Ecology, Biogeography, and Epidemiology of the DEVASTATING

Phytophthora infestans

Phytophthora cinnamomi

Phytophthora ramorum

Paul Tooley, USDA-ARS, Ft. Detrick, MD, USA

Ecology

- Branch of science concerned with the interrelationships of organisms and their environment

- In *Phytophthora*, environment includes host diversity as well as human activities

Phytophthora infestans

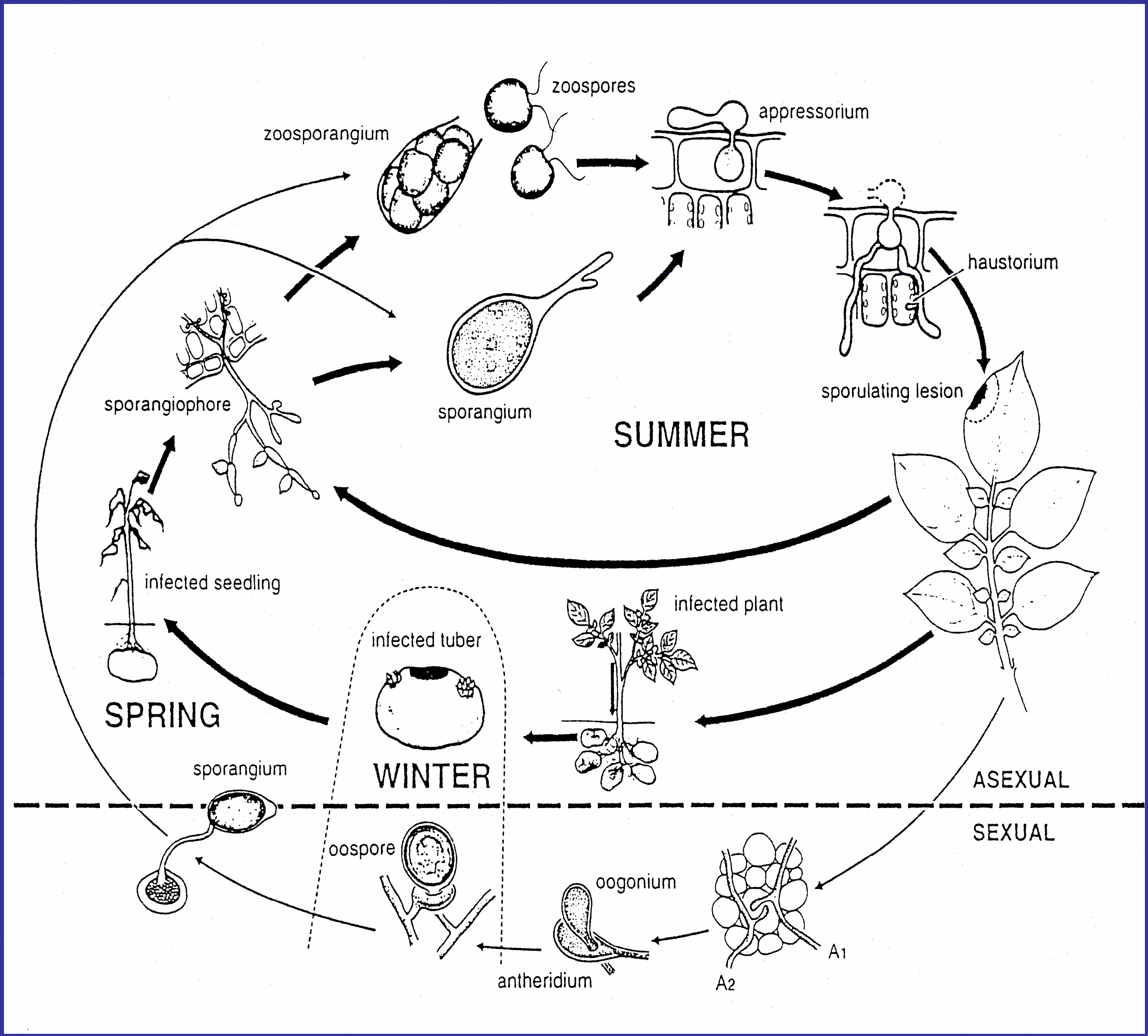
- member of Waterhouse Group IV

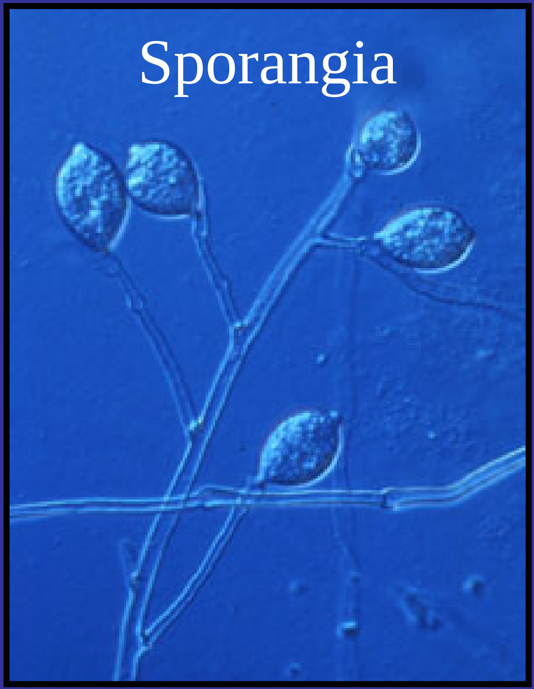
  (sporangia semipapillate, usually deciduous; antheridia predominantly amphigynous)

- requires two mating types (A1 and A2) for sexual reproduction

- oospores are long lived resting structures

Toluca, Mexico, 1982





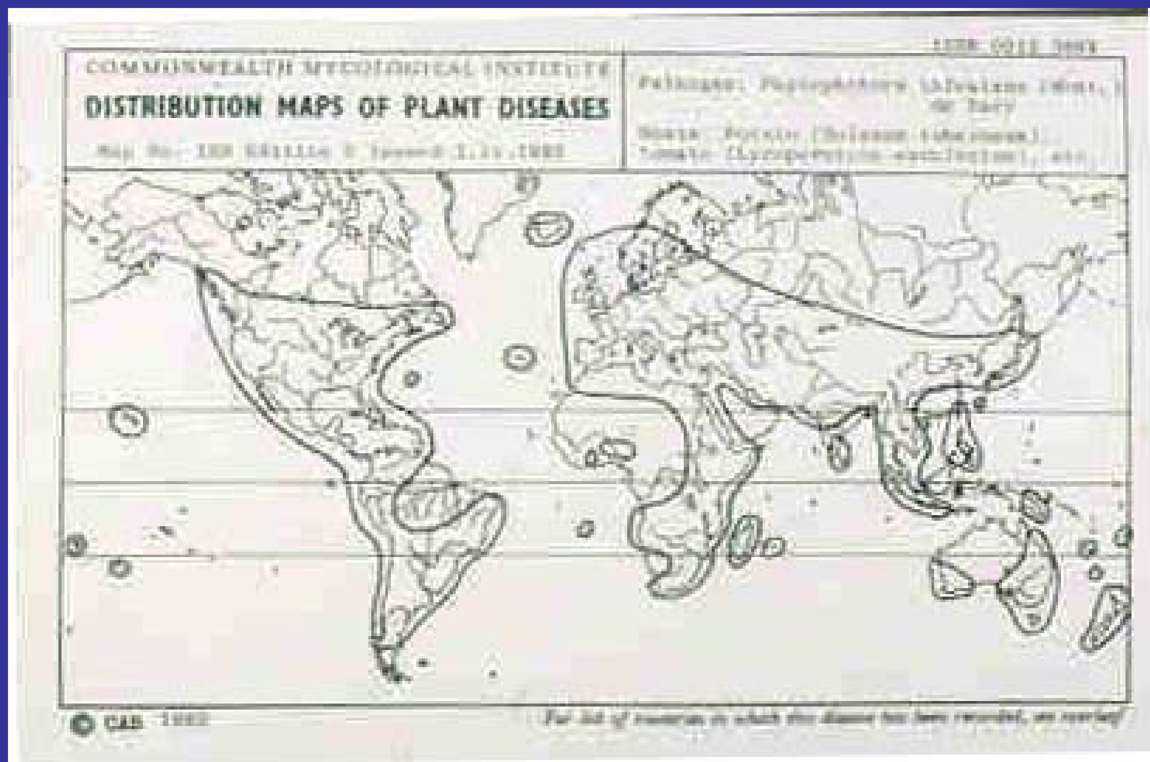
Disease cycle of potato late blight caused by *Phytophthora infestans*

Phytophthora infestans: the cause of late blight

on potato

and tomato

Global distribution of *P. infestans*



Peruvian Highlands




Mexican origin

High level of genetic diversity-isozyme
markers in Hardy-Weinberg equilibrium

Genetic subdivision within Mexico

Single A1 clonal lineage outside Mexico
in the past

Closely related species on different hosts
found in central Mexico

Andean origin

More multilocus sequence diversity compared
with Mexican populations

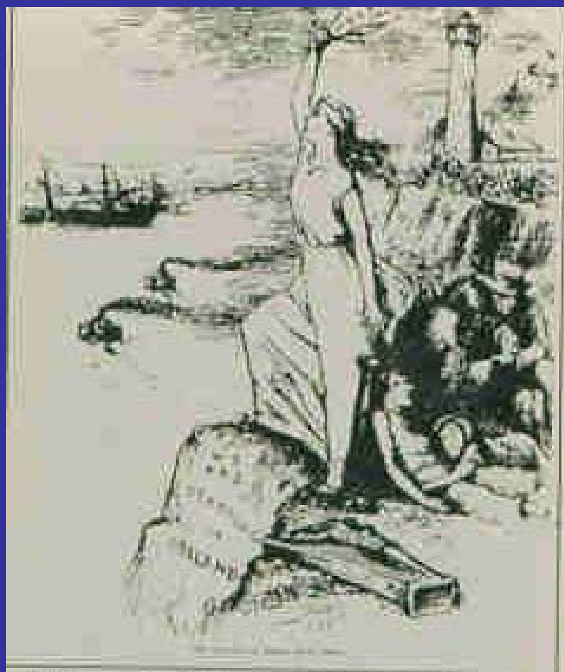
Mexican populations were genetically differentiated
from other populations examined (mt loci)

Andean population haplotypes were derived from
two mtDNA lineages and were more similar to US
and Ireland populations

P. infestans introduction to new ecosystems

- 1840’s migration to U.S., Europe (Irish Famine)
- summer 1976, Mexico to W. Europe
- 1980’s migrations- NW Mexico to U.S. and Canada

P. infestans - IRELAND connection



(Page 15) A political cartoon printed in the United States at the time of the Irish potato famine.

