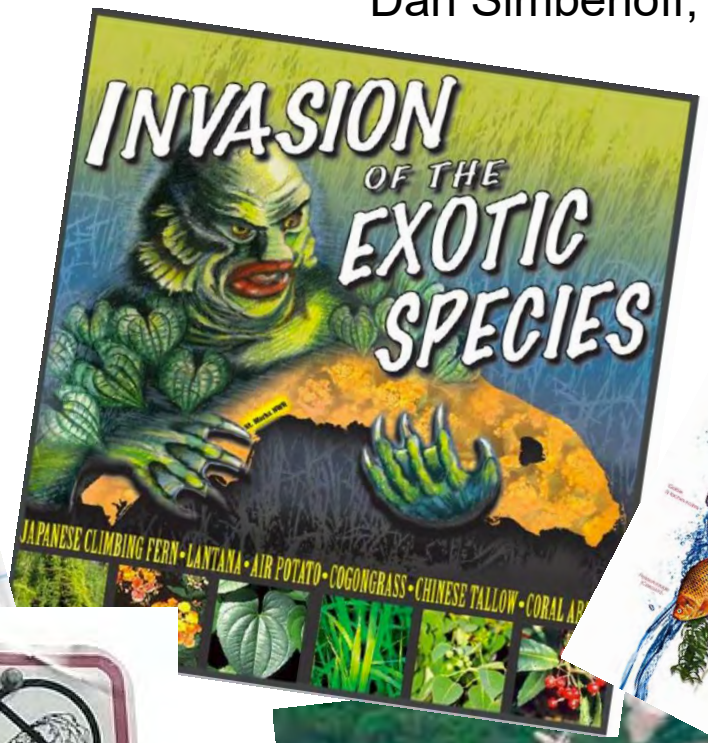
Managing Invasives: Progress, Problems, and Polemics

Dan Simberloff, University of Tennessee



18th century

A picture commonly believed to portray Pehr Kalm, although some modern-day historians have claimed it might well portray Kalm's colleague Pehr Gadd.[1]

En
Reſa
Til
Norra AMERICA,
På
Kongl. Swenſka Wetenſkaps
Academiens befallning,
Och
Publici koſtnad,
Förrättad
Af
PEHR KALM,
Oeconomiæ Profeſſor i Åbo, samt Ledamot af
Kongl. Swenſka Wetenſkaps-Academien.

Tom. I.

Med Kongl. Majtts Allernådigſte *Privilegio.*

STOCKHOLM,
Tryckt på LARS SALVII koſtnad 1753.

Charles Darwin in Patagonia, 1832:

"The whole country may be called one great bed of these plants. The cardoon [Europe and North Africa] is as high as a horse's back, but the Pampas thistle [southern Europe and Asia] is often higher than the crown of the rider's head. The road itself is partly, and in some cases entirely, closed."

1958

. Richardson and P. Pyšek

Figure 1 Charles Sutherland Elton (1900–1991). His book *The ecology of invasions by animals and plants* is widely acknowledged as launching the systematic study of biological invasions. Photo courtesy of the Department of Zoology, University of Oxford.

IN RETROSPECT

The book that began invasion ecology

Charles Elton's 50-year-old text founded a field and is now cited more than ever.

The Ecology of Invasions by Animals and Plants
by Charles S. Elton
Methuen: 1958. 181 pp.

Anthony Ricciardi and Hugh J. MacIsaac

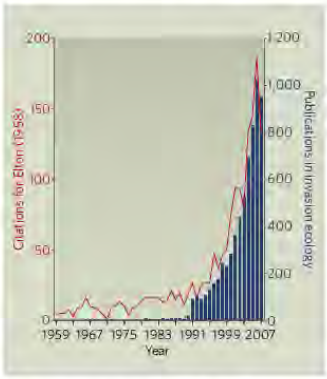
Human activities have introduced alien animals, plants and microbes to all but the remotest regions of Earth. These biological invasions threaten ecosystems, economies and human health, and are the focus of a highly productive subdiscipline of ecology, the origin of which can be traced to a book that was published 0 years ago.

The Ecology of Invasions by Animals and nts by British ecologist Charles S. Elton emarkably, not a scientific treatise or an lemic text, but an expansion of a short s of BBC radio broadcasts aimed at blic. At the time, Elton was the most tial figure in animal ecology, having ed studies on population dynamics d chains. He was particularly interwhat he called "ecological explonormous, uncontrolled increases on.

y, ecologists had treated invasions s. Elton characterized them as omatic of a process that could gical landscape of the planet. g one of the great historical the world's fauna and flora," effort to move the study of natural historical accounts, testable generalizations arate disciplines, includpidemiology and human ntified large-scale patther number of invaders ompared with tropical versus mainland areas recently verified by

n demonstrated the uman activities in ions. For example, sts began to focus en aquatic species, on to the transport of organ- ships' ballast tanks, the intercontinental movement of oysters and their associated flora and fauna, and the role of canals in linking regions formerly isolated from each other for millions of years.

Many of the concepts raised in *The Ecology of Invasions by Animals and Plants* have flourished into important research themes that continue to be vigorously debated. Most notable of these is the 'biotic resistance' hypothesis: that species-rich communities



DATA FROM THOMSON SCIENTIFIC WEB OF SCIENCE

are more resistant to invasion. Elton proposed that diverse communities use reso es more fully, leaving fewer niches for po nists to exploit. Recent studies that invaders in small, species indeed fare worse than those biodiversity. But the pattern over large areas, apparently d environmental conditions and alien species alike.

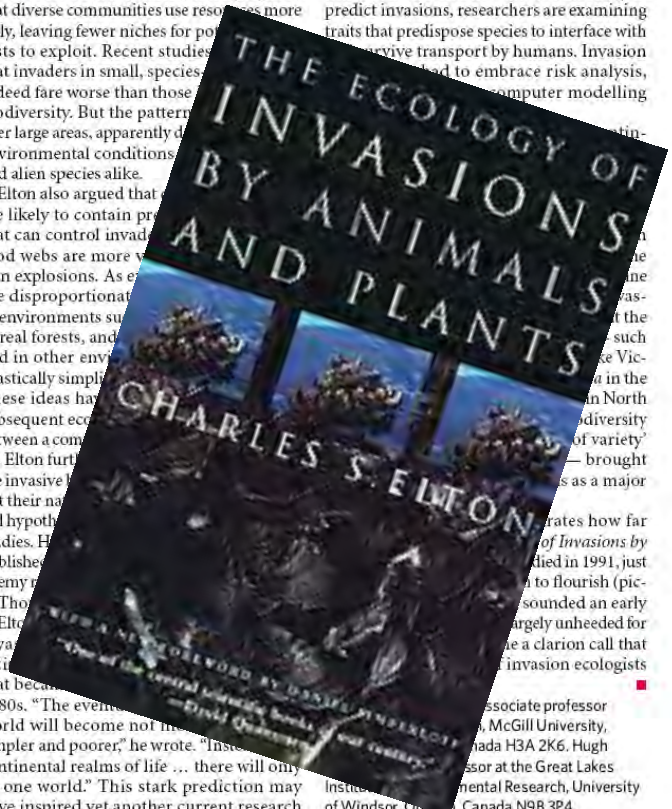
Elton also argued that are likely to contain pr that can control invad food webs are more v tion explosions. As e the disproportionat in environments su boreal forests, and and in other envi drastically simpli These ideas ha subsequent ec between a com ity. Elton furth are invasive out their na sial hypoth studies. H publishe enemy i to Tho

Elt inva exti that beca

1980s. "The even world will become not m simpler and poorer," he wrote. "Ins continental realms of life … there will only be one world." This stark prediction may

theme: the consequences of the replacement of unique assemblages of plants and animals by widespread alien species that coexist with humans, such as rats, starlings and carp.

Half a century on, invasion ecology has progressed well-beyond the scope of Elton's book. Several topics that are now crucial to our current understanding were overlooked or only touched on by Elton. These include: the number of introductions or individuals a population requires to become established; the evolutionary effects of invasions; and interactions among alien species that enhance each other's success. Commerce in agriculture, aquaculture, ornamental plants and pets has opened up the world to thousands of potential invaders, often aided by rapid unregulated trade through the Internet. The release of genetically modified organisms has added another dimension. To try to predict invasions, researchers are examining traits that predispose species to interface with rvive transport by humans. Invasion d to embrace risk analysis, omputer modelling



tin- ne as- t the such e Vic- a in the n North odiversity of variety' — brought s as a major

rates how far *of Invasions by* died in 1991, just to flourish (pic- sounded an early rgely unheeded for e a clarion call that invasion ecologists ■

ssociate professor , McGill University, nada H3A 2K6. Hugh ssor at the Great Lakes nental Research, University Canada N9B 3P4.

from Richardson and Pyšek 2008

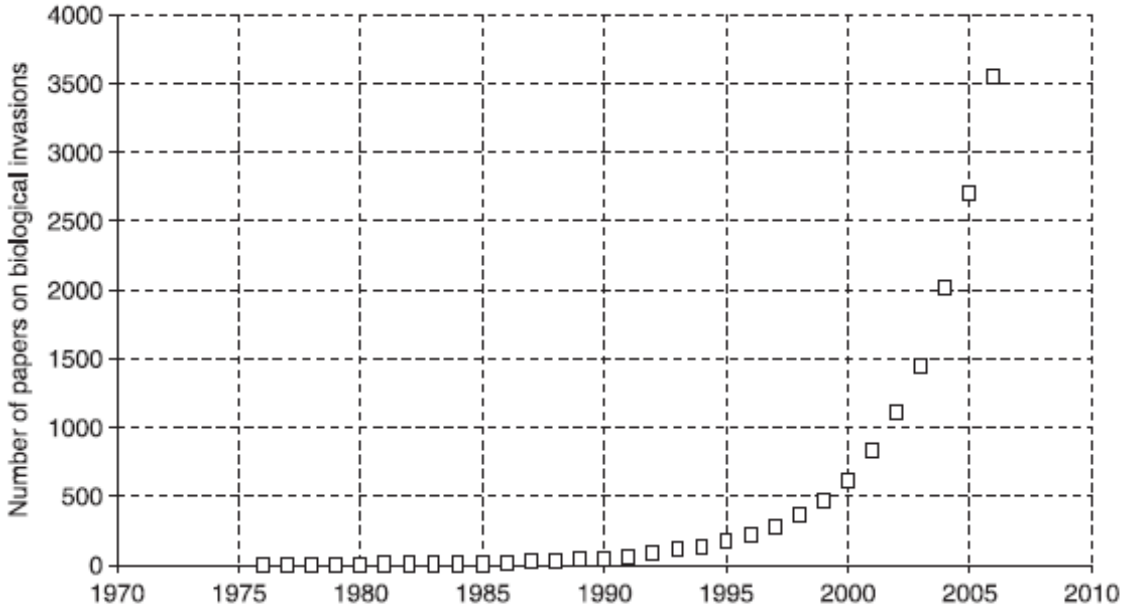


Figure 2 Growth in the number of papers in invasion ecology published up to 2006 and registered on the Web of Science (see text for the methods of screening for relevant papers).

Elton's book

1980 – SCOPE conference on ecology of Mediterranean-type ecosystems.

SCOPE

ICSU INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

SCOPE NEWSLETTER

N° 23 - March 1985 SCIENTIFIC COMMITTEE ON PROBLEMS OF THE ENVIRONMENT

ECOLOGY OF BIOLOGICAL INVASIONS

Since mid-1982, SCOPE has developed a new programme to examine the ecology of invasive plants, animals, and micro-organisms. Emphasis is centered on the study of those species which have sucessfully invaded non-agricultural regions and have disrupted natural ecosystem processes. Specific questions addressed are :

1) What are the factors which determine whether a species will be an invader or not?

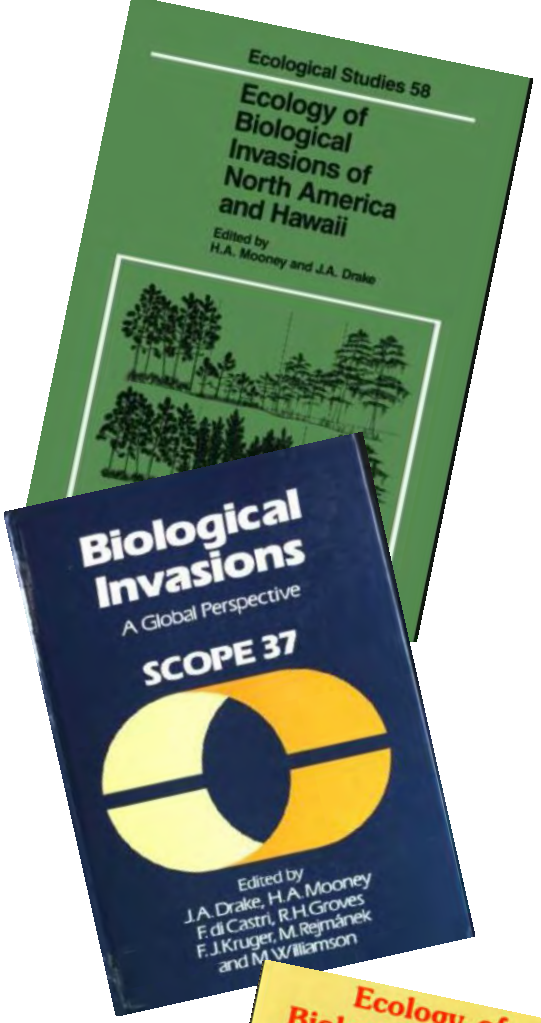
2) What are the site properties which determine whether an ecological system will be relatively prone to, or resistant to, invasion?

3) How should management systems be developed to utilize the knowledge gained from answering questions 1 and 2.

Under the guidance of the Scientific Advisory Committee for the project established under the chairmanship of Professor H.A. Mooney, a series of national and international workshops and working group meetings have been organized which will summarize knowledge in this area and will be followed by an international synthesis in 1986 and 1987.

