Optimal Strategies for Detecting Invasive Pests in a Forest Landscape

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Management of Invasive Pests

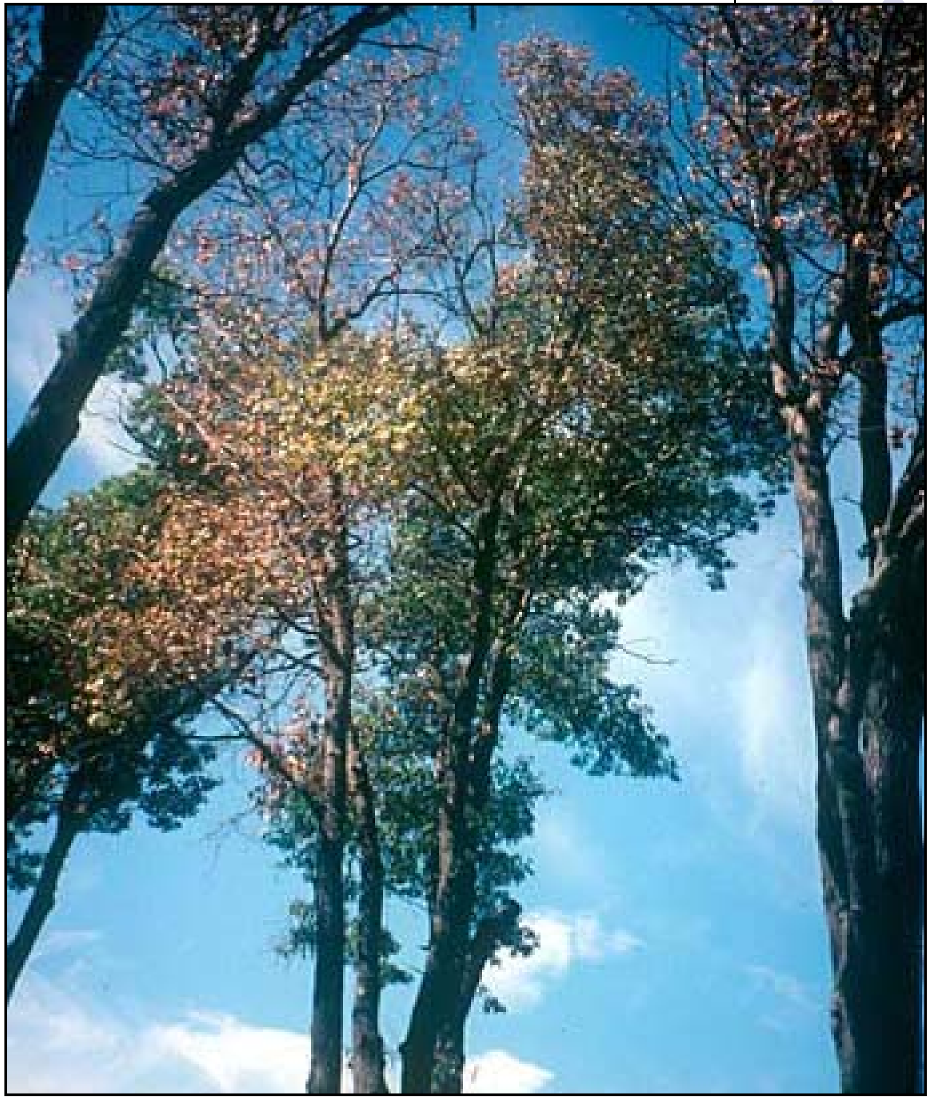
- Exclusion
- Detection
- Management
    - Eradication
    - Suppression
- Restoration

Two Research Contexts

- Pest has established, and is spreading within an area
  - How much effort should be devoted to detection if detection triggers an immediate local eradication?
- Pest is not yet established, but advance of the invasion front is inevitable
  - How much effort should be devoted to detection if detection triggers the management of sub-populations ahead of the front?