Thomas O'Grady Farm

Co. Mayo, Ireland

St. John Valley, Maine- Oct. 1994

Gil du Four
(middle) grower

Blighted, soft rotted potatoes on grader

Late blight damage, Maine, Fall 1994

P. infestans epidemiology:

- May be years between serious epidemics (bottleneck effect on genotypes)
- In U.S. prior to both mating types, must be introduced each season (cull piles, volunteer plants)
- Can cover vast distances through airborne dispersal

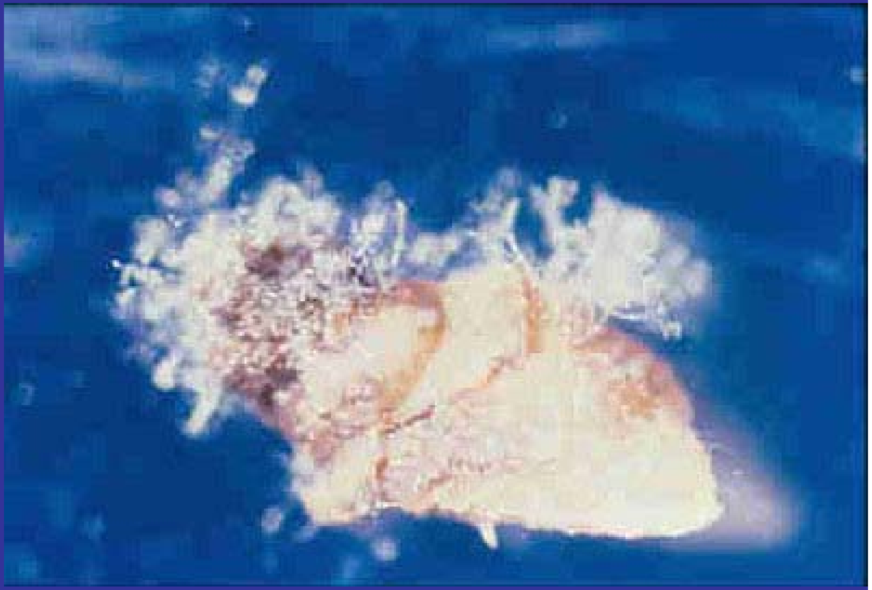
P. infestans keys to success:

- abundant sporulation

- wind dissemination and long distance migration

- persistent, tenacious pathogen

- overwintering ability on tubers in storage or in field



1995 Minireview, Phytopathology 85:1053-1056

Mini Review

Biology, Ecology, and Epidemiology of the Potato Late Blight Pathogen *Phytophthora infestans* in Soil

D. Andrivon

Zoospore survival in soil uncertain; sporangia remained infective to potato tubers for 15-77 days in different soils.

Oospores able to survive at least one winter in the field under European conditions.

After 150 years of research, more questions about the soil stages remain unanswered than have been elucidated

European Journal of Plant Pathology **106:** 667–680, 2000.

Inoculum sources and genotypic diversity of *Phytophthora infestans* in Southern Flevoland, the Netherlands

M.J. Zwankhuizen[1,2], F. Govers[1,3,*] and J.C. Zadoks[1,2]
[1]*Laboratory of Phytopathology, Wageningen University,* [2]*C.T. de Wit Graduate School for Production Ecology & Resource Conservation,* [3]*Graduate School for Experimental Plant Sciences, Wageningen, The Netherlands;*
**Author for correspondence: Laboratory of Phytopathology, Wageningen University, Binnenhaven 9, 6709 PD, Wageningen, The Netherlands (Fax: +31-317-483412; E-mail: francine.govers@medew.fyto.wau.nl)*

Accepted 3 July 2000

Intensive characterization of genotypes in a small region of the Netherlands

170 genotypes identified within 1048 isolates using probe RG57 including 138 'rare' genotypes

A significant role for oospores in generating new genotypes was proposed

Population Genetics and population diversity of *Phytophthora infestans*

William E. Fry, Cornell University, Ithaca NY, USA
Niklaus J. Grünwald, USDA, Corvallis OR, USA
David E. L. Cooke, Scottish Crop Research Institute, Dundee, Scotland
Adele McLeod, Stellenbosch University, Stellenbosch, South Africa
Gregory A. Forbes, International Potato Center, Lima, Peru
Keqiang Cao, Agricultural University of Hebei, Baoding, China

Europe- 'new' population established - A2 frequency varies regionally

Proof of role of oospores elusive- Dominance of asexual clones in many populations

South America- up to 1998 only a few clonal lineages. Since 1998 situation varies by region. Diversity in N. Andes region on other hosts. New species *P. andina* proposed, very close to *P. infestans*

Asia- US-1 genotype still dominant in many areas; A2 in many areas now

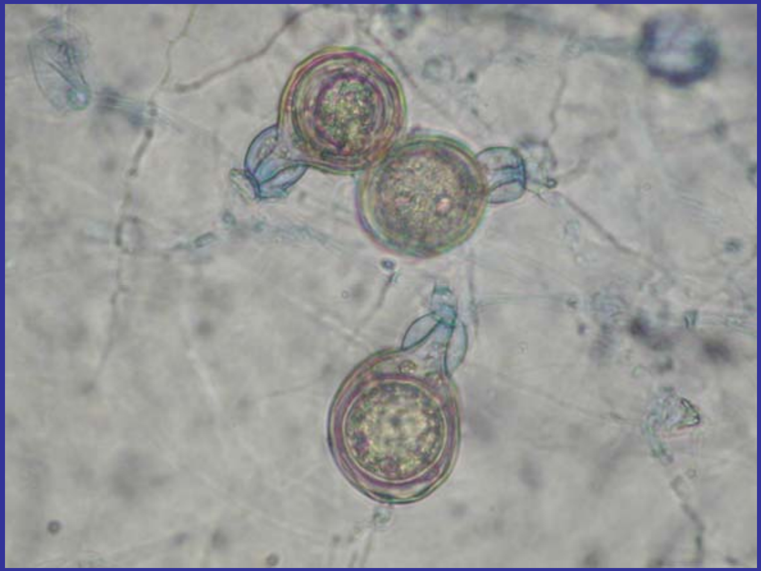
U.S. and Canada- populations have simple structure with US-8 dominant. Mating types spatially separated- persisting sexual population not documented

P. cinnamomi


culture on V8 agar

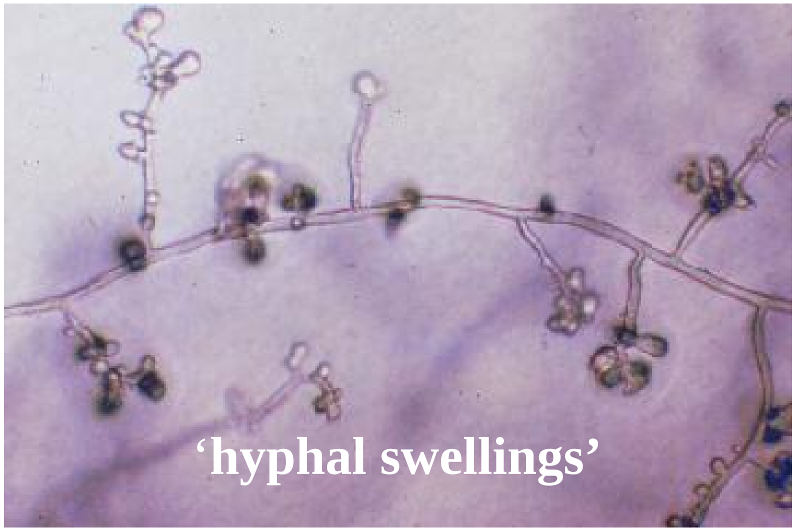

zoospore formation

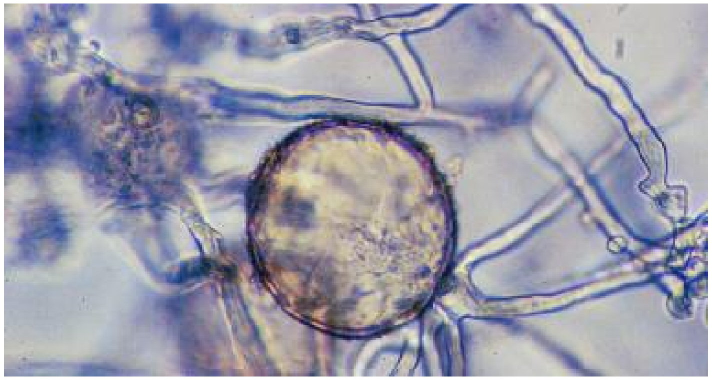

sporangium


oospores

P. cinnamomi chlamydospores

- **Chlamydospore**
  - long-term survival
  - best in moist soil
  - less well in dry soil
  - killed at 0 C





INK DISEASE in the U.S.