* *
*

Within the framework of the international programme outline, various national projects have developed independently. Their main purpose is to assemble data bases, identify problems and specialists and to synthesize knowledge. The conclusions of the meetings organized at the national level will provide the general background for the synthesis phase. The specific programmes developed by the National Committees in Australia, South Africa, United Kingdom and USA are described in the following pages. Additional contributions are



Todd Murphy with his record-setting catch (Maryland Department of Natural Resources)

Boiga irregularis,
the brown tree snake
on Guam

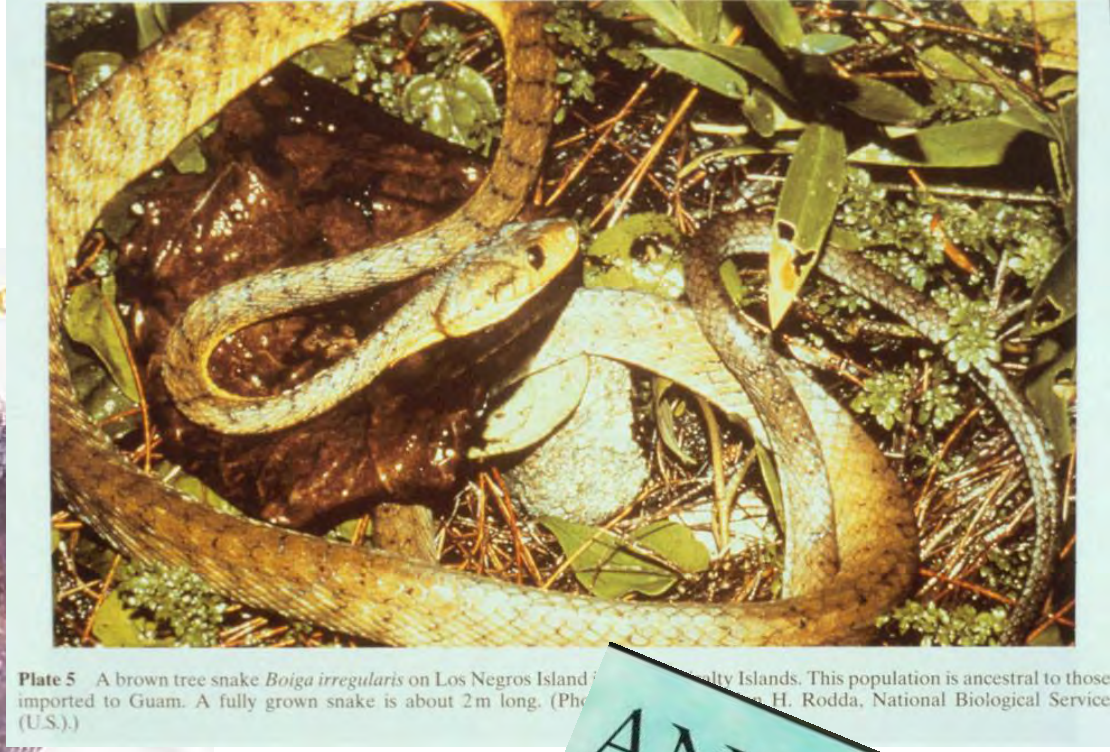
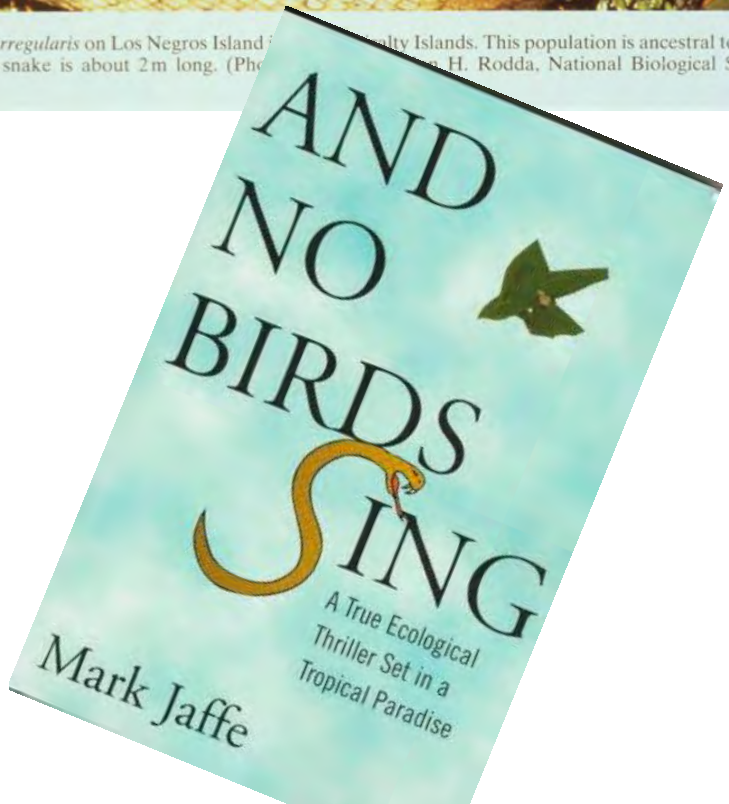
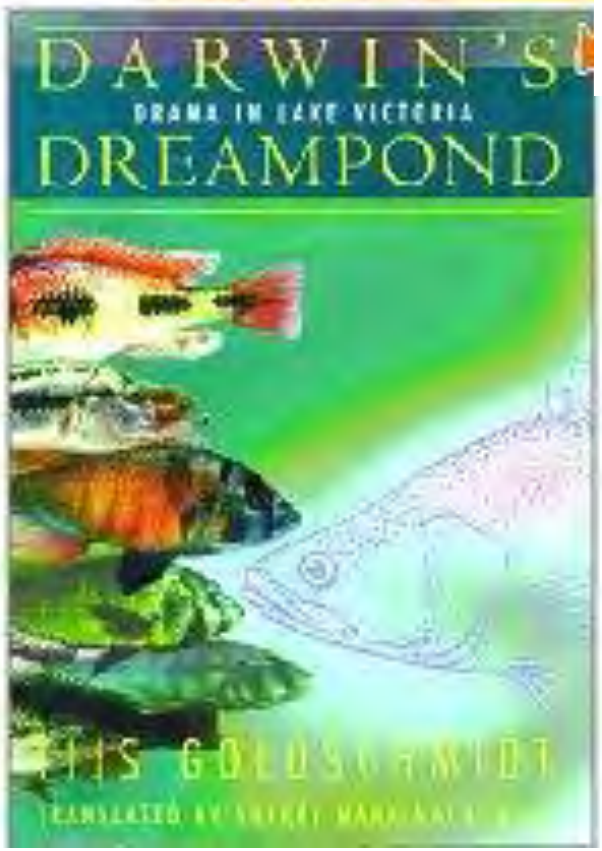


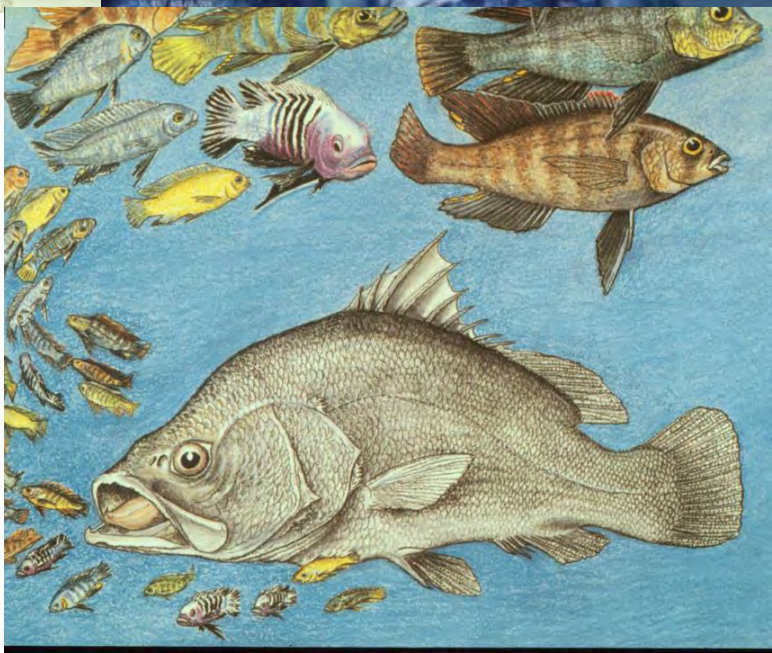
Plate 5 A brown tree snake *Boiga irregularis* on Los Negros Island … alty Islands. This population is ancestral to those imported to Guam. A fully grown snake is about 2m long. (Pho… H. Rodda, National Biological Service (U.S.).)



Burmese python, Florida



Nile perch in Lake Victoria



Caulerpa taxifolia

Mediterranean


CHEATGRASS
FIRE AND FORAGE
ON THE RANGE
JAMES A.
YOUNG
CHARLIE D.
CLEMENTS

And introduced species also:

Compete with native species
Parasitize or infect native species
Vector diseases to native species
Hybridize with native species
Etc., etc., etc.


What's
New

BIOLOGICAL INVASION BY *MYRICA FAYA* IN HAWAI'I: PLANT DEMOGRAPHY, NITROGEN FIXATION, ECOSYSTEM EFFECTS[1]

PETER M. VITOUSEK AND LAWRENCE R. WALKER[2]
Department of Biological Sciences, Stanford University, Stanford, California 94305 USA

1989. Ecol. Monogr.
59: 247-259

BIOLOGICAL INVASION BY *MYRICA FAYA* IN HAWAI'I: PLANT DEMOGRAPHY, NITROGEN FIXATION, ECOSYSTEM EFFECTS[1]

PETER M. VITOUSEK AND LAWRENCE R. WALKER[2]
Department of Biological Sciences, Stanford University, Stanford, California 94305 USA

1989. Ecol. Monogr.
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invasional meltdown

Figure 1 Study system. (a) Aorangaia (5.6 ha), a typical island used in this study. (b) Forest floor on Tawhiti Rahi, a rat-free island. (c) Forest floor on Aiguilles, a rat-invaded island. Rat-free islands are characterized by dense seabird burrows on forest floor (such as those of Buller's shearwater, *Puffinus bulleri*, shown in b). Burrow entrances are about 20–50 cm wide, some of which are indicated by arrows in (b). Rat-free islands are in sharp contrast to rat-invaded islands, where seabird burrows are virtually non-existent owing to rat predation of seabirds (c).

T Fukami et al. 2006
Ecology Letters 9:1299-1307

"Above- and below-ground impacts of introduced predators in seabird-dominated island ecosystems"

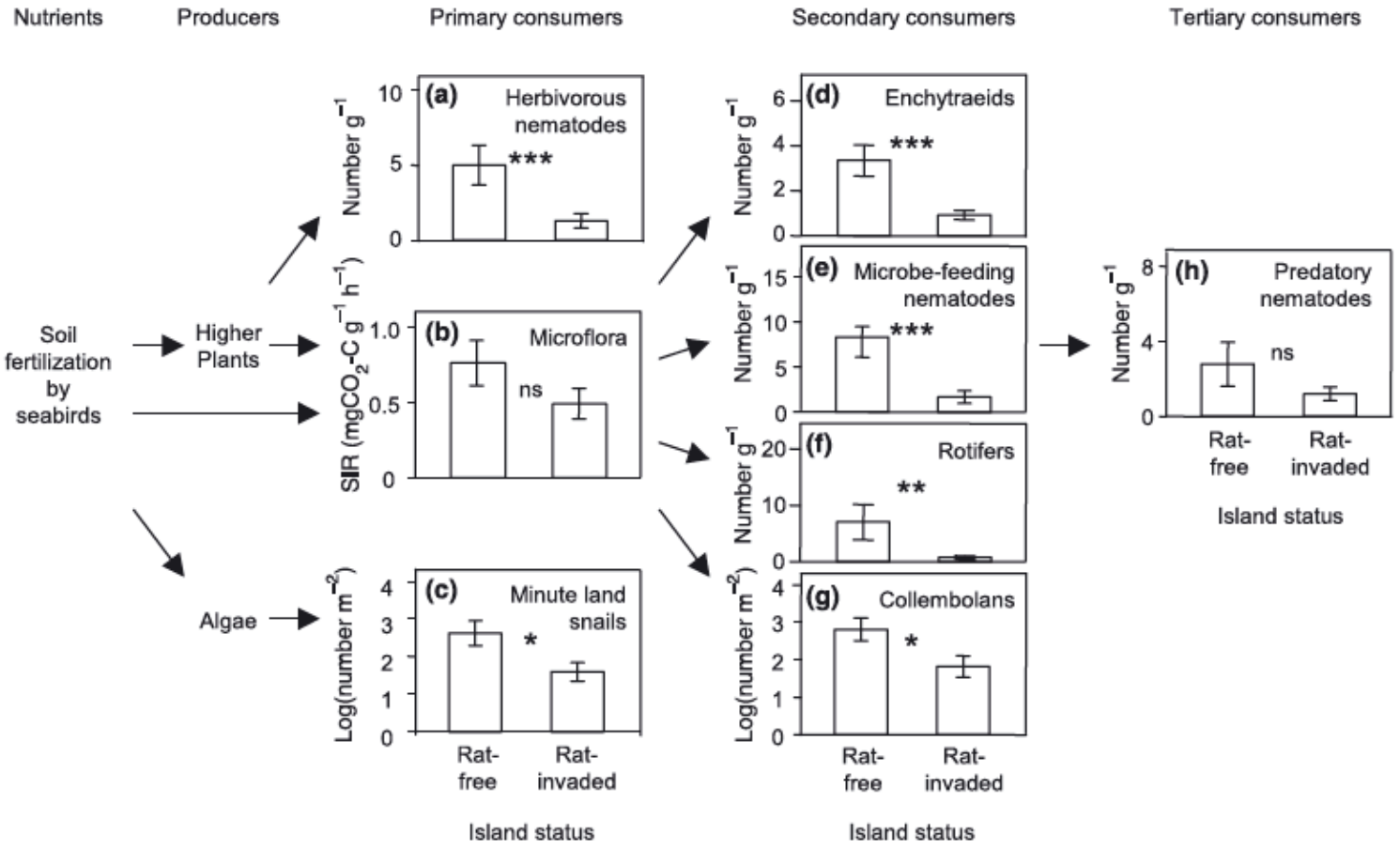
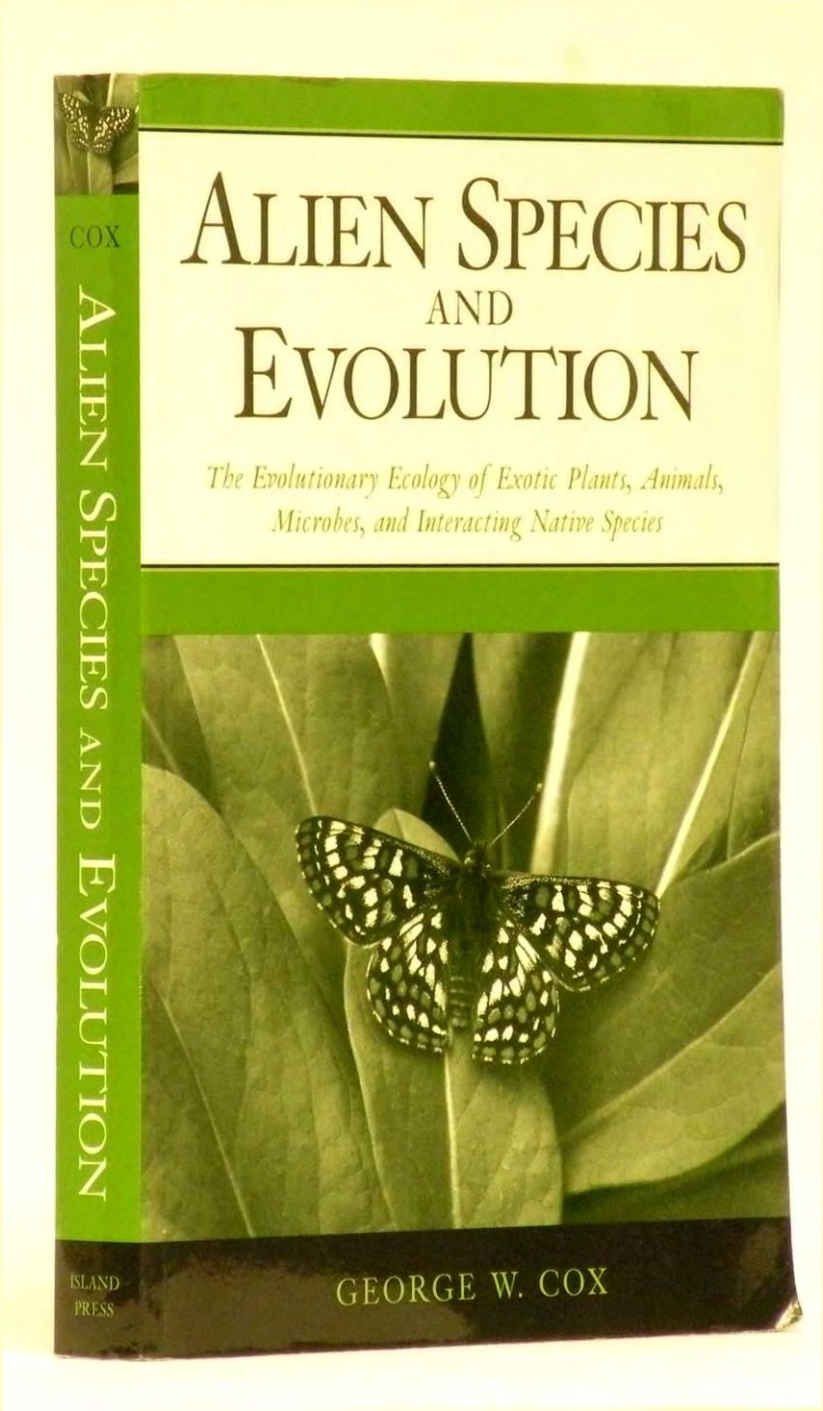


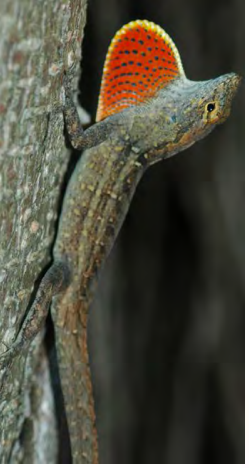
Figure 2 Response of belowground trophic groups to rat invasion of islands. Arrows indicate directions of nutrient flow (note that only a subset of the soil food web is shown). Results are shown as means ± SEM (n = 9 rat-free and 9 rat-invaded islands). * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns, non-significant; SIR, substrate-induced respiration in litter and soil.