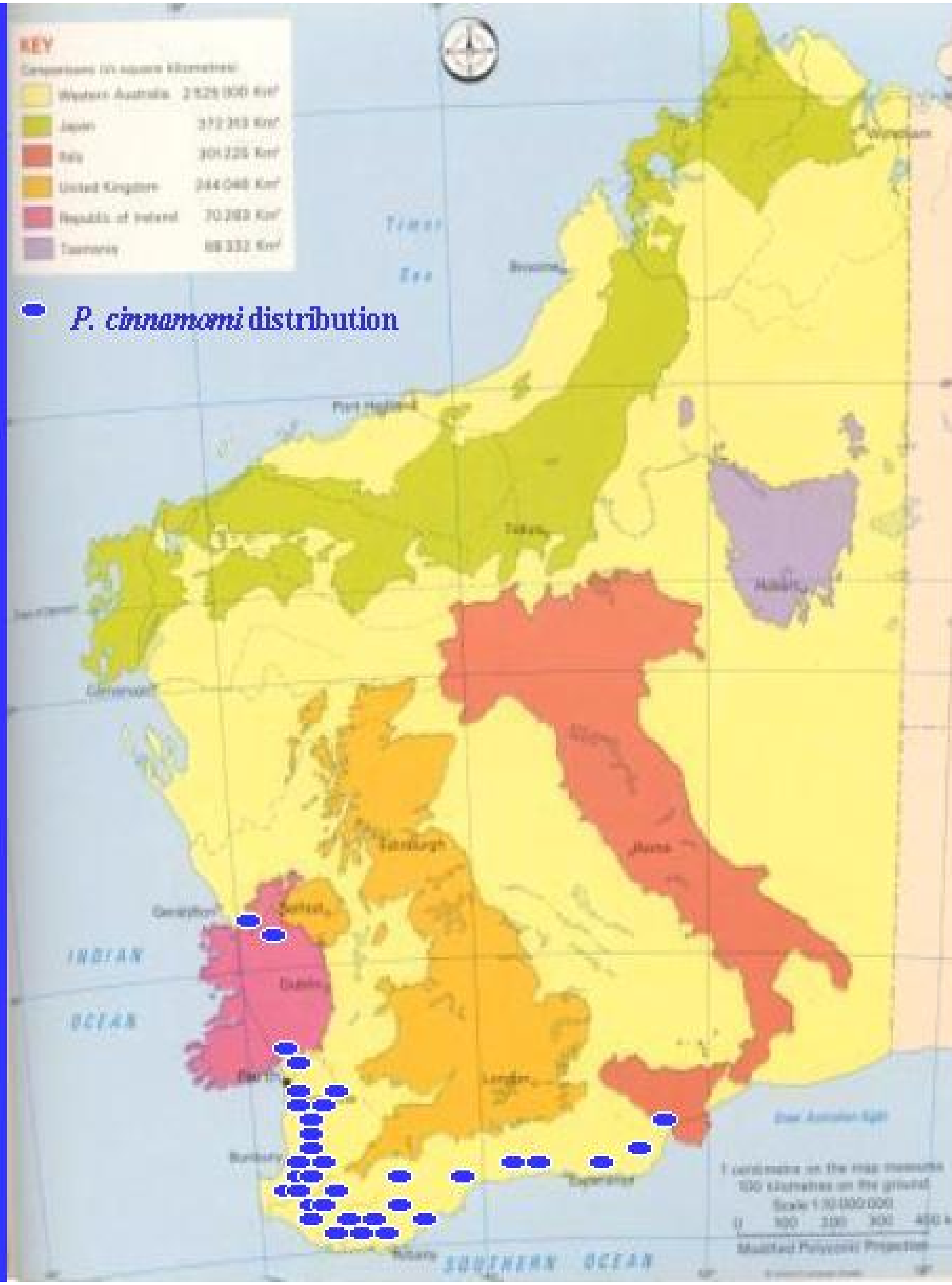
CAUSED BY
Phytophthora cinnamomi

ENTERED U.S. BEFORE 1824

CHESTNUTS IN THE GULF AND SOUTHERN ATLANTIC STATES, ON POORLY DRAINED SOILS, WERE ALL KILLED

P. L. Buttrick, 1913
The Recession of the Chestnut from Certain Sections of North Carolina

"Clearing made across hill by deadening trees. Pure chestnut near summit of the Blue Ridge."



Distribution of *P.cinnamomi* in Western Australia

Dying trees first noticed in 1921.

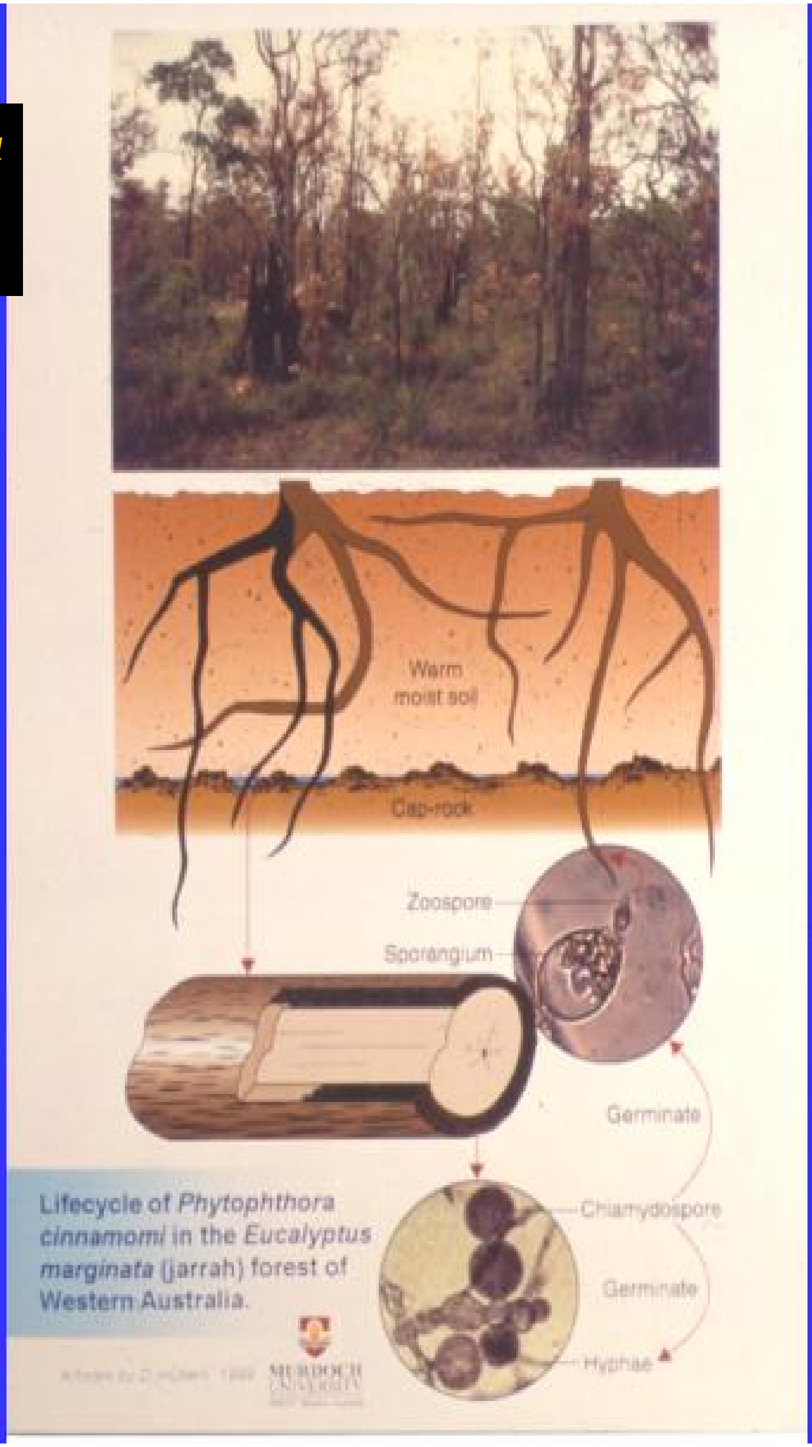
P. cinnamomi found to be causal agent in 1964

Impacts on plant communities

Dead and dying montane vegetation from *Phytophthora cinnamomi*. The pathogen would have been introduced on the boots of bush walkers. Note the ‘grey’ areas (blue arrows) showing change in vegetation type along streamzones due to *P. cinnamomi.* Picture Sarah Barrett

Extent of diseased area (in red) in Stirling Ranges (65-70% infected)

Life cycle of *Phytophthora cinnamomi* in the jarrah forest.



Impact on Plant Diversity

- 5710 plant species in Western Australia's SW Botanical Province

- 2284 are susceptible to *P. cinnamomi* (*Shearer et al. 2004*)

- Indirect effects of *P. cinnamomi* on plant communities is unknown

- Recognized as a KEY THREATENING PROCESS to Australia's biodiversity in the Environ. Biodiversity and Conservation Act of 1999

Healthy jarrah forest

Cinnamomi moving downhill in mixed eucalypt- killing Xanthoria first. Victoria.

P. cinnamomi- Jarrah dieback W. Australia

CSIRO PUBLISHING

www.publish.csiro.au/journals/app *Australasian Plant Pathology*, 2003, **32**, 247–256

The dieback cycle in Victorian forests: a 30-year study of changes caused by *Phytophthora cinnamomi* in Victorian open forests, woodlands and heathlands

Gretna Weste

Botany School, University of Melbourne, Vic. 3010, Australia; email: g.weste@botany.unimelb.edu.au

Dieback and death of 50-75% of the species, including the dominant *Zanthorrhoea australis*, dramatically altering species composition.

For 14 years the pathogen could be recovered from 100% of root samples, then declined.

Regeneration of 30-40 susceptible species observed but unsure whether it will represent stable recovery.

P. cinnamomi devastation/losses

- *Eucalyptus marginata* (jarrah) in Australia

(First observed in 1920s, now up to 75% native flora destroyed)

- Major limiting factor in production of many ericaceous ornamentals- Root Rot

- Root rot of Fraser Fir in North Carolina- M. Benson

- Root rot of Avocado (Persea americana)- $30 million/yr loss in California, 60-70% of orchards affected

- Others too numerous to mention

P. cinnamomi

- Opposite extreme from *P. infestans*
- Distribution limited by temperature and other factors (active in soil above 10°C)
- Very few sporangia but very active soil phase. Can survive as saprophyte up to 6 years in moist soil (Zentmyer and Mircetich, 1966)
- Long distance migration limited
- Very large host range (> 1000 species)

CSIRO PUBLISHING

www.publish.csiro.au/journals/app

Australasian Plant Pathology, 2005, **34**, 333–338

The role of chlamydospores of *Phytophthora cinnamomi* — a review

K. L. McCarren[A], *J. A. McComb*[A], *B. L. Shearer*[B] *and G. E. St J. Hardy*[A,C]

[A]School of Biological Sciences and Biotechnology, Murdoch University, Murdoch, WA 6150, Australia.
[B]Department of Conservation and Land Management, Perth, WA 5152, Australia.
[C]Corresponding author. Email: G-Hardy@murdoch.edu.au

Gaps remain in understanding of their behavior in nature, how long they survive dormant in soil, and factors that stimulate their germination.

Behaviour of *Phytophthora cinnamomi* Zoospores on Roots of Australian Forest Species

Jillian Hinch and Gretna Weste

Botany School, University of Melbourne,
Parkville, Vic. 3052.

Austr. J. Botany 1979. 27:679-691

Chemotaxis to 23 forest species was neither species-specific nor host-oriented.and apparently not related to host susceptibility

Microbial Populations of three Forest Soils: Seasonal Variations and Changes Associated with *Phytophthora cinnamomi*

Gretna Weste and Kumudini Vithanage

School of Botany, University of Melbourne,
Parkville, Vic. 3052.

Austr. J. Botany. 1977. 25:377-383.

- -Microbial populations were lowest in Spring and Autumn when *P. cinnamomi* was most active, and zoospore production, dispersal, and infection was maximal.
- -Absence of disease in wet sclerophyll forests

Special Report

Plant Disease 84:394-398. 2000.

Phytophthora cinnamomi as a Cause of Oak Mortality in the State of Colima, Mexico

F. H. Tainter, Department of Forest Resources, Clemson University, Clemson, SC 29634-0331; **J. G. O'Brien,** USDA Forest Service, 1992 Fowell Ave., St. Paul, MN 55108; **A. Hernández,** Secretaría de Medio Ambiente, Recursos Naturales y Pesca, Progreso No. 5, Col. de Carmen, Coyoacan, c.p. 04110, México, D.F.; **F. Orozco,** Secretaría de Medio Ambiente, Recursos Naturales y Pesca, Victoria No. 360, Colima, Colima, México; and **O. Rebolledo,** Univer

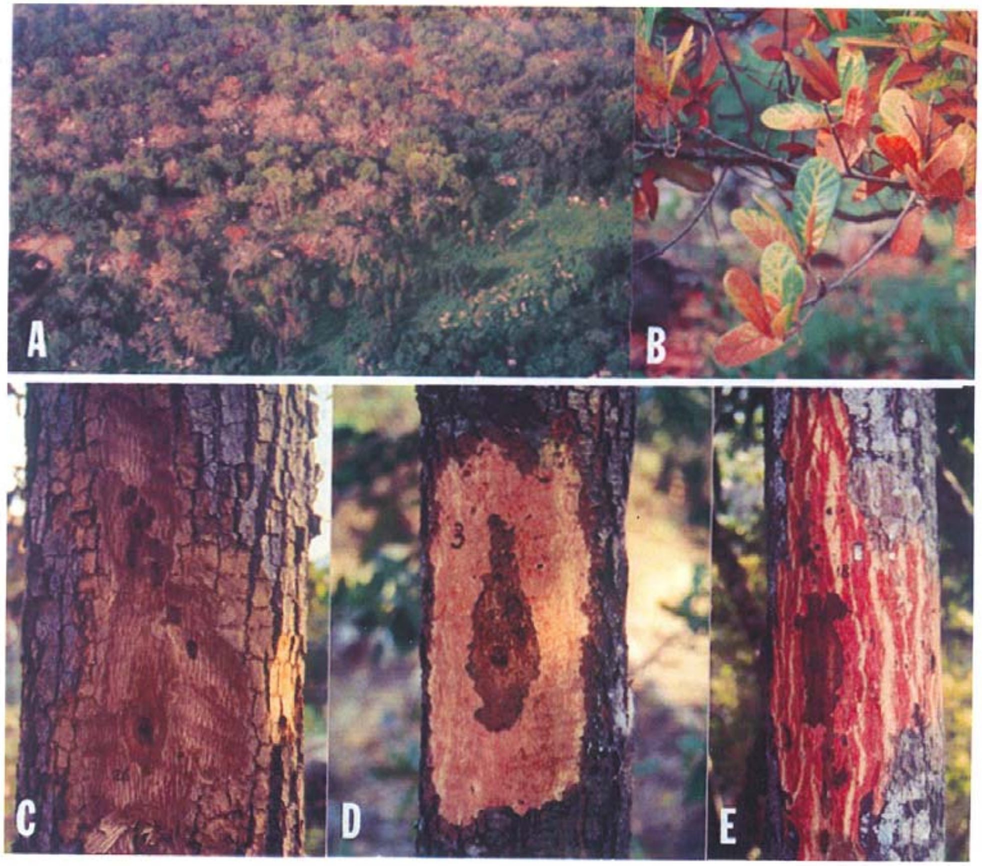
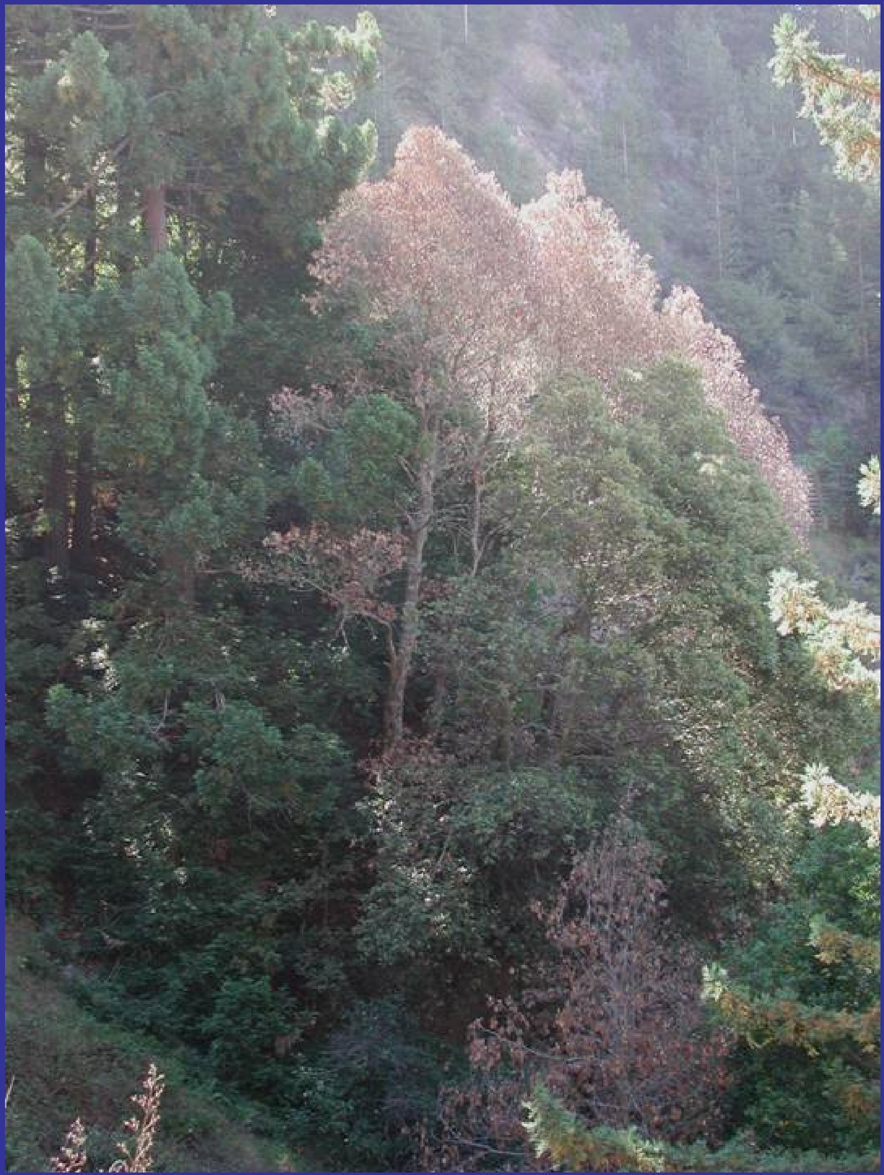


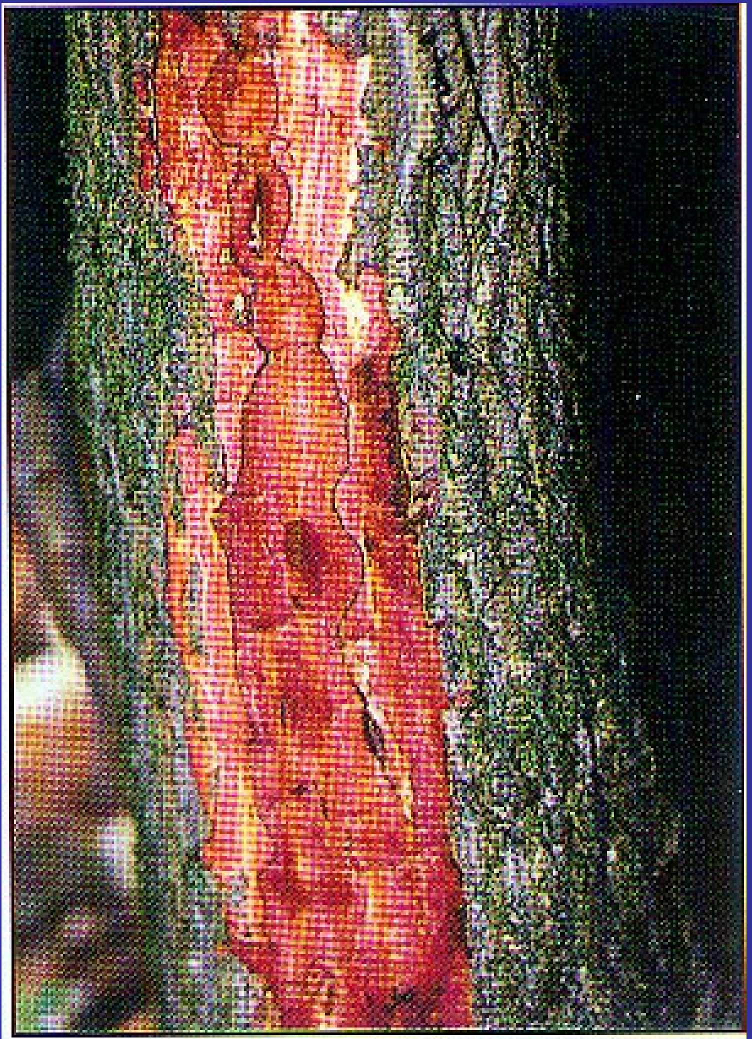
Fig. 2. Views of *Phytophthora cinnamomi*-caused oak mortality in Mexico. **(A)** Aerial photograph of portion of oak mortality area; **(B)** foliar discoloration on *Quercus peduncularis*; **(C)** phloem canker on *Quercus glaucoides*; **(D)** phloem canker on *Quercus peduncularis*; and **(E)** phloem canker on *Quercus salicifolia*.



Big Sur, CA

Marin Co., CA

Santa Cruz Co., CA



Black zone lines under diseased bark in oak.