Above- and below-ground impacts of introduced predators in seabird-dominated island ecosystems

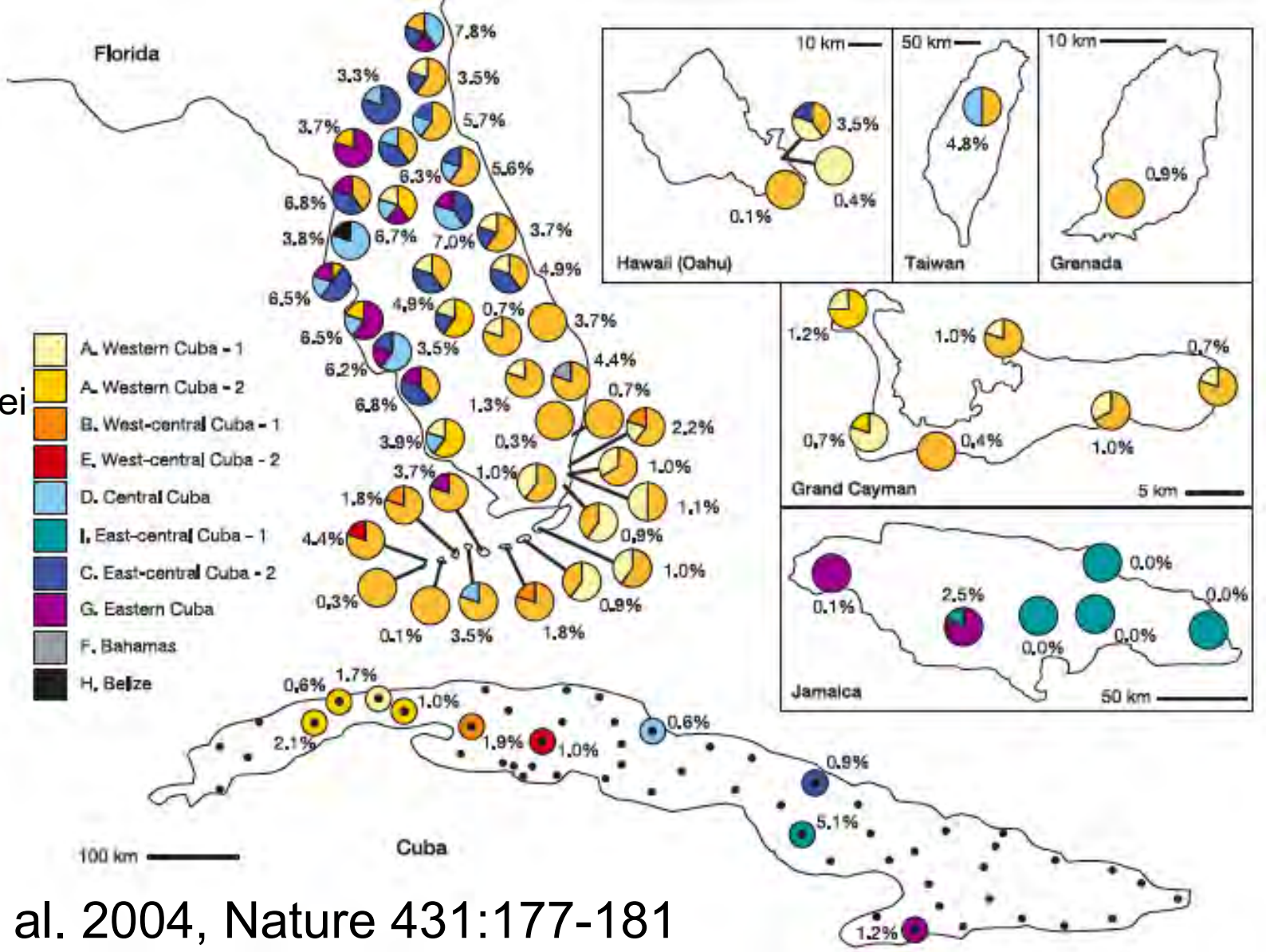
T Fukami et al. 2006
Ecology Letters 9:1299-1307

2004


COX
ALIEN SPECIES AND EVOLUTION
ISLAND PRESS
ALIEN SPECIES AND EVOLUTION
The Evolutionary Ecology of Exotic Plants, Animals, Microbes, and Interacting Native Species
GEORGE W. COX



Anolis sagrei



Kolbe et al. 2004, Nature 431:177-181

Figure 2 Source of genetic variation in introduced *A. sagrei* populations. The map shows the distribution of genetic variation in introduced populations in Florida, Hawaii, Taiwan, Grenada, Grand Cayman and Jamaica, and the source of this genetic variation from native Cuban populations. Blacks dots indicate native Cuban populations sampled. Colours encircling some black dots denote Cuban populations containing haplotypes to which introduced-population haplotypes are most closely related. Pie charts representing each introduced population indicate the frequency of haplotypes from different Cuban sources (populations for which only one individual was sampled are not shown). Percentages next to each pie chart give the mean pairwise mtDNA sequence divergence within that population (overall means are 3.5% for Florida and 1.7% for Cuba). Letters (A–I) in the key correspond to clades in Fig. 1 and haplotype networks in Supplementary Fig. S2.

Increased genetic variation and evolutionary potential drive the success of an invasive grass

Sébastien Lavergne* and Jane Molofsky

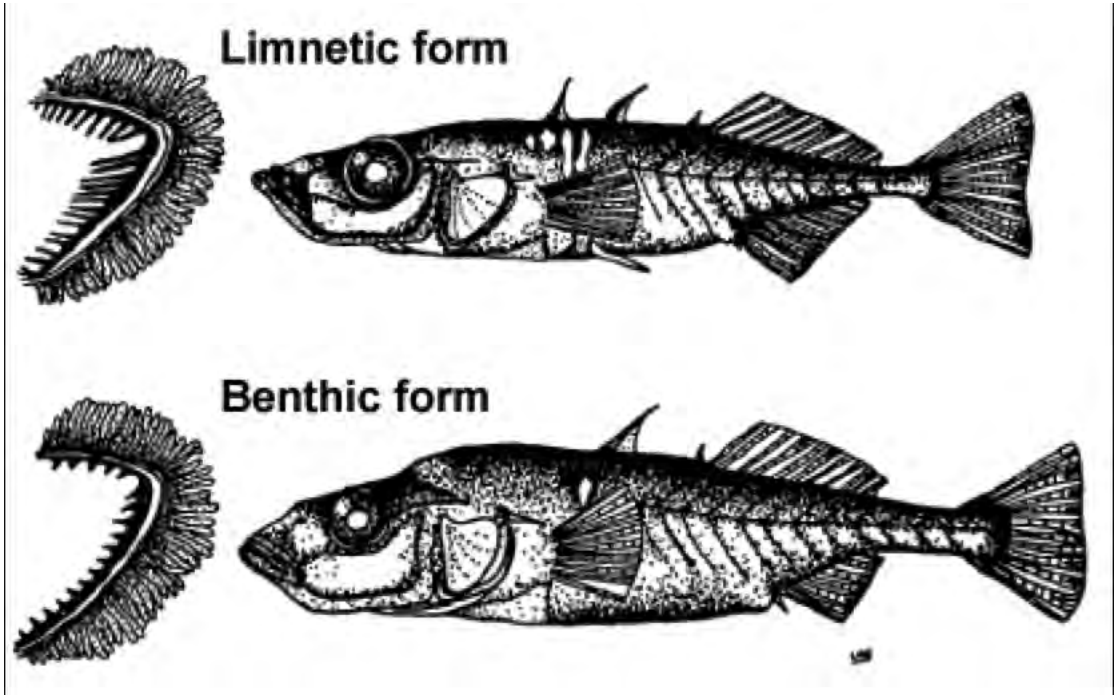
Department of Plant Biology, University of Vermont, Marsh Life Sciences Building, 109 Carrigan Drive, Burlington, VT 05405

reed canary grass
Phalaris arundinacea

2007. Proc. Natl. Acad. Sci. 104: 3883-3888

HYBRIDIZATION

"reverse speciation" in a three-spined stickleback species pair



2012. Canadian Journal of Zoology 90:1328-1338

ARTICLE / ARTICLE

Effects of invasive American signal crayfish (*Pacifastacus leniusculus*) on the reproductive behaviour of threespine stickleback (*Gasterosteus aculeatus*) sympatric species pairs

G.J. Velema, J.S. Rosenfeld, and E.B. Taylor

Molecular Ecology (2006) **15**, 343–355

Speciation in reverse: morphological and genetic evidence of the collapse of a three-spined stickleback (*Gasterosteus aculeatus*) species pair

E. B. TAYLOR,* J. W. BOUGHMAN,*‡ M. GROENENBOOM,*† M. SNIATYNSKI,* D. SCHLUTER* and J. L. GOW*§

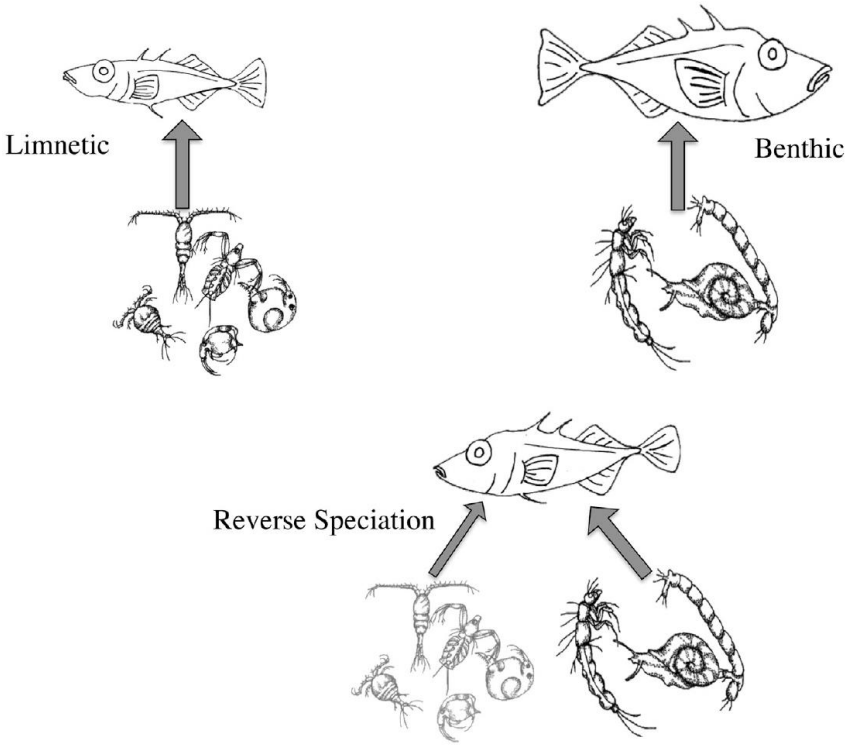
CellPress

Current Biology
Report

Ecological Impacts of Reverse Speciation in Threespine Stickleback

Seth M. Rudman[1,*] **and Dolph Schluter**[1]
[1]Department of Zoology and Biodiversity Research Centre, University of British Columbia, 4200–6270 University Boulevard, Vancouver, BC V6T1Z4, Canada
*Correspondence: rudman@zoology.ubc.ca
http://dx.doi.org/10.1016/j.cub.2016.01.004

Bosmina sp.



A forester engages in efforts to eradicate the velvet tree *Miconia calvescens* in Hawaii.

Don't judge species on their origins

Conservationists should assess organisms on environmental impact rather than on whether they a natives, argue **Mark Davis** and 18 other ecologists

Over the past few decades, 'non-native' species have been vilified for driving beloved 'native' species to extinction and generally polluting 'natural' environments. Intentionally or not, such characterizations have helped to create a pervasive bias against alien species that has been embraced by the public, conservationists, land managers and policy-makers, as well by as many scientists, throughout the world.

approaches to the conservation ment of species — approach to our fast-changing plan

The concept of native by the English botanis By the late 1840s, b terms native and help them disting posed a 'true' British

Over the next century,

exaggerated claims of impending harm to help convey the message that introduced species are the enemies of man and nature.

Certainly, some species introduced by humans have driven extinctions and undermined important ecological services such as clean water and timber resources. In Hawaii, for instance, avian malaria — probably introduced in the early 1900s when European settlers brought in song and game birds — has killed off more than half of the islands' native bird species. Zebra mussels (*Dreissena polymorpha*), originally native to the lakes of southeast Russia and accidentally introduced to North America in the late 1980s, have cost the US power industry and water utilities hundreds of millions (some sa lions) of dollars in damage by clogging es.