Phytophthora ramorum

– causes sudden oak death and foliar disease of many ornamentals (since 1995)

– host range currently over 80 species

– Waterhouse Group IV, semipapillate sporangia, amphigynous antheridia

– Transatlantic differences- mating type, growth rates, etiology

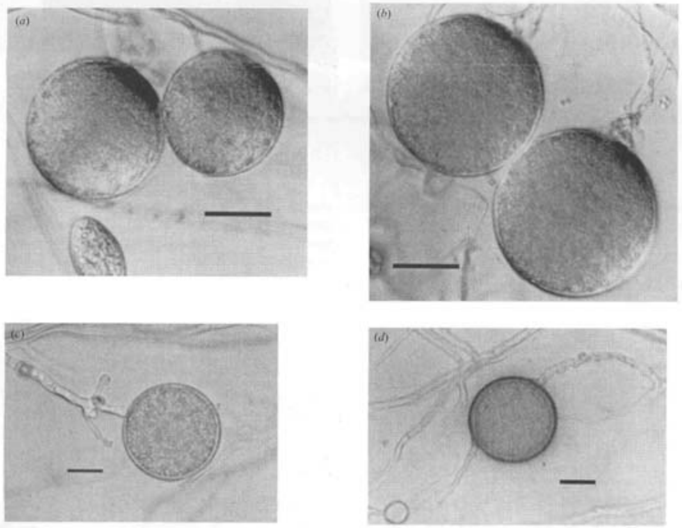
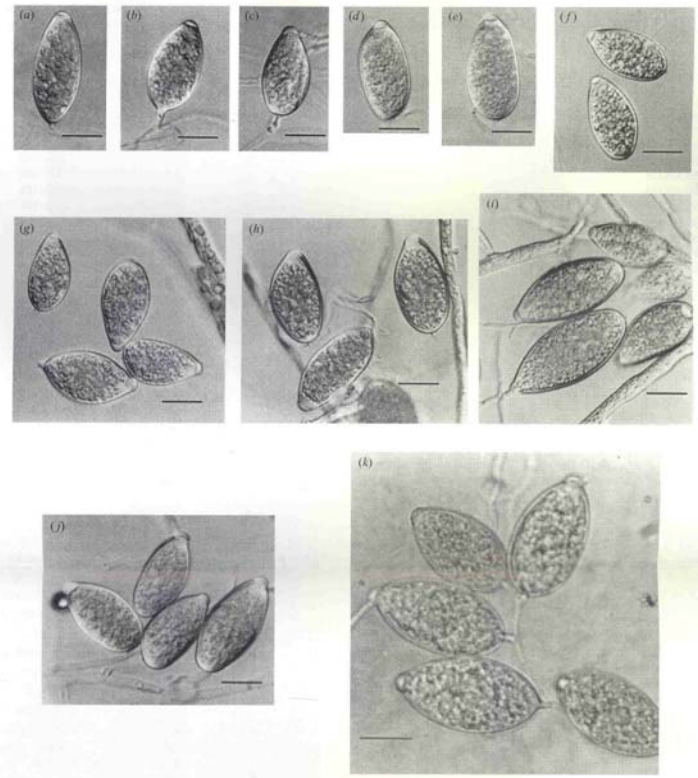


Fig. 3. Chlamydospores of *Phytophthora ramorum* (a, b = CBS 101553; c, d = CBS 109278). Bar = 20 μm.

chlamydospores

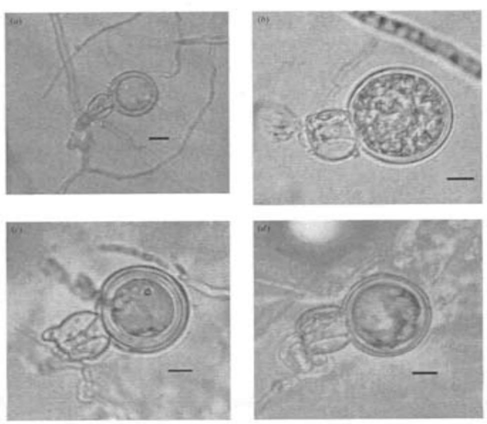


Phytophthora ramorum, a new pathogen 116

Fig. 2. Sporangiophore and sporangia of *Phytophthora ramorum* (different isolates). (Bar = 20 μm).

sporangia

oospores



Phytophthora ramorum, a new pathogen 1162

Fig. 4. Amphigynous antheridia, oogonia and oospores of *Phytophthora ramorum* (a, b = CBS 101552 × *P. cryptogea* BBA 63651; c, d = CBS 101549 × *P. cryptogea* BBA 63651. (Bar = 20 μm).

P. ramorum

PLANT PATHOLOGY

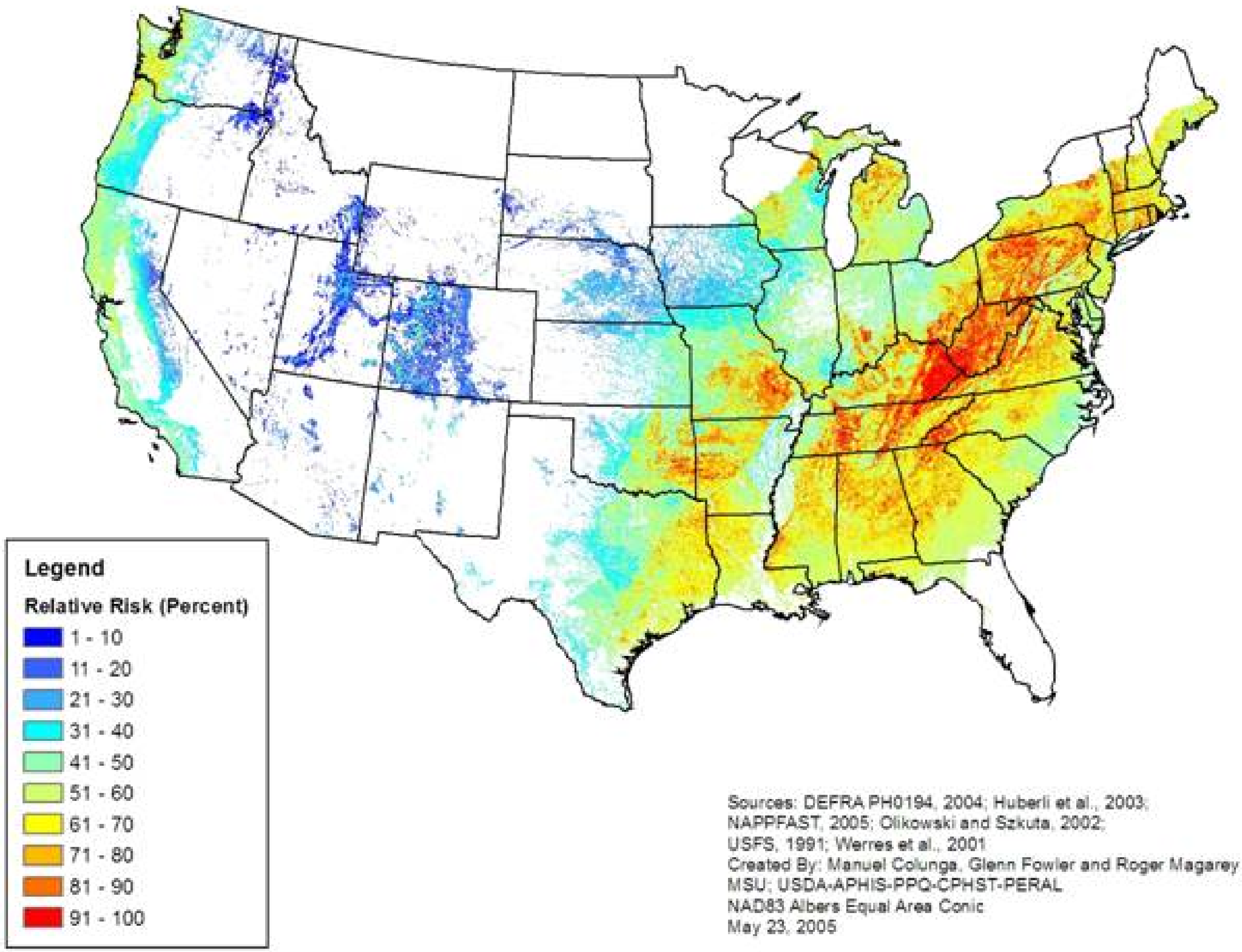
Nurseries May Have Shipped Sudden Oak Death Pathogen Nationwide

A funguslike pathogen that kills oak trees and has devastated forests in California now has plant pathologists scrambling to halt its spread outside the state. In a nightmare come true, the California Department of Food and Agriculture (CDFA) announced on 10 March that the sudden oak death pathogen, *Phytophthora ramorum*, had been found at a nationwide nursery supplier. Although sales of all species that can harbor the pathogen were halted immediately, the

hectare facility in Asuza, Los Angeles County, owned by Monrovia Nursery. Because the nursery supplier has a high-volume business throughout the country, the discovery "dwarfs all the others," says David Rizzo of the University of California, Davis. The pathogen had infected six varieties of camellias. Another nursery in San Diego

Stokstad, 2004. Science 303: 1959

Model showing native hosts and conducive conditions

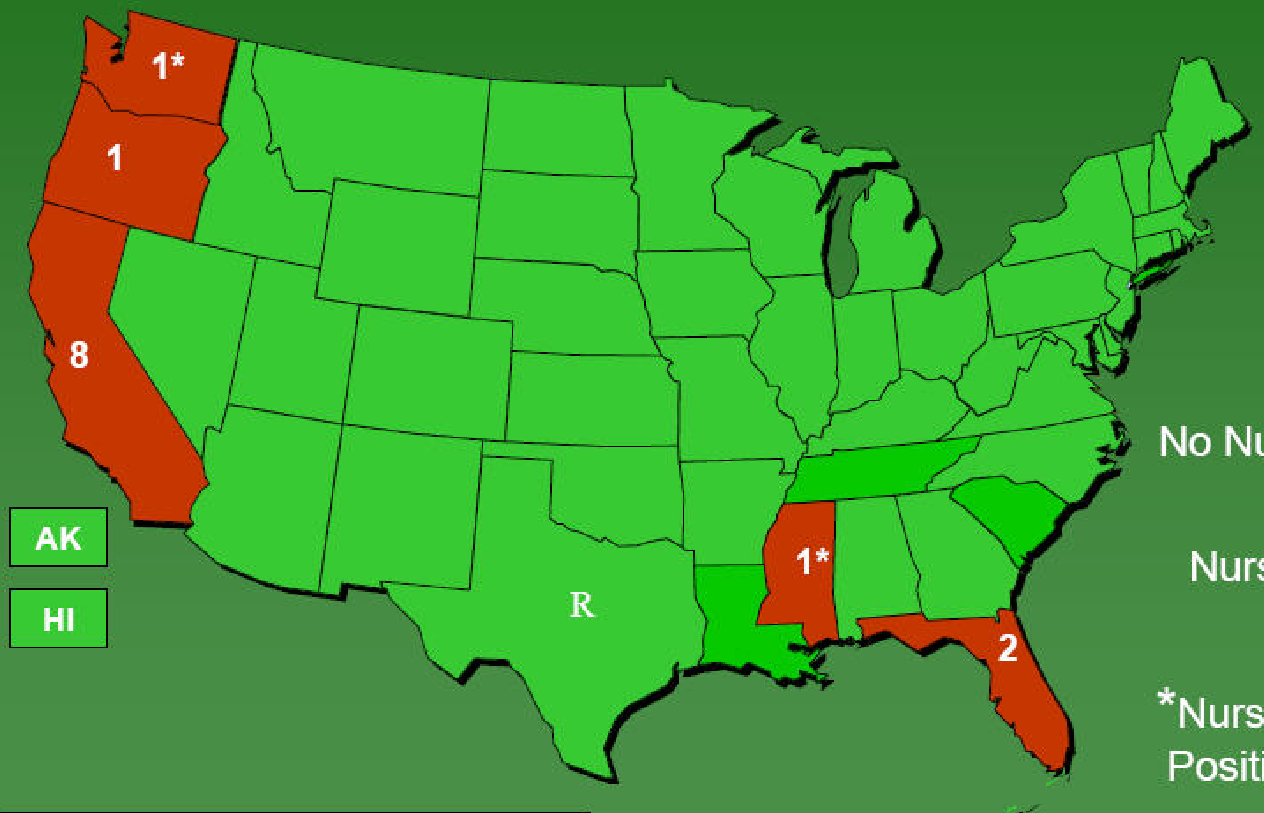


Map: USDA- APHIS –PPQ-CPHST

United States Department of Agriculture
Animal and Plant Health Inspection Service
Plant Protection and Quarantine

USDA APHIS

Positive Nursery Detections 2008



No Nursery Positives

Nursery Positives

*Nursery-Associated Positive Water Find

R – Nursery Associated Residential Find

13 Positive Nursery Sites

Situation so far in 2008

- 7 Nurseries are still under eradication from 2007
- 2 detections (repeats) in FL
- 1 detected repeat in MS
- 8 Nurseries in California, 7 in the certification program, were found infested. One is an interstate shipper and has shipped to 22 states, primarily small numbers sent collectors and hobbyists. Trace information sent out and being followed up, with a nursery find in California and a residential find in Texas.

Most recent:

P. ramorum -infected *Rhododendron* and *Kalmia* sp. were found at a S. Carolina retail nursery on July 14, 2008 as a result of a trace-forward investigation from an NC detection on June 6. Neither nursery has previously been found positive for the pathogen.

California bay laurel, *Umbellularia californica*

Sporangial formation on Cunningham’s White Rhododendron leaf tip

Davidson et al. 2008. Sources of inoculum for *Phytophthora ramorum* in a redwood forest. Phytopathology 98:860-866.

Results indicate that the majority of *P. ramorum* inoculum in redwood forest is produced from infections on bay laurel leaves. Years with extended rains pose an elevated risk for tanoak because inoculum levels are higher and infectious periods continue into late spring.

DOI: 10.1017/S0953756203227660

SUDDEN OAK DEATH: *PHYTOPHTHORA RAMORUM* EXHIBITS TRANSATLANTIC DIFFERENCES

'Sudden oak death,' a rapid mortality of oaks (mainly tan oak and live oaks) spreading in the coastal fog belts of northern California and southern Oregon, was shown to be caused by a *Phytophthora* pathogen in June 2000 by Rizzo *et al.* (2001). This same *Phytophthora* was recently named *P. ramorum* (Werres *et al.* 2001). *P. ramorum* attacks the bark of the lower stem of oaks, causing typical *Phytophthora* bleeding cankers.

Brasier. 2003.
Mycol. Res. 107:258-9

US isolates less aggressive to *Quercus rubra* (N. red oak) and rhododendron stems

US isolates slower-growing then European isolates

US isolates variable in morphology and growth rate

Possible reasons: association of fitness factors with mating type
genetically different founder populations
differential adaptation since introduction

Draws parallels with *P. infestans* and *P. cinnamomi*

European symptoms- *P. ramorum*

on *Viburnum* sp.

On Rhododendrons

Molecular Ecology (2008) **17**, 2755–2768 doi: 10.1111/j.1365-294X.2008.03773.x

Reconstruction of the Sudden Oak Death epidemic in California through microsatellite analysis of the pathogen *Phytophthora ramorum*

S. MASCHERETTI,* P. J. P. CROUCHER,* A. VETTRAINO,† S. PROSPERO‡ and M. GARBELOTTO*
**Department of Environmental Science, Policy and Management, 137 Mulford Hall, University of California, Berkeley, CA 94720-3114, USA, †Department of Plant Protection, University of Tuscia, I-01100 Viterbo, Italy, ‡INRA, UMR 1202 Biodiversité Gènes et communités, Equipe de pathologie Forestiere, BP 81, 33883 Villenave d'Omon Cedex, France*

- 7 variable microsatellites were used, 35 multilocus genotypes were identified among 292 samples from 14 forest sites and the nursery trade.

- Identified 3 common genotypes as likely founders of the California populations.

- Historical human spread of the pathogen, local generation of new genotypes.

February 2008, Volume 92, Number 2
Page 314
DOI: 10.1094/PDIS-92-2-0314B

Disease Notes

First Report of the European Lineage of *Phytophthora ramorum* on *Viburnum* and *Osmanthus* spp. in a California Nursery

N. J. Grünwald, **E. M. Goss**, **M. M. Larsen**, **C. M. Press**, and **V. T. McDonald**, Horticultural Crops Research Laboratory, USDA ARS, Corvallis, OR; **C. L. Blomquist** and **S. L. Thomas**, California Department of Food and Agriculture, Sacramento

Keys to *P. ramorum* success:

Ability to cause widespread infection of coast live oak and tanoak in CA and OR

Ability to infect a wide range of understory species and ornamental species.

Movement of ornamentals in nursery industry contribute to its spread (Stokstad, 2003)

P. ramorum questions:

- Where and when does sporulation occur?

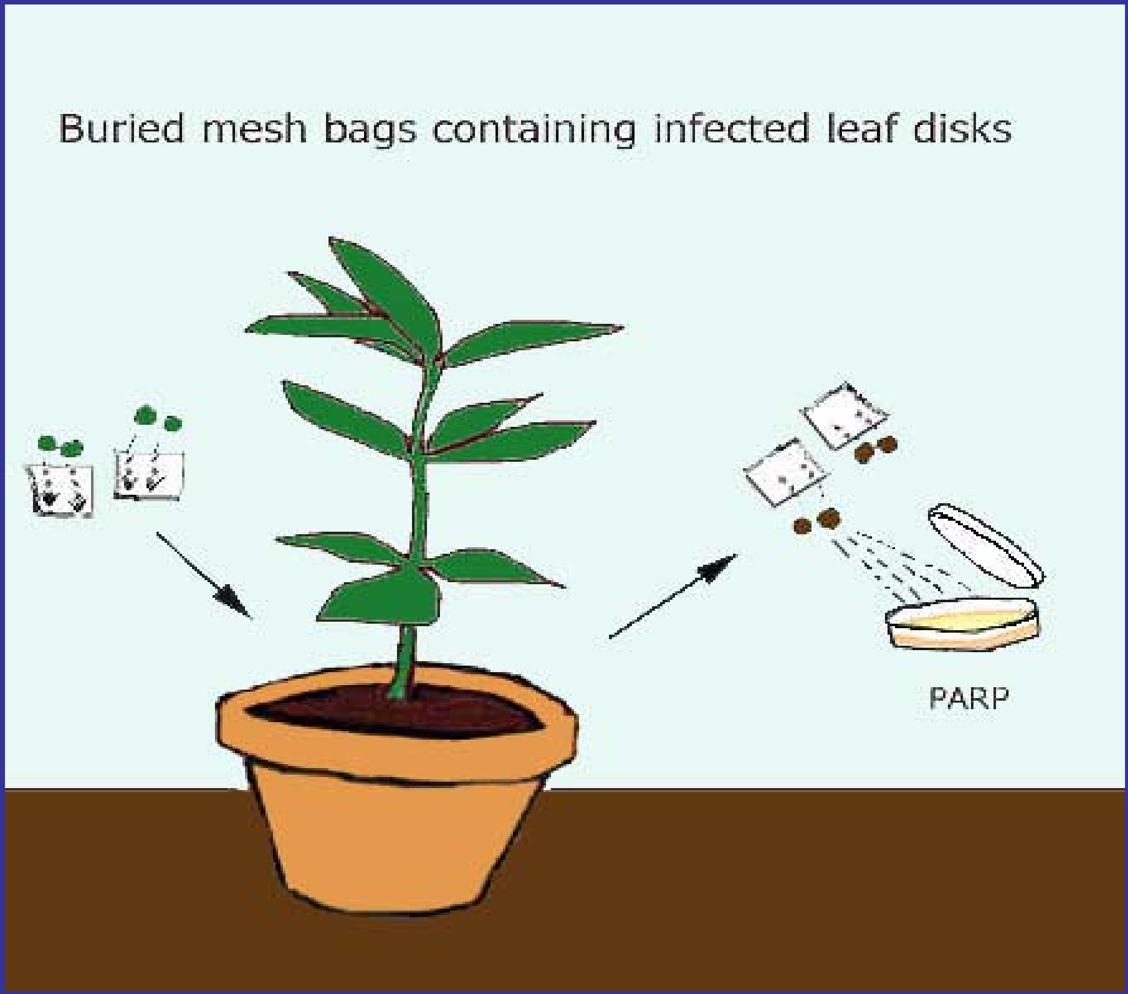
- How is it dispersed?