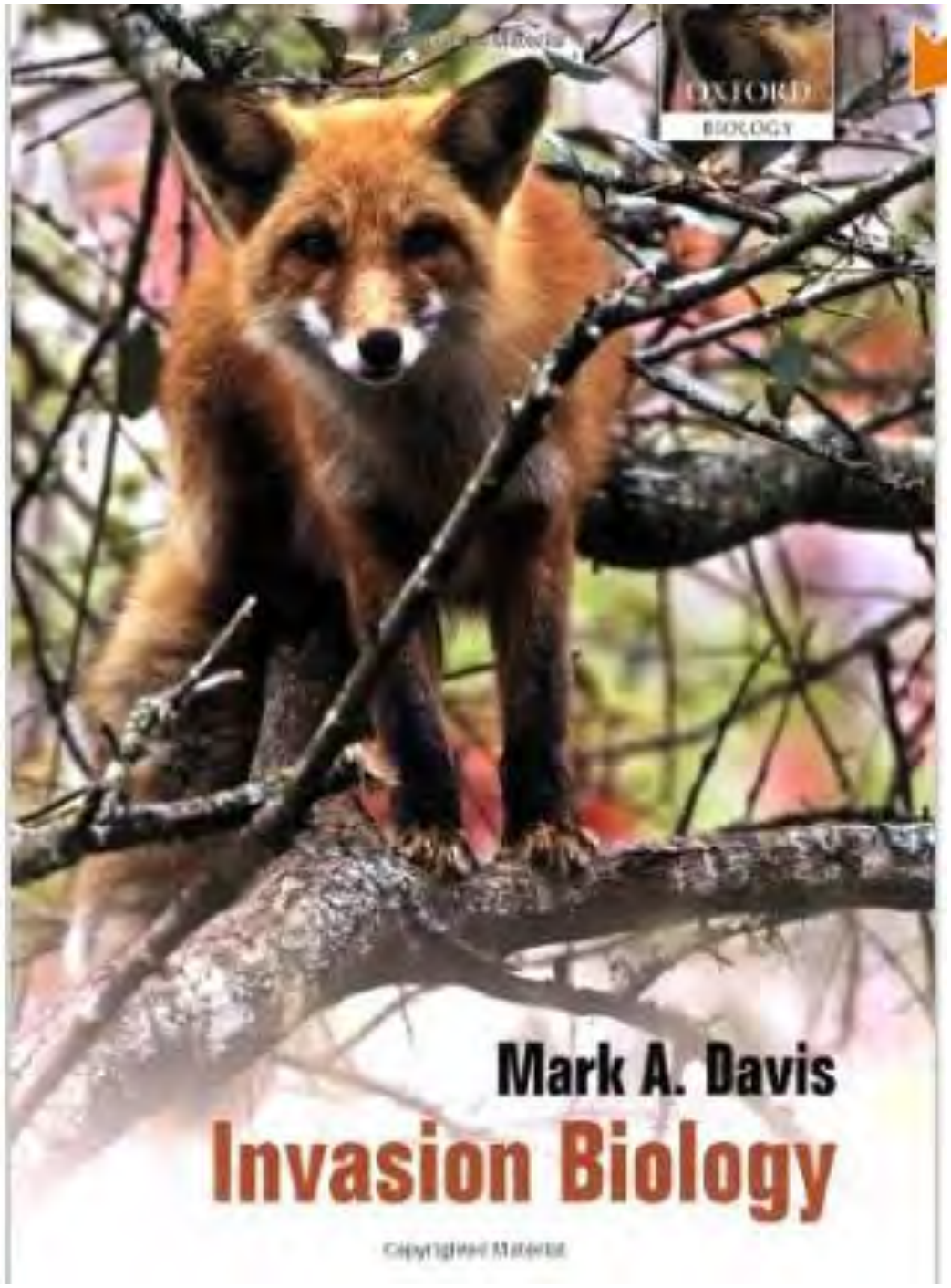
But many of the claims perception that introdu apocalyptic threat to backed by data. Take a 1998 paper[4] that greatest threat t or endangere tion. Little this clai author recer re

CORRESPO

Non-natives: 141 scientists object

We the undersigned feel that in advocating a change in the environmental management of introduced species (*Nature* 474, 153–154; 2011), Mark Davis and colleagues a straw men. First, most co biologists a

Nature 2011



2009

Oikos 2013

Another call for the end of invasion biology

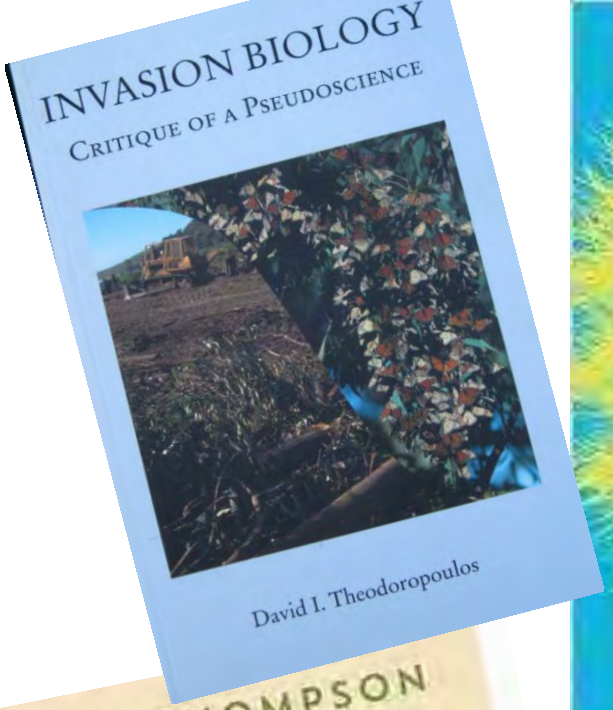
Loïc Valéry, Hervé Fritz and Jean-Claude Lefeuvre

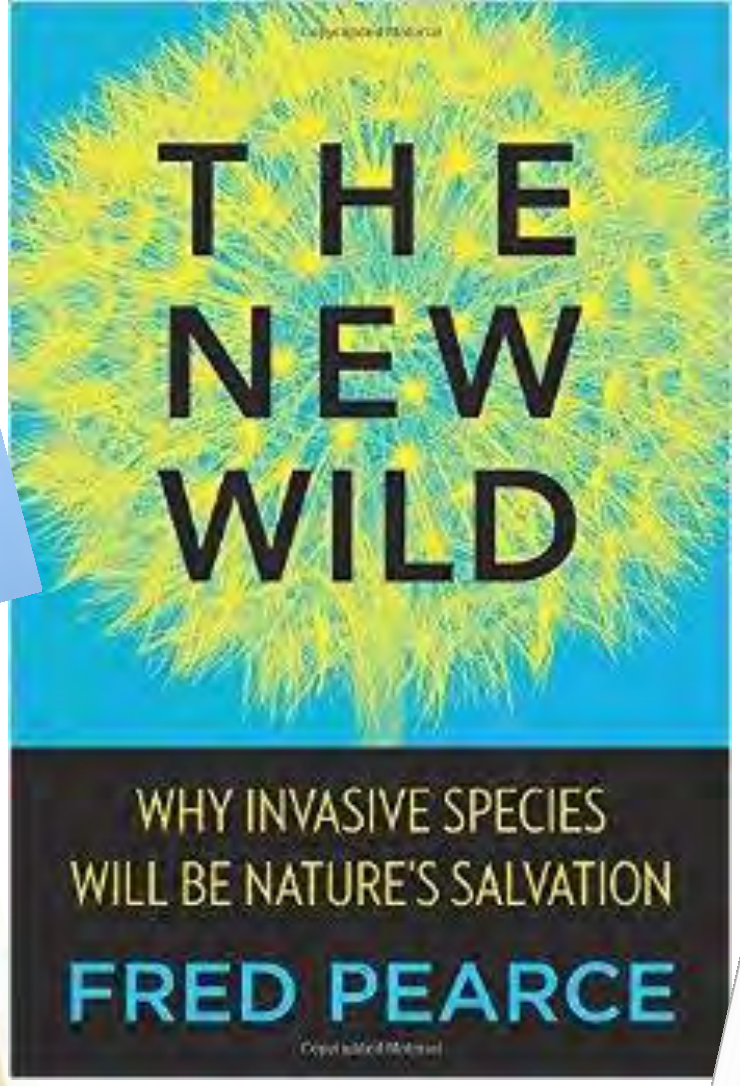
L. Valéry (lvalery@mnhn.fr) and J.-C. Lefeuvre, Dépt d'Ecologie et de Gestion de la Biodiversité, Muséum National d'Histoire Naturelle, and URU Biodiversité et Gestion des Territoires, Univ. de Rennes 1, Bât 25 – Avenue du Général Leclerc, FR-35042 Rennes cedex, Franc – H. Fritz, Laboratoire de Biométrie et Biologie Evolutive, Univ. Lyon 1; CNRS; UMR 5558, 43 boulevard du 11 Novembre 1918, FR-69622 Villeurbanne, France.

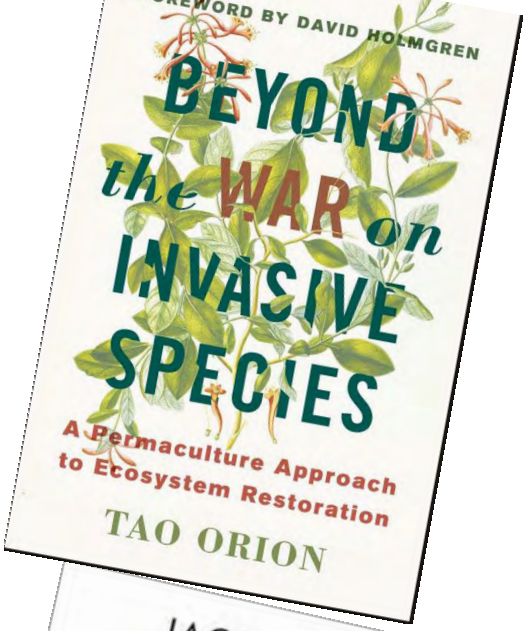
A call for an end to calls for the end of invasion biology

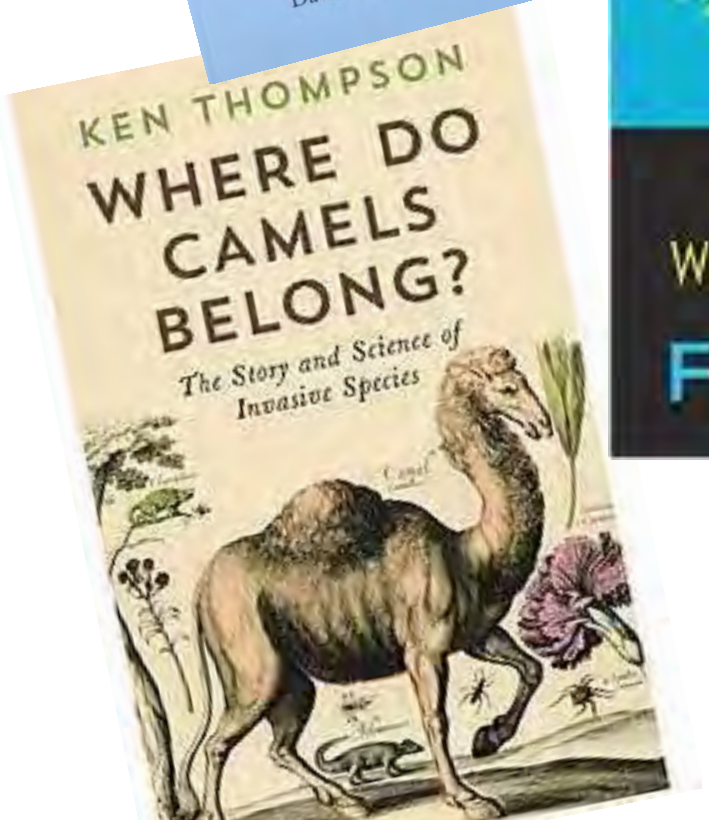
Daniel Simberloff and Jean R. S. Vitule

D. Simberloff (dsimberloff@utk.edu), Dept of Ecology and Evolutionary Biology, Univ. of Tennessee, Knoxville, TN 37996, USA. – J. R. S. Vitule, Laboratório de Ecologia e Conservação, Depto de Engenharia Ambiental, Setor de Tecnologia, Univ. Federal do Paraná, 81531, 980, Curitiba, Paraná, Brazil.


INVASION BIOLOGY
Critique of a Pseudoscience
David I. Theodoropoulos


THE NEW WILD
WHY INVASIVE SPECIES WILL BE NATURE'S SALVATION
FRED PEARCE


FOREWORD BY DAVID HOLMGREN
BEYOND the WAR on INVASIVE SPECIES
A Permaculture Approach to Ecosystem Restoration
TAO ORION


KEN THOMPSON
WHERE DO CAMELS BELONG?
The Story and Science of Invasive Species


JACQUES TASSIN
LA GRANDE INVASION
QUI A PEUR DES ESPÈCES INVASIVES ?
Odile Jacob
sciences

International New York Times

Invasive Species Aren't Always Unwanted

By ERICA GOODE FEB. 29, 2016

In Spain, nonnative crayfish serve as prey for migratory wetland birds. Rafa Huertas/Reuters

Invasive species are bad news, or so goes the conventional wisdom, encouraged by persistent warnings from biologists about the dangers of foreign animals and plants moving into new territories.

Conservation organizations bill alien species as the foremost threat to native wildlife. Cities rip out exotic trees and shrubs in favor of indigenous varieties. And governments spend millions on efforts to head off or

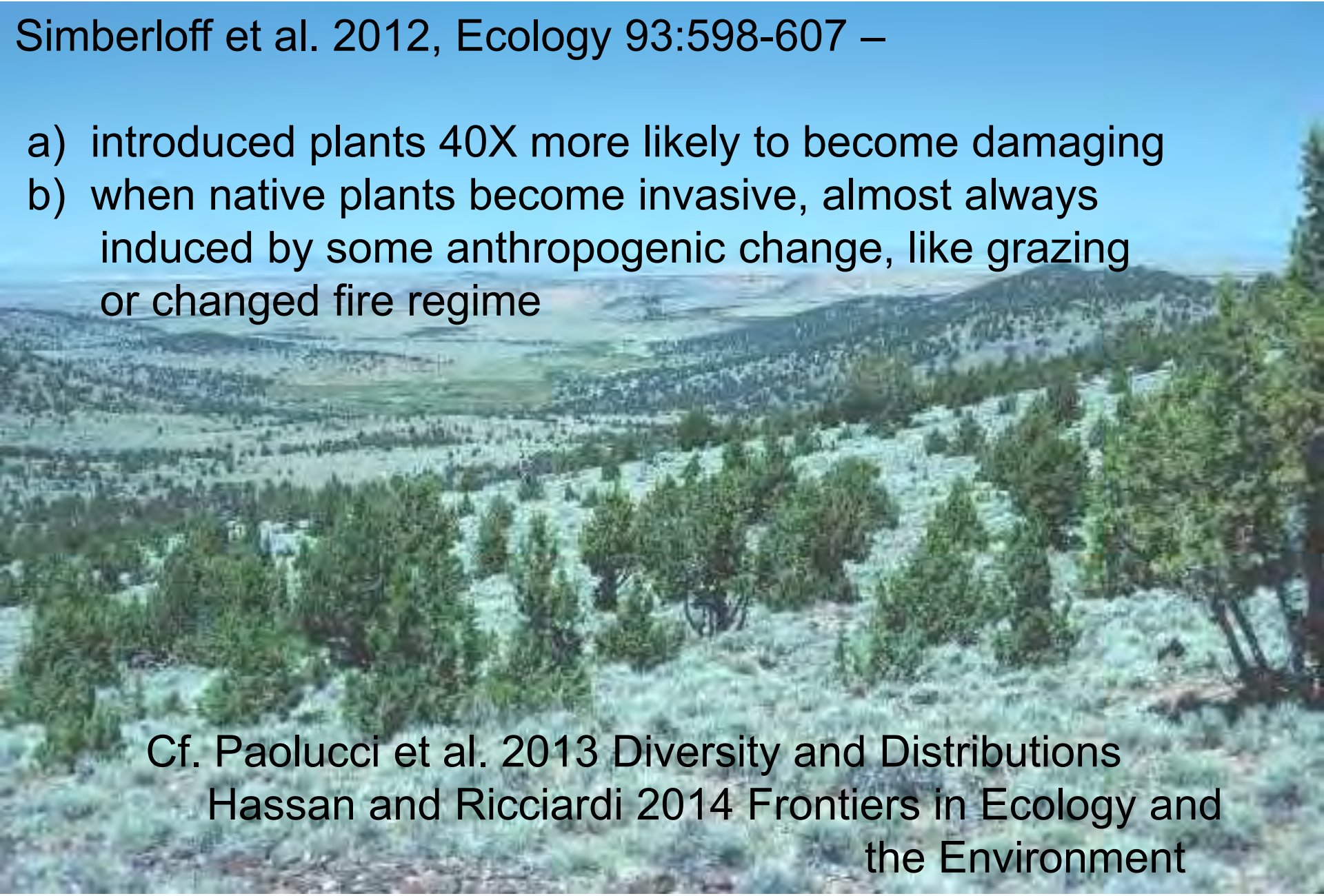
1) How many introduced species are harmful?

1) How many introduced species are harmful?

a) Some native species become “invasive.”