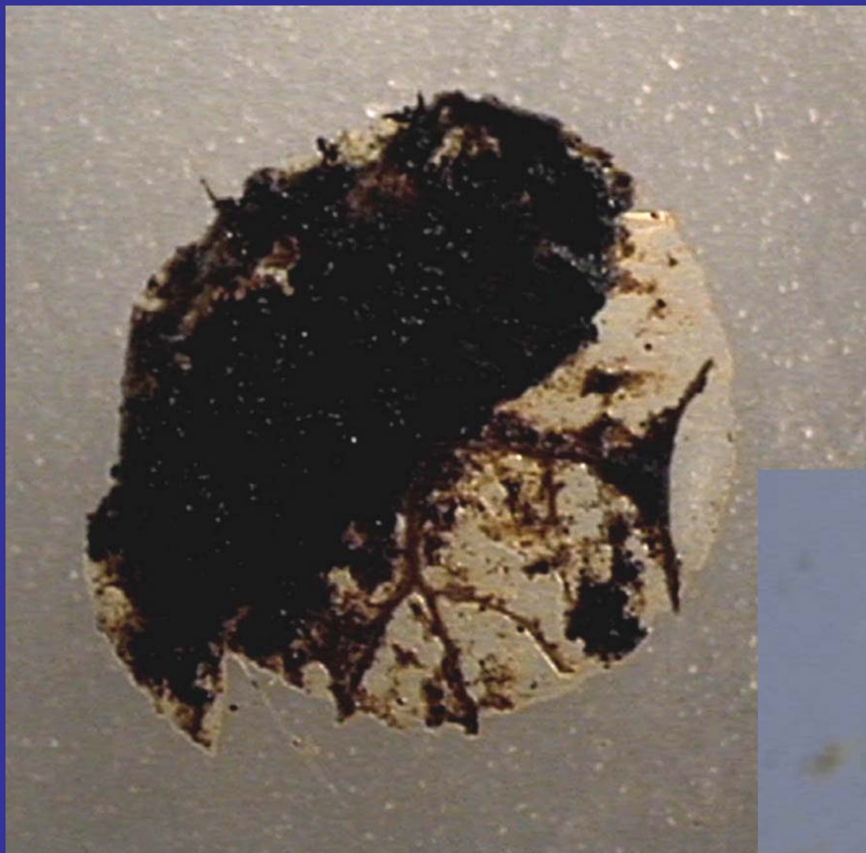
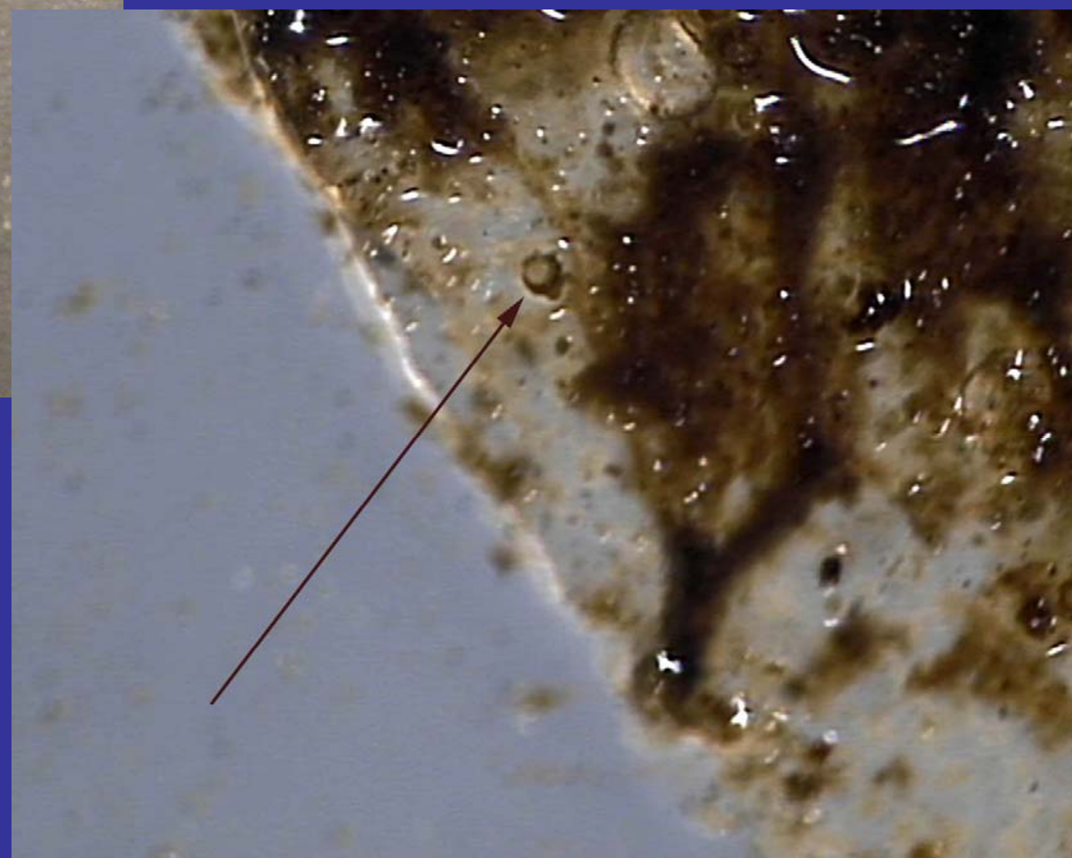
- Is there an 'active' soil phase and can it exist as a saprophyte?

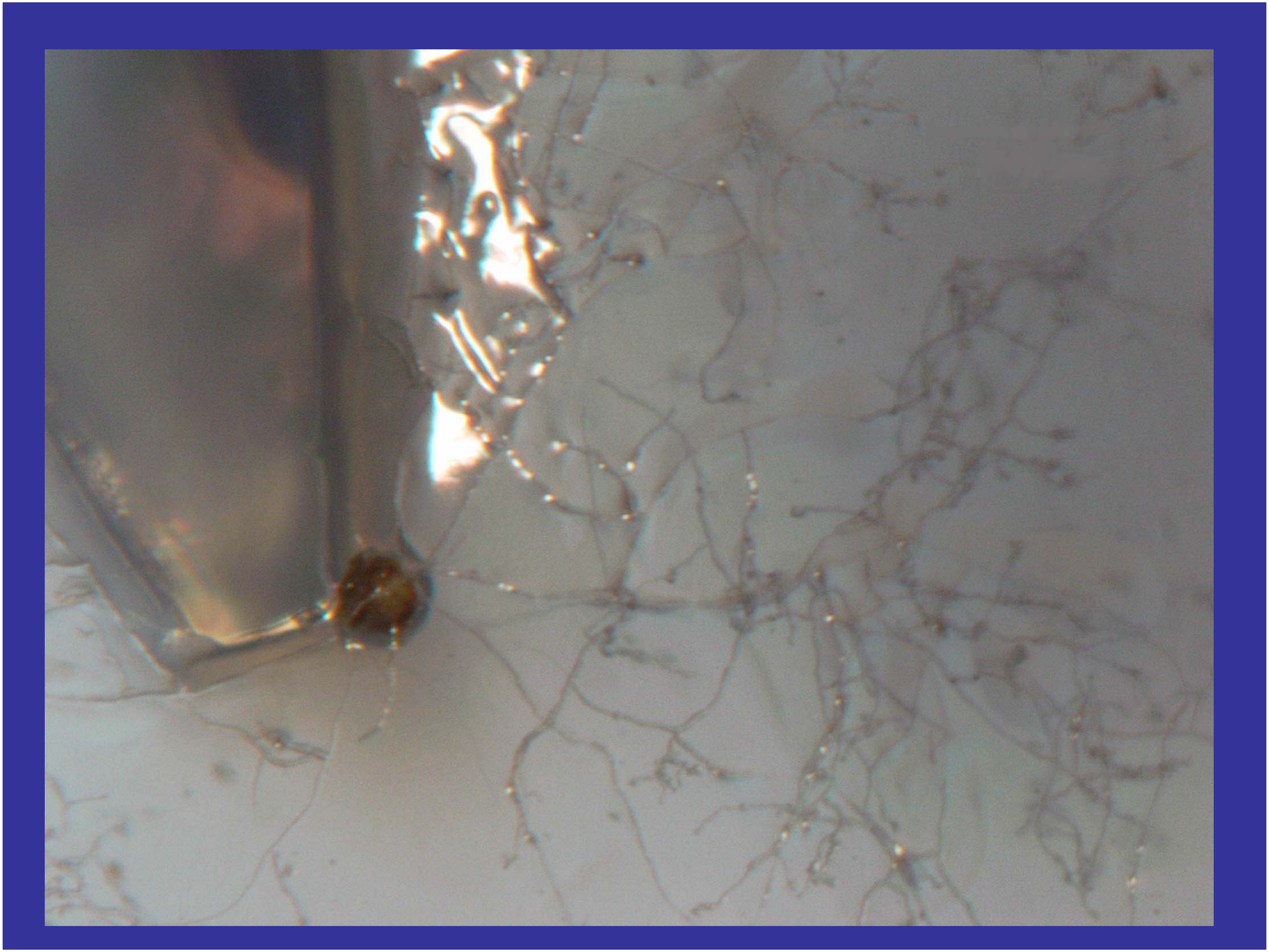
Persistence of *Phytophthora ramorum* in Soil Mix and Roots of Nursery Ornamentals

Nina Shishkoff, Research Scientist, ARS/USDA, Foreign Disease/Weed Science Research Unit. Frederick, MD 21702