Simberloff et al. 2012, Ecology 93:598-607 –

a) introduced plants 40X more likely to become damaging
b) when native plants become invasive, almost always induced by some anthropogenic change, like grazing or changed fire regime



Cf. Paolucci et al. 2013 Diversity and Distributions
Hassan and Ricciardi 2014 Frontiers in Ecology and the Environment

Encroachment by *Juniperus occidentalis*

1) How many introduced species are harmful?

1) Are actions against introduced species xenophobic?

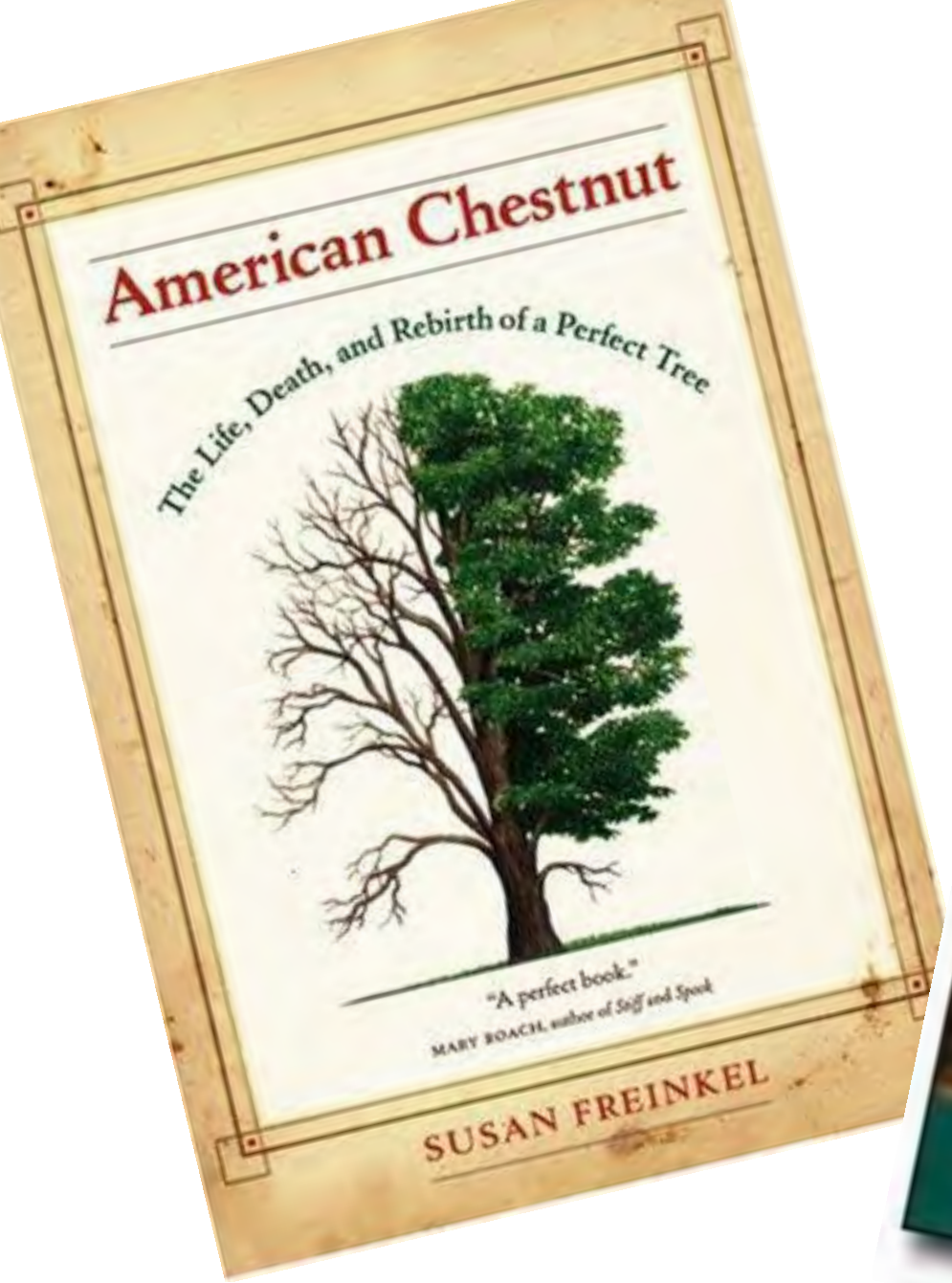
Restrictive United States Laws

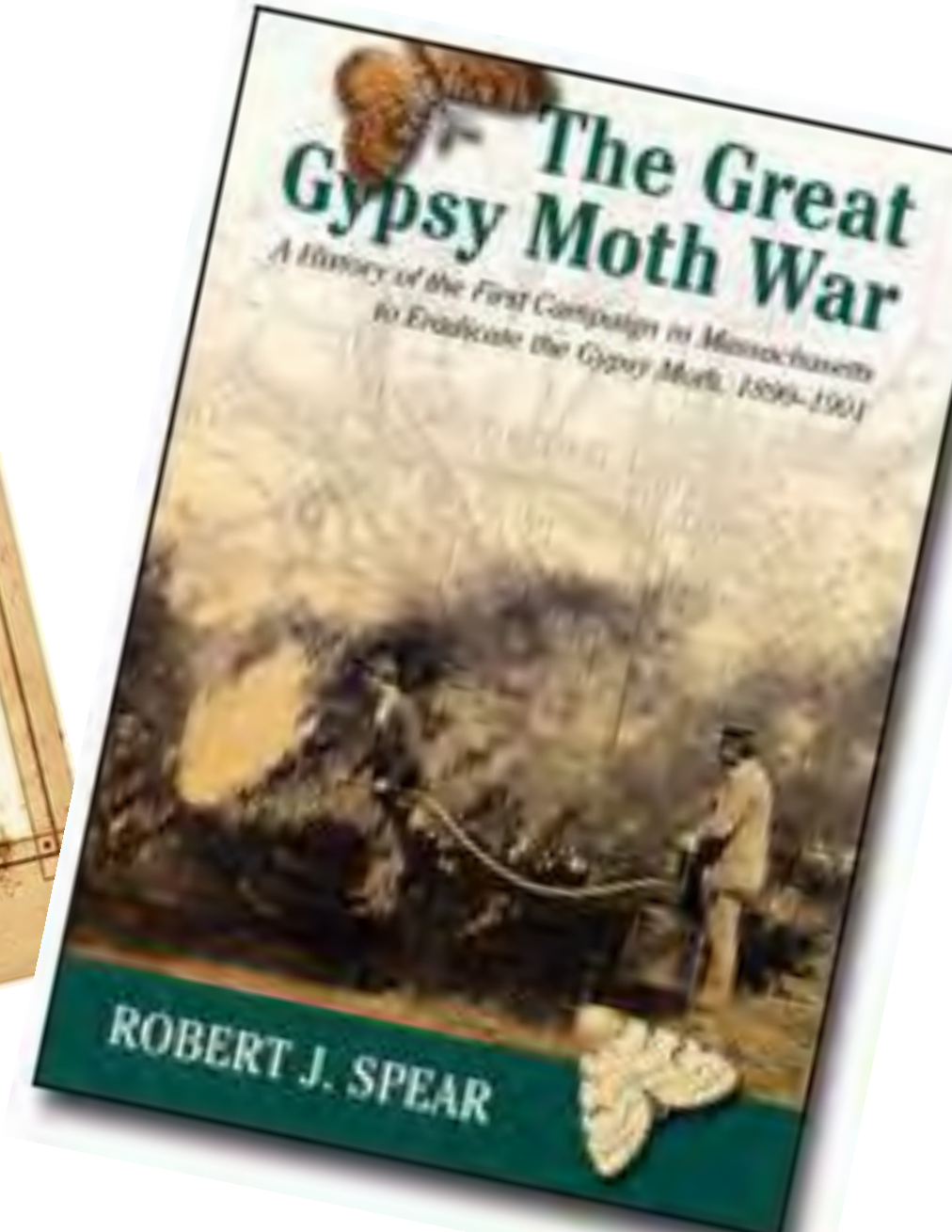
introduced species	human immigration
1900 – Lacey Act	1901 – beginning of Ellis Island restrictions
1912 – Plant Quarantine Act	1921 – 1st national quotas
	1924 – Immigration Act

Philip Pauly
1950-2008

"…attitudes towards foreign pests merged with ethnic prejudices: the gypsy moth and the oriental chestnut blight both took on and contributed to characteristics ascribed to their presumed human compatriots."

- P. Pauly, 1996

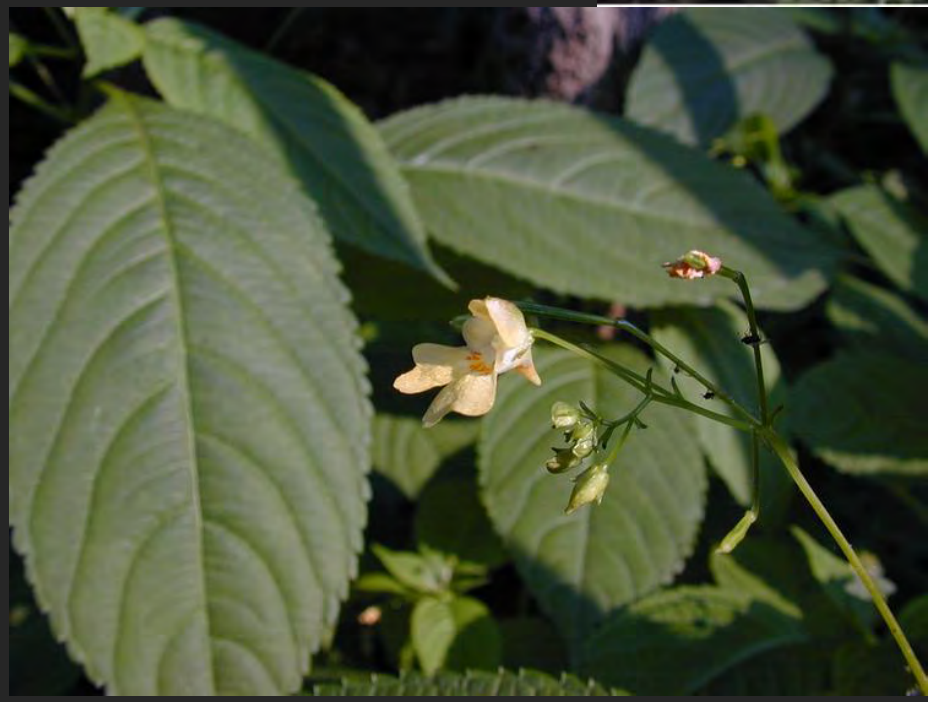

American Chestnut
The Life, Death, and Rebirth of a Perfect Tree
"A perfect book."
MARY ROACH, author of Stiff and Spook
SUSAN FREINKEL


The Great Gypsy Moth War
A History of the First Campaign in Massachusetts to Eradicate the Gypsy Moth, 1890–1901
ROBERT J. SPEAR

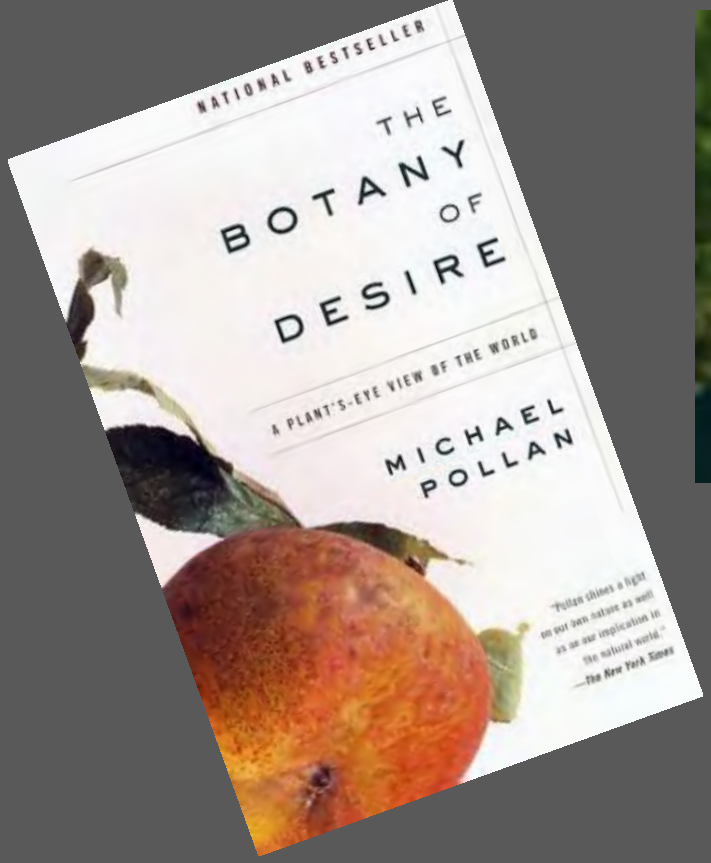
“to cleanse the German landscape of unharmonious foreign substance.” – R. Tuexen, 1939

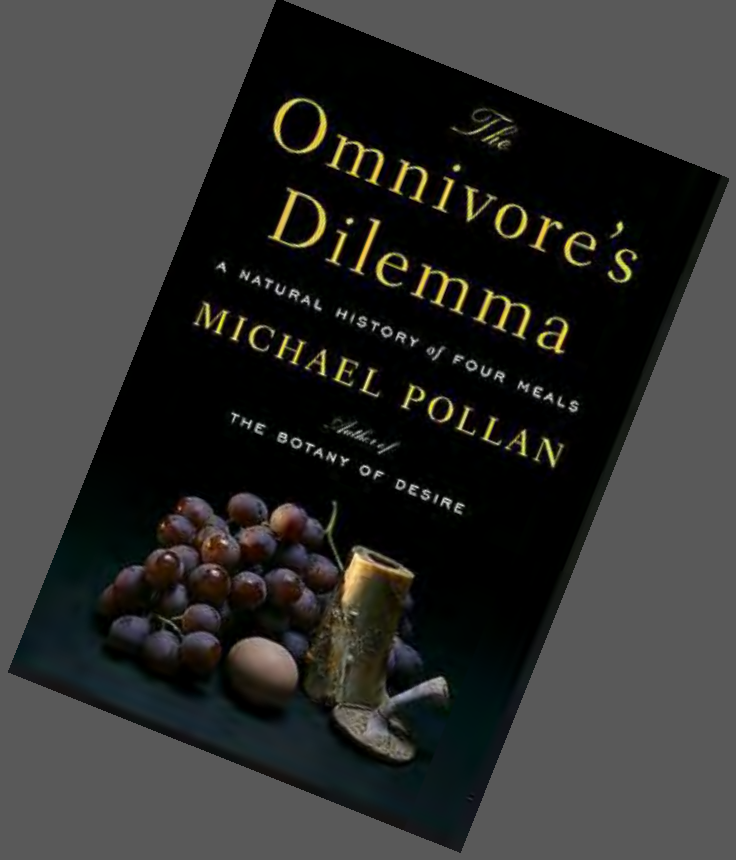
Reinhold Tuexen

“As with the fight against Bolshevism, our entire occidental culture is at stake, so with the fight against this Mongolian invader, an essential element of this culture, namely the beauty of our forest [is at stake].” – R Tuexen, 1942



Impatiens parviflora





"The German example also suggests we would do well to beware of ideology in the garden masquerading as science. It's **hard to believe that there is nothing more than scientific concern about invasive species** behind the current fashion for natural gardening and native plants in America – not when our national politics are rife with anxieties about immigration and isolationist sentiment." – M Pollan, 1994

Hugh Raffles

The anti-immigrant sentiment sweeping the country, from draconian laws in Arizona to armed militias along the Mexican border, has taken many Americans by surprise. It shouldn't — nativism runs deep in the United States. **Just ask our non-native animals and plants**: they too are commonly labeled as aliens, even though they also provide significant benefits to their new home. While the vanguard of the anti-immigrant crusade is found among the likes of the **Minutemen and the Tea Party**, the native species movement is led by environmentalists, conservationists and gardeners. Despite cultural and political differences, both are motivated by **the fear of being swamped by aliens.**

H. Raffles, 2011
NY Times

1) How many introduced species are harmful?

1) Are actions against introduced species xenophobic?

2) Efforts to contain invasions are futile.

Mark Gardener, Director, Charles Darwin Research Station, Galapagos, 2011:

"It's time to embrace the aliens. Blackberries now cover more than 30,000 ha here, and our studies show that island biodioversity is reduced by at least 50% when it's present. But as far as I'm concerned, it's now a Galapagos native, and it's time we accepted it as such."

Rubus niveus

www.islandconservation.org

eradicated
81 populations of 14 species
on 59 islands worldwide

Largest Conservation Project Ever in French Polynesia Hits Historic Milestone!

BirdLife INTERNATIONAL

ISLAND CONSERVATION
Preventing Extinctions

Manu

ACTEON + GAMBIER

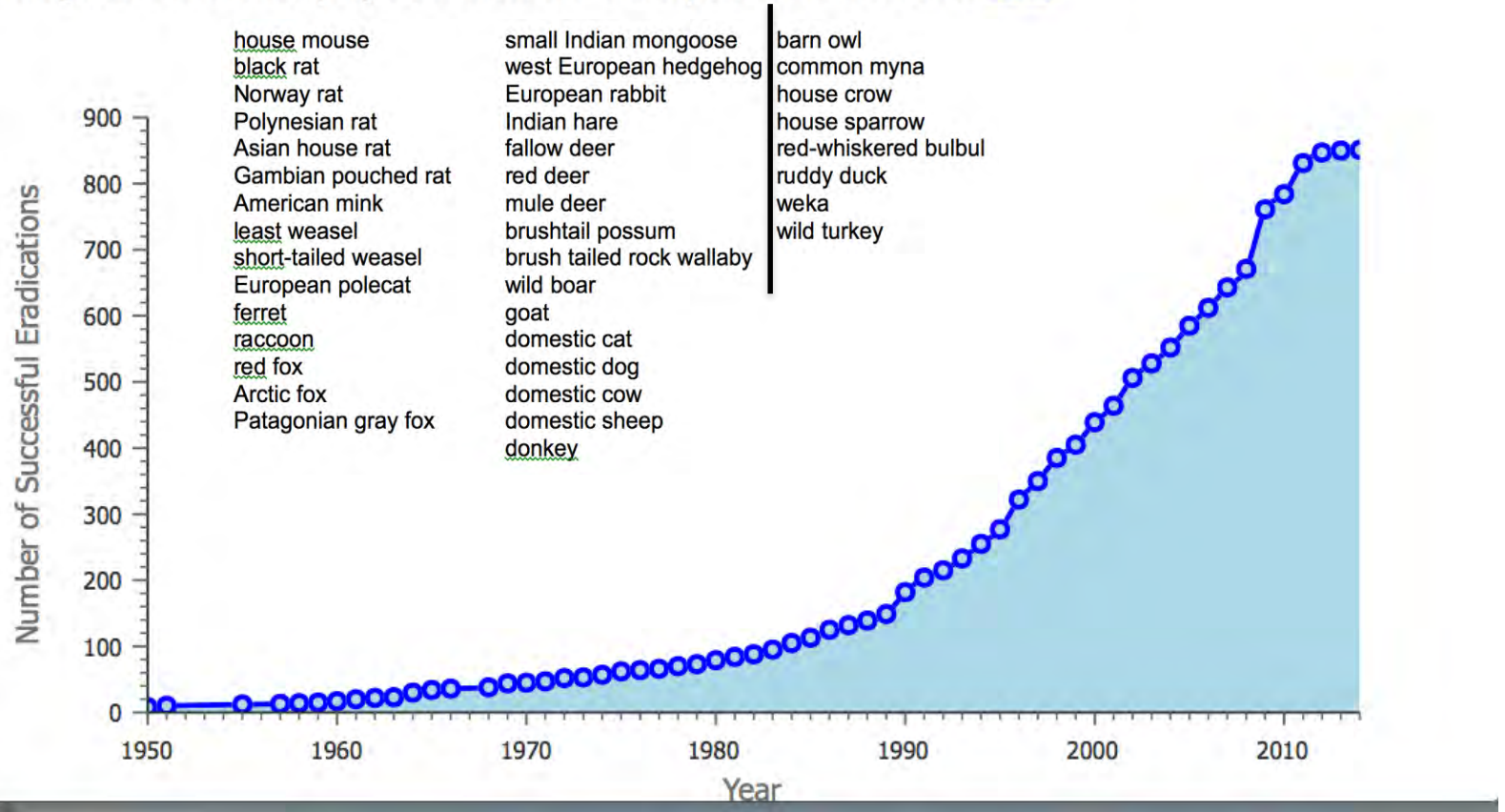
French Polynesia

http://diise.islandconservation.org/

What is the Database of Island Invasive Species Eradications?

Islands are the epicenter of the current global extinction crisis and invasive vertebrates are a key threat to native plants and animals on islands. Removing invasive vertebrates from islands is an important island restoration tool to protect and restore island ecosystems and prevent extinctions.

The Database of Island Invasive Species Eradications attempts to compile all historical and current invasive vertebrate eradication projects on islands. The vast majority of the dataset is focused on invasive mammals. Data gathered from each project includes island location and characteristics, details about the eradication including focal species, methods and outcome, plus links and or contact details for learning more about the project. Parameter descriptions are described here.



2016

PNAS

Invasive mammal eradication on islands results in substantial conservation gains

Holly P. Jones[a,b,1], Nick D. Holmes[c], Stuart H. M. Butchart[d], Bernie R. Tershy[e], Peter J. Kappes[f], Ilse Corkery[g], Alfonso Aguirre-Muñoz[h], Doug P. Armstrong[i], Elsa Bonnaud[j], Andrew A. Burbidge[k], Karl Campbell[c,l], Franck Courchamp[j], Philip E. Cowan[m], Richard J. Cuthbert[n,o], Steve Ebbert[p], Piero Genovesi[q,r], Gregg R. Howald[c], Bradford S. Keitt[c], Stephen W. Kress[s], Colin M. Miskelly[t], Steffen Oppel[n], Sally Poncet[u], Mark J. Rauzon[v], Gérard Rocamora[w,x], James C. Russell[y,z], Araceli Samaniego-Herrera[h], Philip J. Seddon[aa], Dena R. Spatz[c,e], David R. Towns[bb,cc], and Donald A. Croll[e]

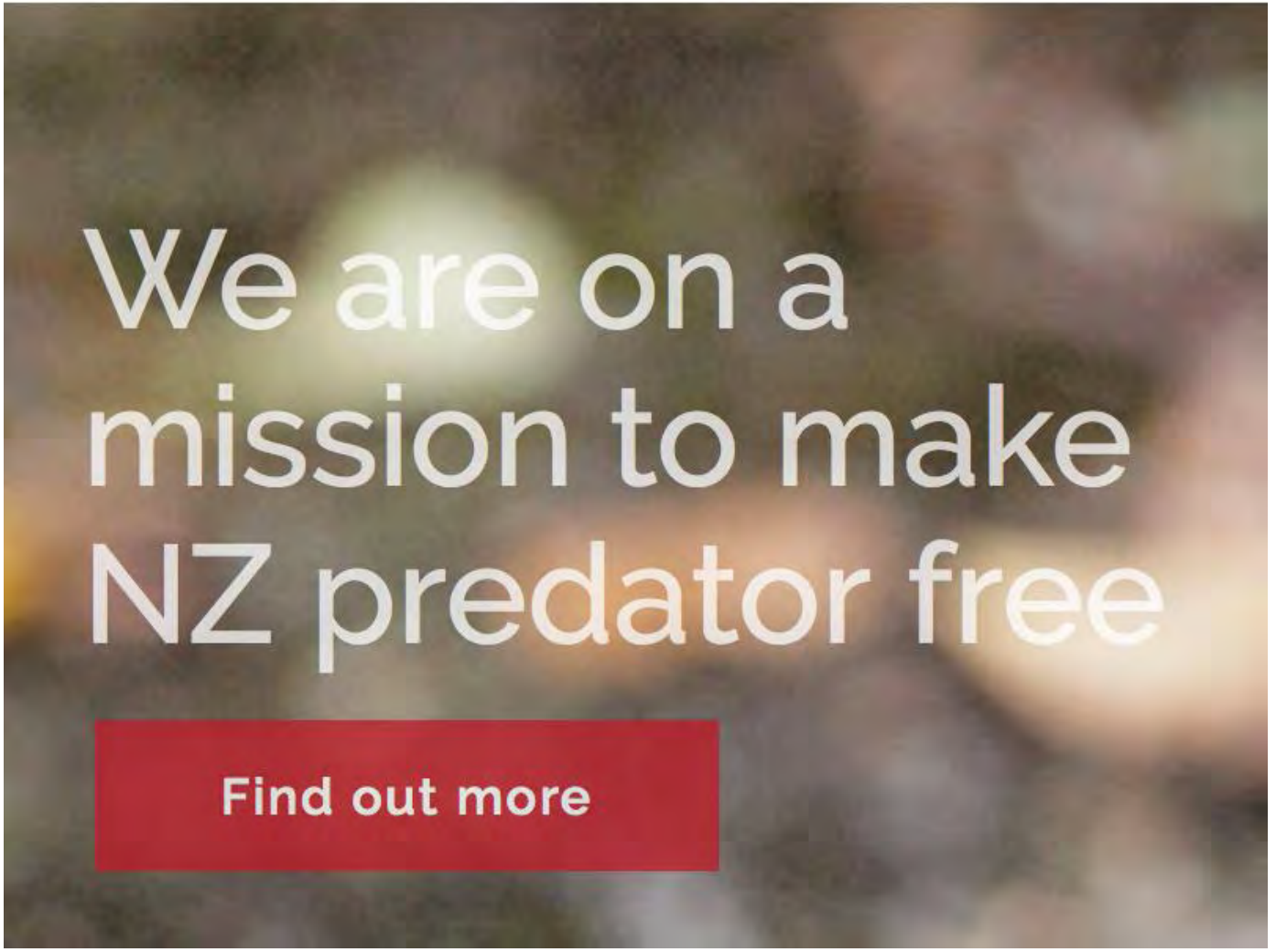
for 251 eradications of invasive mammals on 181 islands:

Table 1. Numbers of species with demonstrated benefits from invasive mammal eradications

Animal	Resident population recovery	Unassisted colonization	Unassisted recolonization	Reintroduction	Conservation introduction
Invertebrate	5 (5)	0	0	16 (29)	1 (1)
Landbird	35 (50)	12 (12)	16 (33)	36 (122)	11 (17)
Seabird	41 (73)	22 (28)	50 (89)	9 (12)	0
Mammal	3 (11)	0	1 (1)	7 (7)	4 (5)
Reptile	31 (55)	0	0	22 (44)	2 (2)

Numbers of populations are shown in parentheses.

PREDATOR FREE NZ



known infested area: 4,000 ha
to be verified: 400,000 ha

proposed budget:Au $39 million/yr
for 10 years

Report of the Independent Review Panel

Independent Review of the National Red Imported Fire Ant Eradication Program

3. Should Australia continue to eradicate?

3a. Is it still in the national interest to eradicate RIFA?

The Review Panel considers that it is in the national interest to eradicate RIFA. In arriving at this conclusion, the Review Panel noted that the eradication of RIFA meets the national interest criteria aimed at reducing potential environmental, social, economic and health impacts as defined by the National Environmental Biosecurity Response Agreement (NEBRA).

melon fly =
Bactrocera cucurbitae

Mytilopsis sallei


Courtesy CSIRO Marine Research Division

Cullen Bay

Kochia scoparia in Western Australia

1990 – introduced

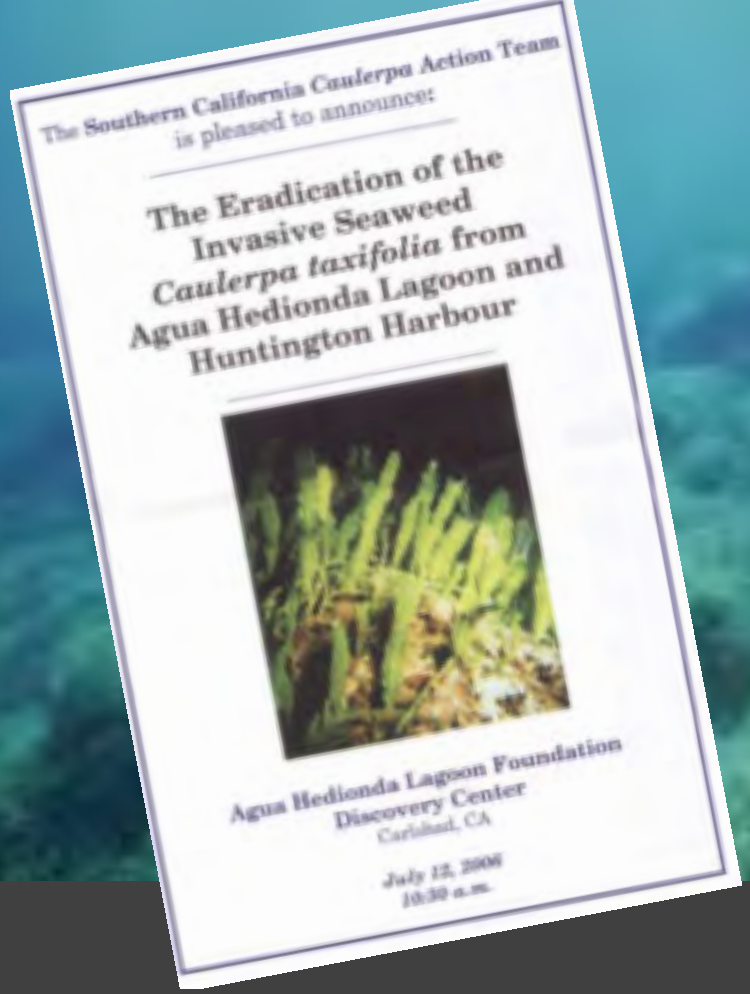
1992 – eradication campaign begun

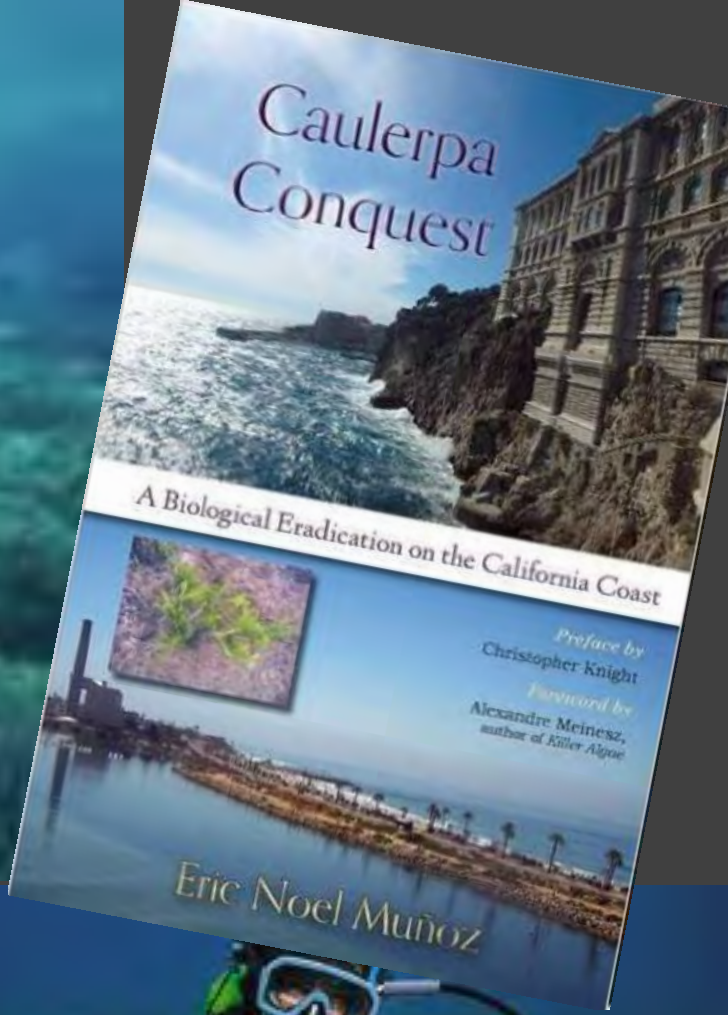
1993 – 3,200 ha over 900 km

1995 – 139 ha

1999 – 5 ha

2000 - eradicated





Caulerpa taxifolia

California

Rinderpest, Scourge of Cattle, Is Vanquished

2011

F. Paladini

BEGONE Dr. William P. Taylor, in 1987 in Sudan, examined a cow for rinderpest. The United Nations is announcing this week that the disease has been wiped off the face of the earth.