Plant Disease 91:1245-1249.2007





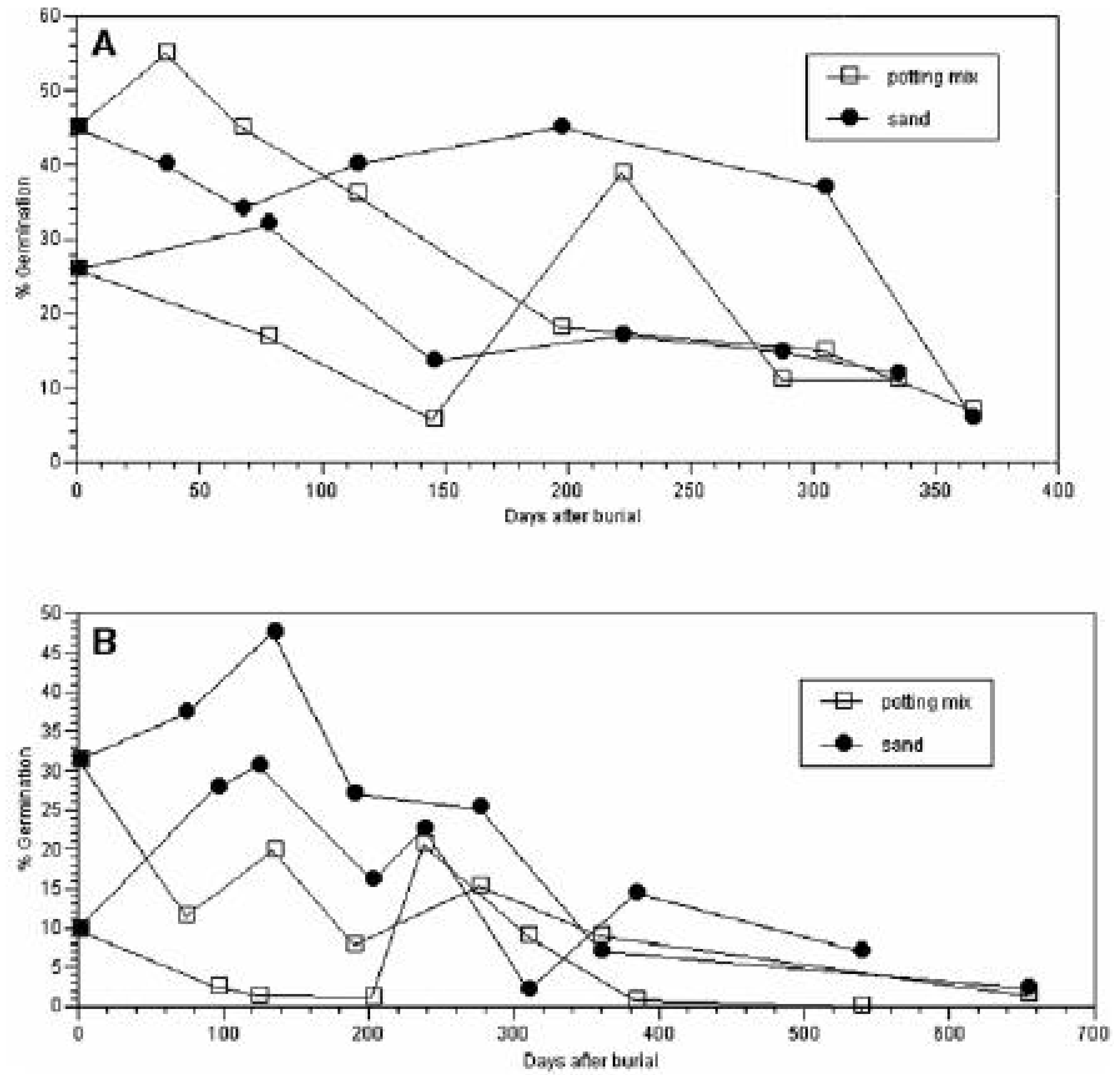


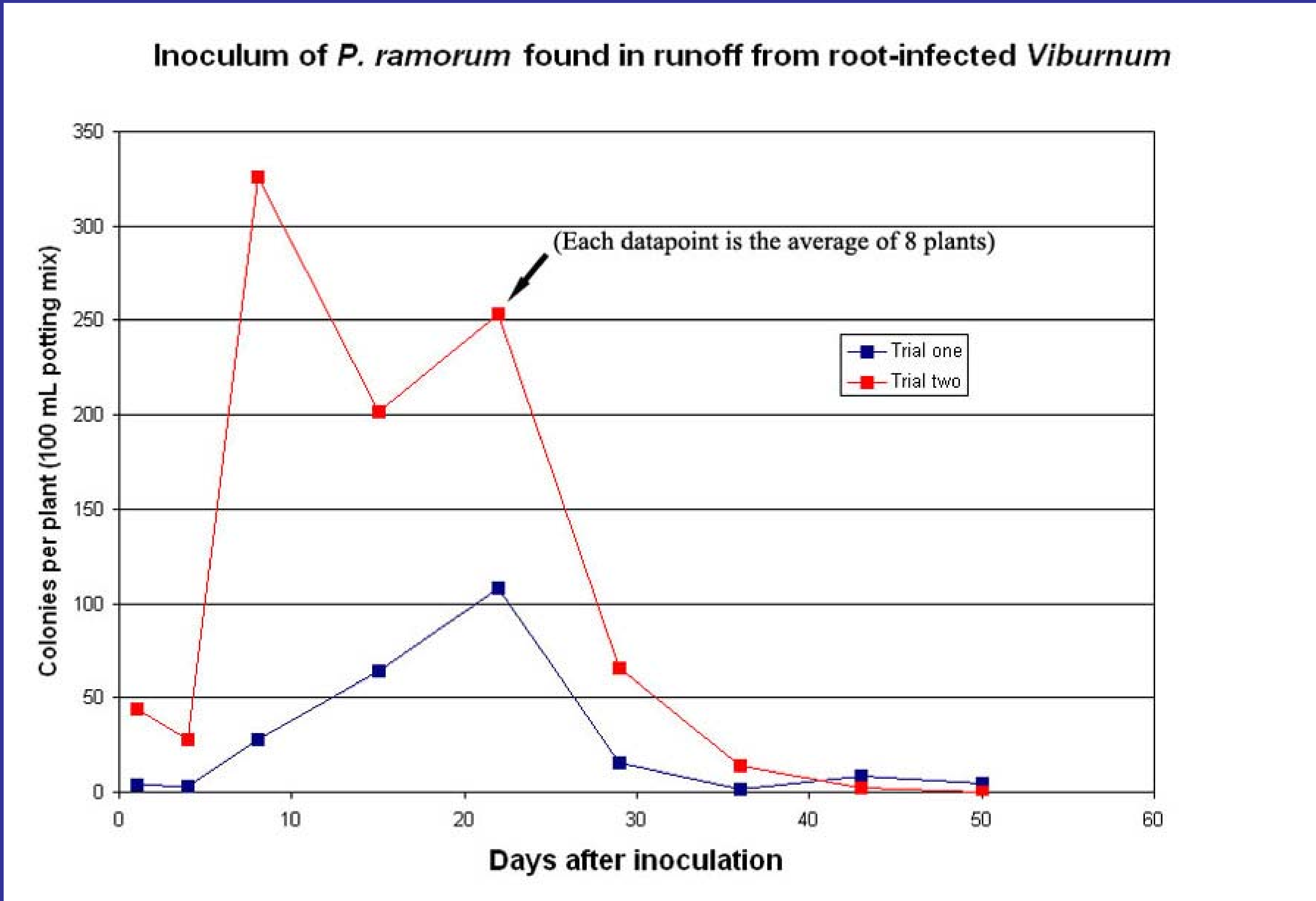
Fig. 2. Recovery of *Phytophthora ramorum* from mesh bags buried in either potting mix or pure sand. **A,** Mycelium including chlamydospores from sterile water culture. **B,** Leaf disks from infected *Camellia* containing embedded chlamydospores.

Each data point represents the average from 2 mesh bags each containing leaf disks with over 100 chlamydospores

Shishkoff, N. 2006. Susceptibility of *Camellia* to *Phytophthora ramorum*. Online. Plant Health Progress doi:10.1094/PHP-2006-0315-01-RS.

Infection of Roots

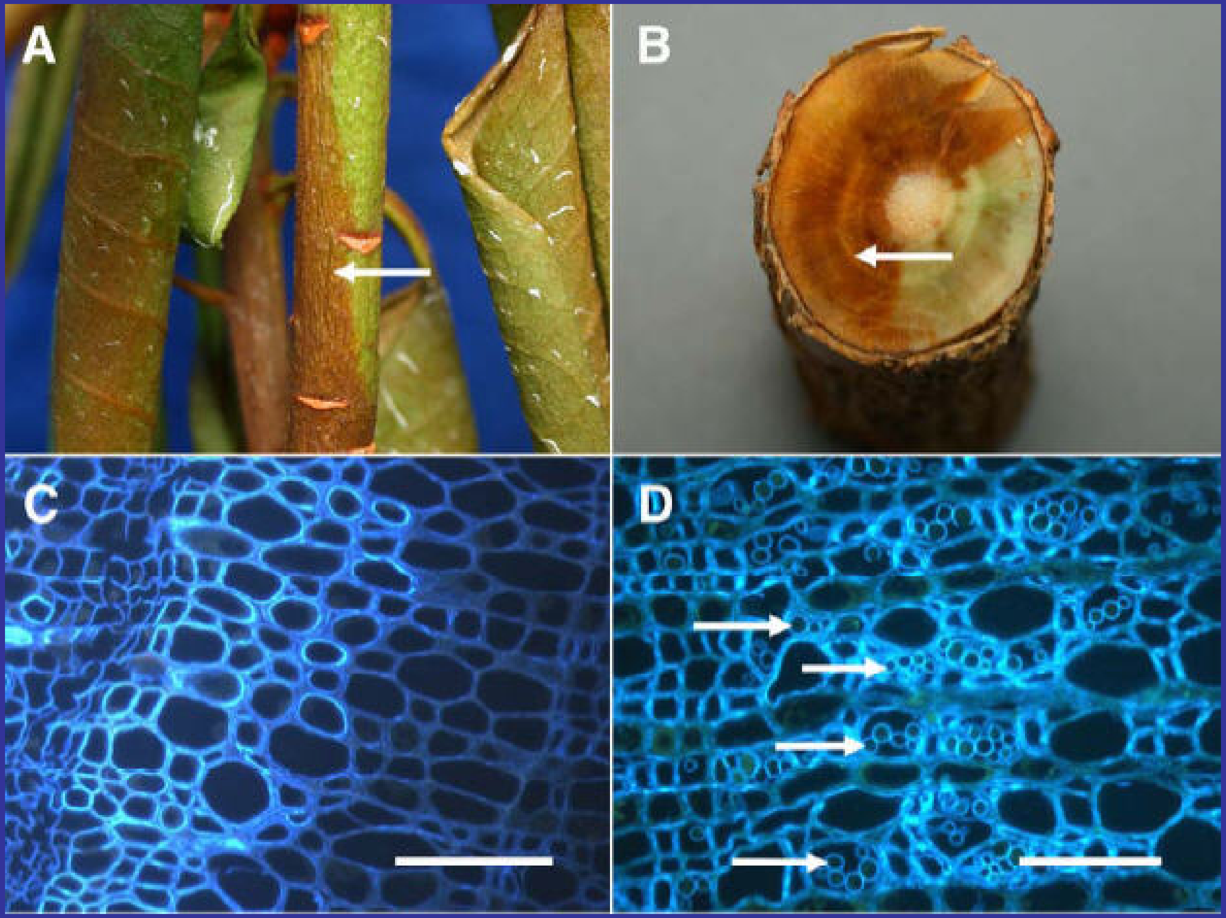
Sections of *C. sasanqua* 'Bonanza' were rooted in 3-inch pots of Turface MVP, a fired montmorillonite clay soil conditioner (Profile Products LLC, Buffalo Grove, IL), and seeds of *C. oleifera* and *C. sinensis* were germinated in 3 inch pots of Turface; plant roots were then drenched with 15 ml of a sporangial solution (approximately 5000 sporangia per ml) of *P. ramorum*. Plants were incubated under greenhouse conditions for a month, then root samples were either washed and directly plated onto PARP media, or surface-sterilized in 0.025% sodium hypochlorite for 5 to 10 min before plating. Roots were asymptomatic but *P. ramorum* was recovered from both washed roots and those surface-sterilized ones at rates of 11 to 38% and 5 to 18%, respectively.


Inoculum of P. ramorum found in runoff from root-infected Viburnum
(Each datapoint is the average of 8 plants)
Trial one
Trial two
Colonies per plant (100 mL potting mix)
Days after inoculation
0
50
100
150
200
250
300
350
0
10
20
30
40
50
60

Root and Stem Infection of Rhododendron from Potting Medium Infested with *Phytophthora ramorum*

Plant Disease 91:1265-1270. 2007.

J. L. Parke, Department of Crop and Soil Science and Department of Botany and Plant Pathology, and **C. Lewis,** Department of Botany and Plant Pathology, Oregon State University, Corvallis 97331



P. ramorum compared with *P. infestans* and *P. cinnamomi*:

appears to combine some features of both!

- able to infect above-ground plant parts
- sporulation low to moderate
- capable of long distance migration
- chlamydospores survive in soil
- ever-widening host range
- grows over wide temperature range

Will *P. ramorum* reach the ‘status’ of *P.infestans* and *cinnamomi*?

- contingent on its ability to continue widening its host range and damaging forests throughout U.S. and Europe
- further movement to additional new regions

Summary

Each of the three species has found its own method of success as a pathogen:

P. infestans: aerial dissemination, explosive epidemics, long distance migration, survival in tubers

P. cinnamomi: vast host range, soil survival and movement, limited by temperature

P. ramorum: foliar and soil phases, pathogen of forest, understory, and ornamental species

Common features of the Devastating

- effective dispersal mechanisms
- adaptable to different environments
- capable of compounded damage
- persistent, tenacious pathogens
- successful survival mechanisms
- assisted by human agricultural activity

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