MAINTENANCE MANAGEMENT

physical and mechanical control

chemical control

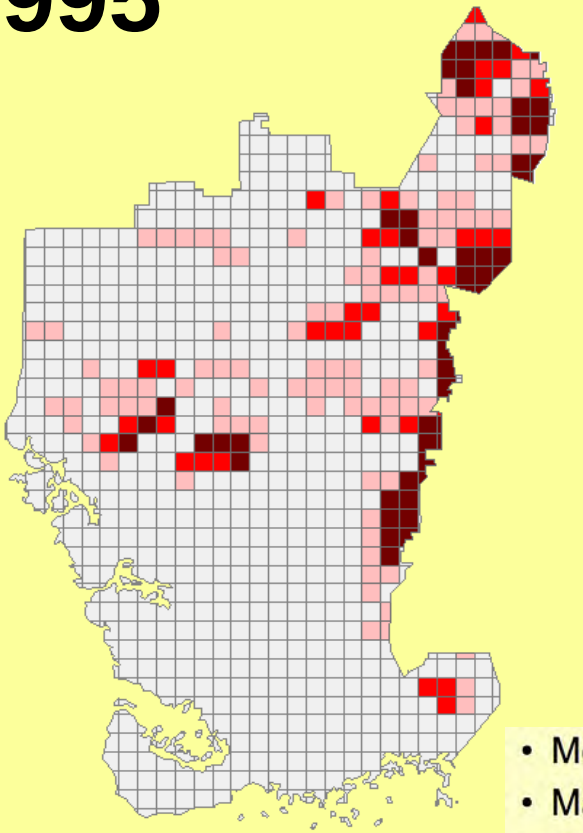
biological control

sterile male, mating disruption, etc.

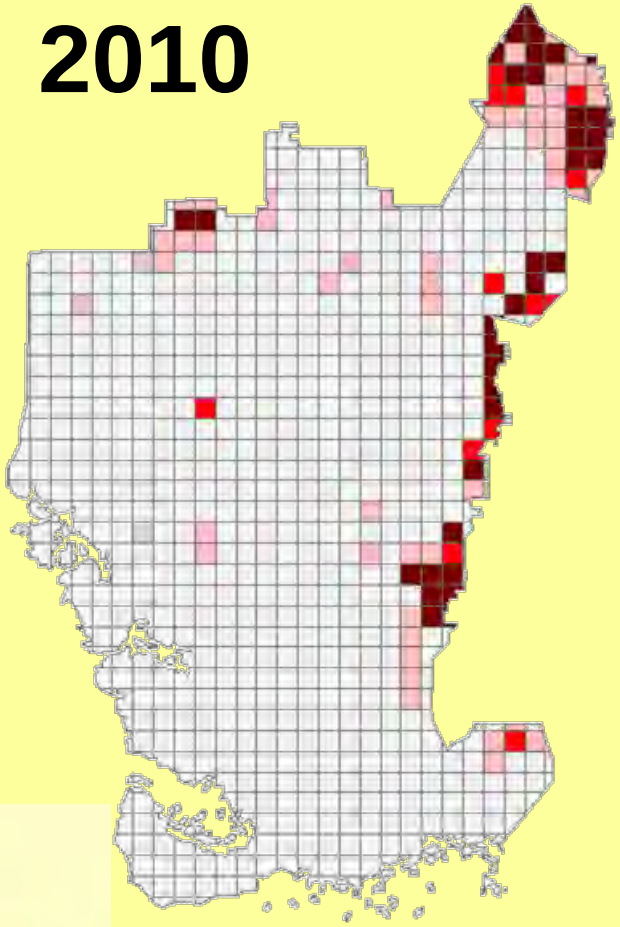
Australian paperbark, *Melaleuca quinquenervia*

15 Years of Melaleuca Management

1995

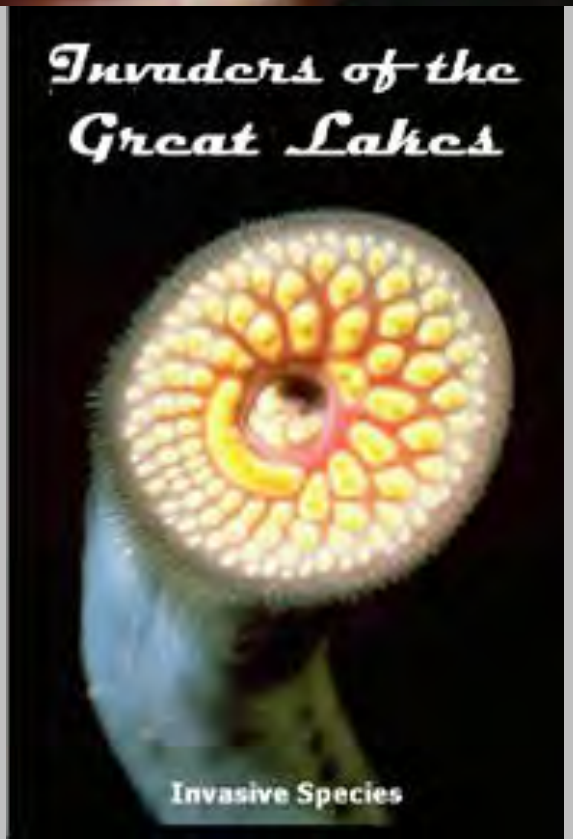


2010



24% **12%**

- Mechanical
- Manual
- Chemical
- Biological
- Prescribed Fire



sea lamprey, *Petromyzon marinus*

Microencapsulated BioBullets for the Control of Biofouling Zebra Mussels

DAVID C. ALDRIDGE,*,†
PAUL ELLIOTT,† AND
GEOFF D. MOGGRIDGE‡
Department of Zoology, University of Cambridge, Downing Street, Cambridge CB2 3EJ, U.K., and Department of Chemical Engineering, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, U.K.

The widespread invasion of freshwaters by the zebra mussel, *Dreissena polymorpha*, during the last 2 decades has made it one of the world's most economically and ecologically important pests. Since arriving in the North American Great Lakes in the 1980s, zebra mussels have become a major biofouler, blocking the raw water cooling systems of power stations and water treatment works and costing U.S. $1−5 billion per year. Despite the development of numerous control methods, chlorination remains the only widespread and licensed technique. Zebra mussels are able to sense chlorine and other toxins in their surrounding environment and respond by closing their valves, thus enabling them to avoid toxic effects for up to 3 weeks. Furthermore, prolonged dosing of chlorine in raw water produces ecotoxic trihalomethanes (THMs) by reaction with organic material in the water. We have developed a novel, environmentally safe, and effective method for controlling the zebra mussel: the BioBullet. Our method uses the encapsulation of an active ingredient (KCl) in microscopic particles of edible material. The mussels' natural filtering ability then removes and concentrates the particles from the water, without stimulating the valve-closing response. By using the mussels' filtering behavior to concentrate BioBullets the absolute quantity of active ingredient added to the water can be reduced substantially. Our approach allows us to engineer the particles to break up and dissolve completely within a few hours, thus eliminating the risk of polluting the wider ecosystem. We demonstrate that the effectiveness of a toxin in the control of biofouling filter-feeders can be enhanced greatly by using our technique. This paves the way for a new approach to the control of some of the world's most important economic pests.

Introduction

The introduction of nonnative taxa into novel localities represents one of the greatest threats to the world's ecosystems and economies (*1*−*3*). One of the most well-known examples comes from the invasion of the zebra mussel, *Dreissena polymorpha*, into the Laurentian Great Lakes of North America during the 1980s (*4*). Zebra mussels are unusual among freshwater bivalves in possessing byssus which enables them to attach to hard substrates and form encrustations many individuals deep (*5*). Rapid population growth and invasion is assisted by high fecundities and the possession of planktonic veliger larvae that can disperse passively in the water column for up to 4 weeks before settling (*6*).

Zebra mussels can lead to system-level changes in invaded ecosystems and have led to local extirpation of some species of North American unionid mussels (*7*, *8*). For industry, zebra mussel biofouling of pipelines that carry raw water can be devastating. In North America, numerous power plants have experienced fouling and blockage of the heat exchange pipes, screenhouses, steam condensers, and trash bars (*9*). In Britain, the recent spread of zebra mussels (*10*) has resulted in many water treatment works experiencing blockage of microstrainers and pumps, the occlusion of pipes, and the compromising of filter bed efficiency (*11*). In Spain, where zebra mussels were discovered in the Ebro River in 2001 (*12*), many thousands of kilometers of irrigation pipeline are threatened by zebra mussel fouling (I. Insausti, Government of Aragon, Spain, 2003, personal communication). In North America alone, zebra mussels are estimated to cost industry ca. U.S. $1−5 billion ($10^9$) each year (*1*, *13*).

Considering the immense economic cost of zebra mussels, it is unsurprising that much effort has been put into developing control strategies (*6*). Physical removal, generally using high-pressure water jets, is only feasible within sections of industrial facilities where ready access is possible. Antifoulant coatings (e.g., copper-based) may offer practical preventative measures for new facilities or retrofitted screens but are difficult to apply to existing pipelines. Biological control using natural enemies offers an attractive option, and while fish and crayfish can regulate zebra mussel populations under some circumstances (*14*, *15*), there appear to be no grounds for expecting the development of a practicable biological control method in the foreseeable future. Chemical control options are favored by industry because treatment can be applied throughout the entire facility from a single dosing point. Many chemicals will kill zebra mussels given sufficient concentration and contact time, but the suitability of a particular chemical is determined by considerations of water quality (e.g., residual concentrations, byproducts), cost, and practicality. Chemicals which have been tested to some success include chloramines, chlorine dioxide, ozone, hydrogen peroxide, potassium permanganate, pH adjustment, and inorganic salts, such as KCl (*6*).

While numerous physical and chemical techniques have been proposed and tested, chlorination remains the only widespread and licensed option (*6*). However, chlorination poses a number of problems for industry and regulators. First, chlorine reacts with organic material in the water to produce trihalomethanes (THMs) which are toxic to humans and other animals. This restricts greatly the chlorine doses that can be applied to water in infested water treatment works. Second, zebra mussels respond to unfavorable environmental conditions by closing their valves for prolonged periods (*6*). This means that control agents, such a chlorine in the form of sodium hypochlorite, must be dosed continuously for up to 3 weeks to have their desired effects. Third, hypochlorite is rather expensive and hazardous to transport, store, and handle. Fourth, chlorine dosed into pipelines that exit into open ecosystems can impact deleteriously on nontarget biota in the recipient waters. Indeed, many of the chemicals used

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† Department of Zoology.
‡ Department of Chemical Engineering.

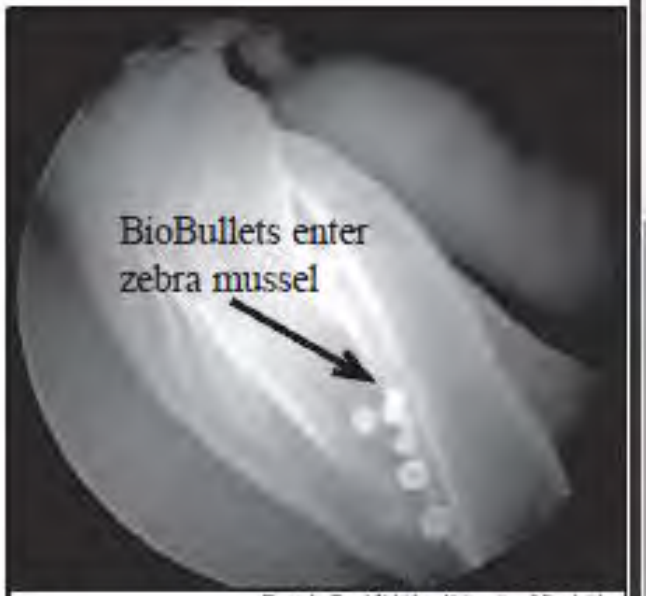

Photo by David Aldridge, University of Cambridge

BioBullets being transported along the gill of a live zebra mussel. The mussel has been fooled into treating the bullets as food, and will ingest their toxic payload.


genetics!!!!

Gene Silencing inhibits these intracellular processes resulting in muted trait expression

Plants infected with the 'gene silencing' vector could have stunted growth, a yellow color, or no flowers (depending on which gene is silenced)

The 'gene silencing' vector (containing RNAi) enters the plant

Transcription

Translation

Phenotype

Gene (DNA)

mRNA

Protein

from E.M. Golenberg -

http://greatlakesphragmites.net/files/GLC-Webinar.pdf

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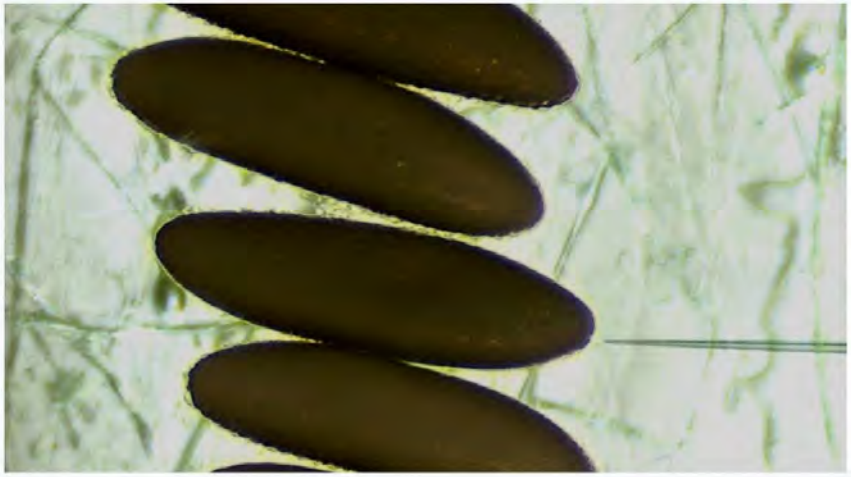

We're applying advanced science to develop new and better pest control

Oxitec's approach uses advanced genetics to develop solutions for controlling dangerous disease-carrying mosquitoes, and harmful agricultural pests.

Haedes, Aegypta and the Oxitec approach

Oxitec's vector control solution – A paradigm shift in mosquito control

TED Talk: Re-engineering mosquitos to fight disease

Dengue fever and the Aedes aegypti mosquito – an Oxitec film

What is Dengue Fever? Why are people and governments so worried about it? What's it got to do with mosquitoes, and how can we control it?

CORRESPONDENCE

International law should govern release of GM mosquitoes

SIR — Your News story 'Sterile mosquitoes near take-off' (*Nature* **453,** 435; 2008) discusses the likely release of genetically engineered mosquitoes to help contain dengue fever. It demonstrates just how close we are to a radically new set of strategies for managing a whole range of diseases and wildlife using genetically modified organisms (GMOs). But after assessing the risks and benefits, nations may reach different conclusions about their use. And that's quite a problem, considering that genetically modified bugs won't recognize national borders.

Malaysia may successfully avoid spreading the sterile

politics, and appropriately so. The potential for conflict over

Biological Station, CSIC, Apdo. 153, 41080 Sevilla, Spain

NEWS OF THE WEEK

SCIENCE AND SOCIETY

GM Mosquito Trial Alarms Opponents, Strains Ties in Gates-Funded Project

For about a decade, scientists have debated how and when to carry out the first test release of transgenic mosquitoes designed to fight human disease—a landmark study they imagined might trigger fierce resistance from opponents of genetic engineering. A stream of papers and reports has argued that a release of any genetically modified (GM) mosquito should be preceded by years of careful groundwork, including an exhaustive public debate to win the hearts and minds of the local population.

But now, it turns out that with little public debate, a company released such mosquitoes a year ago in a fiscal paradise in the Caribbean, where they have been flying under the world's radar screen until last week. At a press conference in London on 11 November, British company Oxitec announced that it carried out the world's first small trial with transgenic *Aedes aegypti* mosquitoes in Grand Cayman in the fall of

"I would completely reject any notion that this was done secretively."

—LUKE ALPHEY, CHIEF SCIENTIFIC OFFICER, OXITEC

says Bart Knols, a medical entomologist at the University of Amsterdam in the Netherlands. "This could well trigger a backlash."

Nor does the trial sit well with the collaborators in a big international project, in which Oxitec is a key member, to develop and test GM mosquitoes. The program, funded by a $19.7 million grant from the Bill & Melinda Gates Foundation and led by Anthony James of the University of Cali-

difficult situation," he says. "I would completely reject any notion that this was done secretively," says Alphey, who notes that the trial was well-known within the island's population of 50,000, "but just not picked up internationally."

Few deny that in the race to develop disease-fighting mosquitoes, Oxitec has an impressive lead. Its key idea, pioneered by Alphey while at the University of Oxford in the 1990s, is to release massive numbers of lab-bred male mosquitoes equipped with a gene that kills any offspring in the larval or pupal stage. When the males mate with females of a natural population, there are no progeny—and if the transgenic males mate more often than the natural ones, the mosquito population will dwindle or even collapse. (And because male mosquitoes don't bite, their release does not increase the risk of disease transmission to humans.)

Oxitec sees a key market in *Ae. aegypti*, the vector for dengue, a painful and sometimes fatal viral infection for which no drugs or vaccines exist. Many middle- and high-income countries already invest heavily in traditional mosquito-control measures to fight dengue, but the results are

International New York Times BUSINESS DAY

Genetically modified mosquito larvae and pupae in an Oxitec laboratory. Andrew Testa for The New York Times

A Biotech Evangelist Seeks a Zika Dividend

A diverse biotechnology company hopes its genetically engineered mosquitoes can help stop the spread of a devastating virus. But that's just a start.

By ANDREW POLLACK MARCH 5, 2016

WINGED WARRIORS

Brazil plans to release billions of designer mosquitoes to stop the spread of infectious diseases. Will it work?

By **Kelly Servick**, *in Brazil*

Every Saturday morning, Maria do Carmo Tunussi goes door to door asking her neighbors to scour their houses and yards for flowerpots, buckets, clogged gutters—anything that could collect water and offer mosquitoes a place to breed. For 17 years, Tunussi has been a community health agent at the local clinic in CECAP/Eldorado, a district of about 5000 people in the small city of Piracicaba, 2 hours northwest of São Paulo, Brazil. She has seen many surges of the mosquito-borne dengue virus, which causes fever, nausea, and agonizing joint pain. The task sometimes feels futile. "You remove the breeding site one day, and the next day, it's back," she says. "It never ends."

Last April, CECAP became the first

that effective against *A. aegypti*, and breeding site removal, which, despite Tunussi's efforts, is hard to keep up year after year. So it's not surprising that, 7 years after releasing the world's first genetically modified (GM) mosquito, Oxitec has chosen Brazil as the site of a major scale-up. It is moving from small-scale pilot projects like the one in CECAP to planned releases covering tens of thousands of people.

Indeed, Brazil is becoming a proving ground for tailored mosquitoes. About 600 kilometers to the east, in the coastal cities of Niterói and Rio de Janeiro, another lab strain of mosquitoes is on the wing. Bred by a nonprofit organization called Eliminate Dengue, this one is infected with a bacterium called *Wolbachia pipientis* that protects it from infection with dengue, Zika, and

Oxitec's transgenic mosquitoes swarm out of a container in Piracicaba, Brazil.

bouncing around in plastic tubs the size of take-out containers.

Oxitec mosquitoes bearing the lethal gene grow up feeding on tetracycline, an antibiotic that blocks *tTAV* activity and keeps

company in 2002, backed by private venture capital firms and Oxford. Last year, the U.S. synthetic biology behemoth Intrexon Corpo-

in three neighb
state of Bahia. I
lation reductio

Science 354:164-167; Oct. 14, 2016

eLIFE elifesciences.org

FEATURE ARTICLE

EMERGING TECHNOLOGY

Concerning RNA-guided gene drives for the alteration of wild populations

KEVIN M ESVELT*, ANDREA L SMIDLER, FLAMINIA CATTERUCCIA* AND GEORGE M CHURCH*

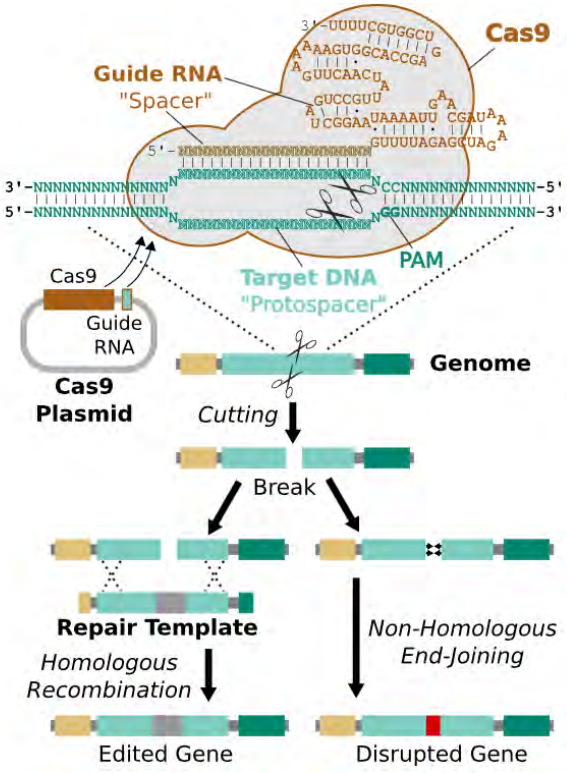

Figure 3. RNA-guided genome editing via Cas9. T

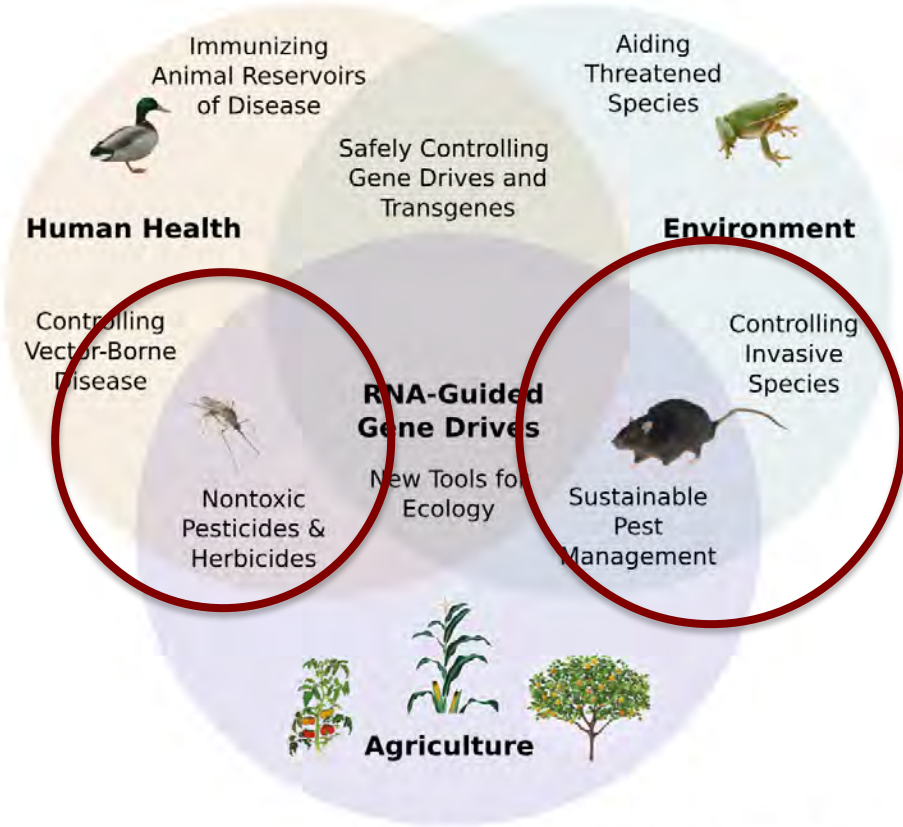

Figure 7. Potential applications of RNA-guided gene drives. Clockwise from left. Disease vectors such as

from A. Hawkes, Bay Nature, 2016

Trends in Biotechnology May 2014, Vol. 32, No. 5

Caution required for handling genome editing technology

Motoko Araki[1], Kumie Nojima[2], and Tetsuya Ishii[1]

[1] Office of Health and Safety, Hokkaido University, Sapporo 060-0808, Japan
[2] Molecular Imaging Center, National Institute of Radiological Sciences, Chiba 263-8555, Japan

Genome-editing technology, although a robust tool for genetic engineering, is creating indistinct regulatory

ism using physical, chemical, or biological methods. The modified cells, such as protoplasts, callus cells, or embryonic

2016

Regulating gene drives

Kenneth A. Oye,[1,2*†] Kevin Esvelt,[3*] Evan Appleton,[4] Flaminia Catteruccia,[5,6] George Church,[3] Todd Kuiken,[7] Shlomiya Bar-Yam Lightfoot,[2] Julie McNamara,[2] Andrea Smidler,[5,8] James P. Collins[9]

Political Science Department, Massachusetts Institute of Technology. [2]Engineering Systems Division, assachusetts Institute of Technology. [3]Wyss Institute, Harvard University. [4]Bioinformatics, Boston iversity. [5]Harvard School of Public Health. [6]University of Perugia, Italy. [7]Woodrow Wilson International nter for Scholars. [8]Harvard Medical School. [9]School of Life Sciences, Arizona State University.
ncipal contributors to this piece.
esponding author. oye@mit.edu

latory gaps must be filled before gene drives could be used in the wild

nome engineering that uses nuclease Cas9 to cut seq fied by guide RNA mole This technique is in widesp has already engineered the more than a dozen specie enable "RNA-guided ger edit nearly any gene in se ducing populations (1).

To reduce potential ne in advance of construction Esvelt et al. have proposed el types of drives (1). Pre could exclusively affect p cies or subpopulations sequences

A Call for Conservation with a Conscience:
No Place for Gene Drives in Conservation

New technologies have played an important role in protecting life on earth, and we the undersigned support innovation and science in conservation. However, we believe that a powerful and potentially dangerous technology such as gene drives, which has not been tested for unintended consequences nor fully evaluated for its ethical and social impacts, should not be promoted as a conservation tool.

From the climate impact of the internal combustion engine to the synthetic chemicals that have poisoned the web of life, we have learned some lessons. We now understand the serious need for precaution when radical new technologies arise, especially with gene drives, which change the rules of genetics and inheritance and have consequences beyond our comprehension.

Gene drives have the potential to dramatically transform our natural world and even humanity's relationship to it. The invention of the CRISPR-CAS9 tool and its application to gene drives (also known as a "mutagenic chain reaction") gives technicians the ability to intervene in evolution, to engineer the fate of an entire species, to dramatically modify

Founding signatories include:

Dr Jane Goodall

Scientists and environmental experts and organizations from around the globe have advocated for a halt to proposals for the use of gene drive technologies in conservation. Announced today, a long list of environmental leaders, including **Dr. Jane Goodall, DBE**, genetics professor and broadcaster **Dr. David Suzuki**, **Dr. Fritjof Capra**, entomologist **Dr. Angelika Hilbeck**, Indian environmental activist **Dr. Vandana Shiva** and organic pioneer and biologist **Nell Newman**, have lent their support to the

Knock Out Any Gene!

CRISPR/CAS 9 Genome Editing Kits

OriGene's system for genome disruption and gene replacement delivers pre-designed plasmids and all the vectors needed to knock out any human or mouse gene. Knockout is as simple as 1-2-3:

1. Search the gene symbol on origene.com and order
2. Follow the simple protocol for transfection and Puro selection
3. Validate the knockout

Scan to view CRISPR/Cas-9 Video

Kit Components Include:

- 2 guide RNA vectors to ensure efficient cleavage
- Donor vector with predesigned homologous arms
- Knockin GFP-Puro for selection
- Scramble qRNA as negative control included

Come to OriGene, the trusted molecular biology expert, for your CRISPR needs.

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www.origene.com/CRISPR-CAS9

Science 354:541
2016

Can any idiot do it?

A reporter does CRISPR

By **Jon Cohen**

I speak biology fluently, but the molecular complexities of the novel genome-editing tool called CRISPR left me as befuddled as when I peruse descriptions of the inflationary universe. So I decided to test what one investigator told me: CRISPR (for "clustered regularly interspaced short palindromic repeats") may sound intimidating, but it is so simple to use that "any idiot" could do it.

I would give it a try.

Biologist Roland Wagner (left) watches as Jon Cohen attempts a key pipetting step in creating a CRISPR construct.

I've already learned that any idiot cannot do CRISPR: It takes, at least, basic laboratory skills.

1) How many introduced species are harmful?

2) Are actions against introduced species xenophobic?

3) Efforts to contain invasions are futile.

4) Animal rights objections to eradication and management of (some) invasive vertebrates.

North American gray squirrel, *Sciurus carolinensis*

rights of species or populations to exist

vs.

rights of individual animals to exist

The Daily Nexus

THE UNIVERSITY OF CALIFORNIA, SANTA BARBARA'S INDEPENDENT, STUDENT RUN NEWSPAPER.

NEWS

Island Pig Eradication Spurs Wild Controversy

Posted by Lindsey Clodfelter on March 2, 2005 at 7:59 am

The National Park Service's decision to gun down the Channel Islands' entire population of wild pigs has left some community members squealing in protest.

Approximately 60 people gathered at a Channel Islands Animal Protection Association (CHIAPA) meeting last night at the Santa Barbara Public Library to discuss the Nature Conservancy and park service restoration policy, which calls for the complete eradication of the island pig on Santa Cruz Island. A press release by the Channel Islands office of the park service stated that the presence of nearly 4,000 non-native pigs, brought to the island by farmers in the 1850s, has attracted golden eagles from the mainland that have become dependent on the native island fox as a food source — threatening the entire island fox population

1) How many introduced species are harmful?

2) Are actions against introduced species xenophobic?

3) Efforts to contain invasions are futile.

4) Animal rights objections to eradication and management of (some) invasive vertebrates.

Michael McWilliams, 2016, Tasmania

“The Usurpers”

QUESTIONS?