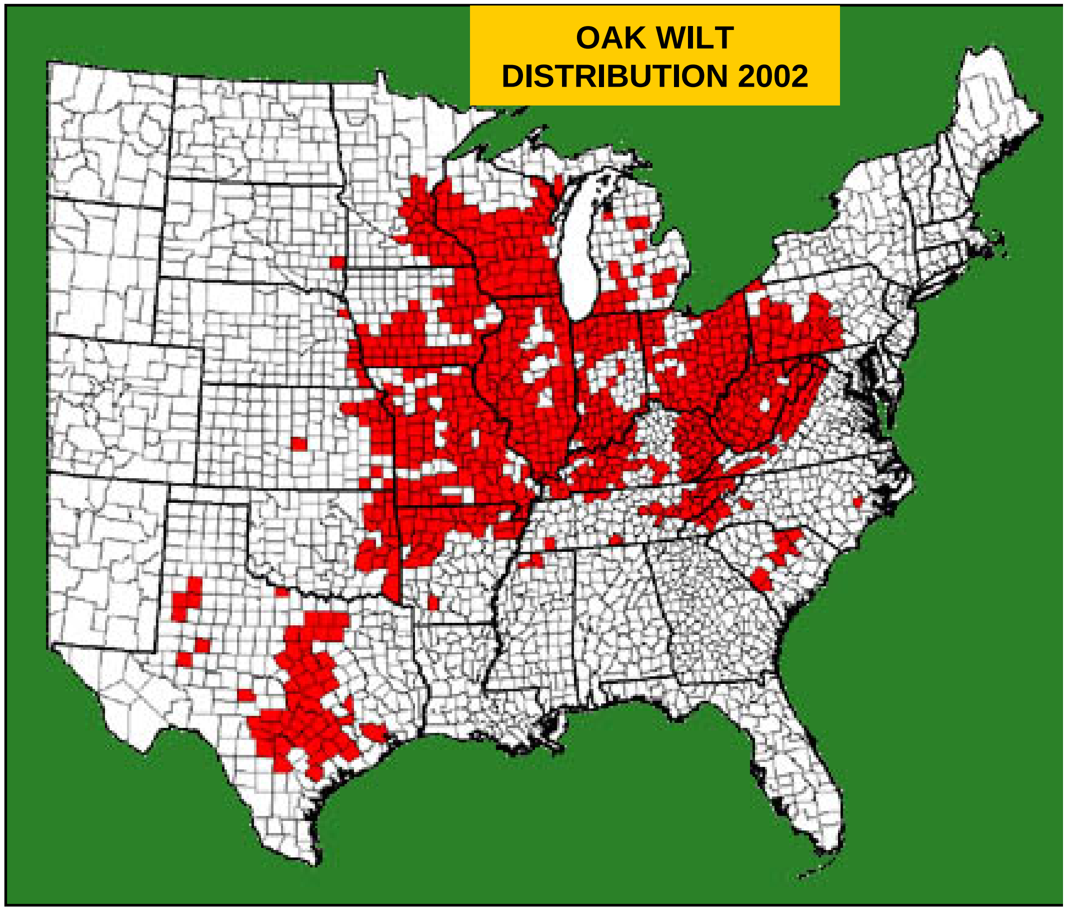
Oak Wilt

- Attacks red and white oaks in eastern USA
- Caused by fungus *Ceratocystis fagacearum*
- Leads to rapid wilting
- Is often fatal to red oaks
- Spreads quickly



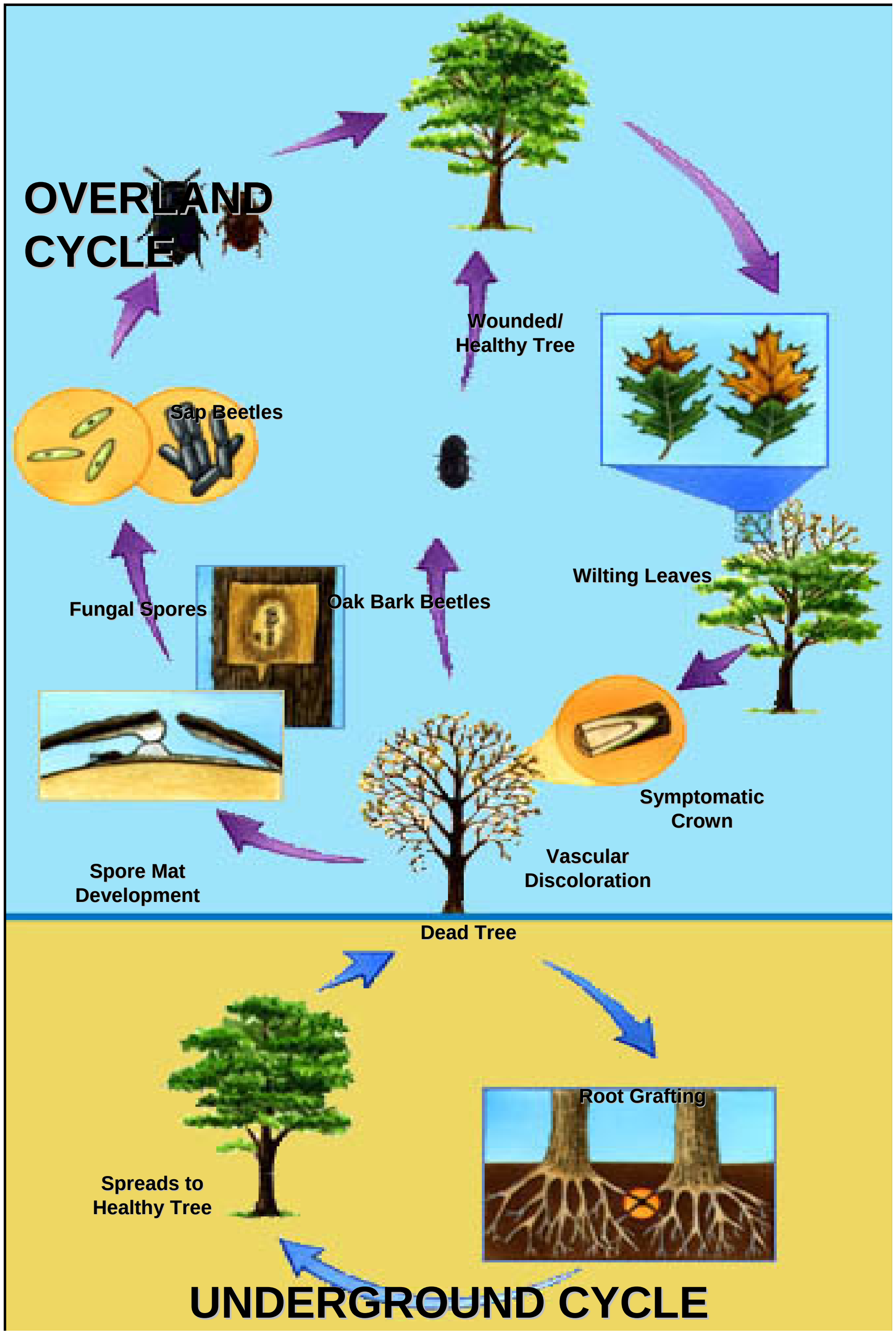
Oak Wilt

- Common in eastern hardwood forests
- Kills 1000s of trees in Minnesota alone



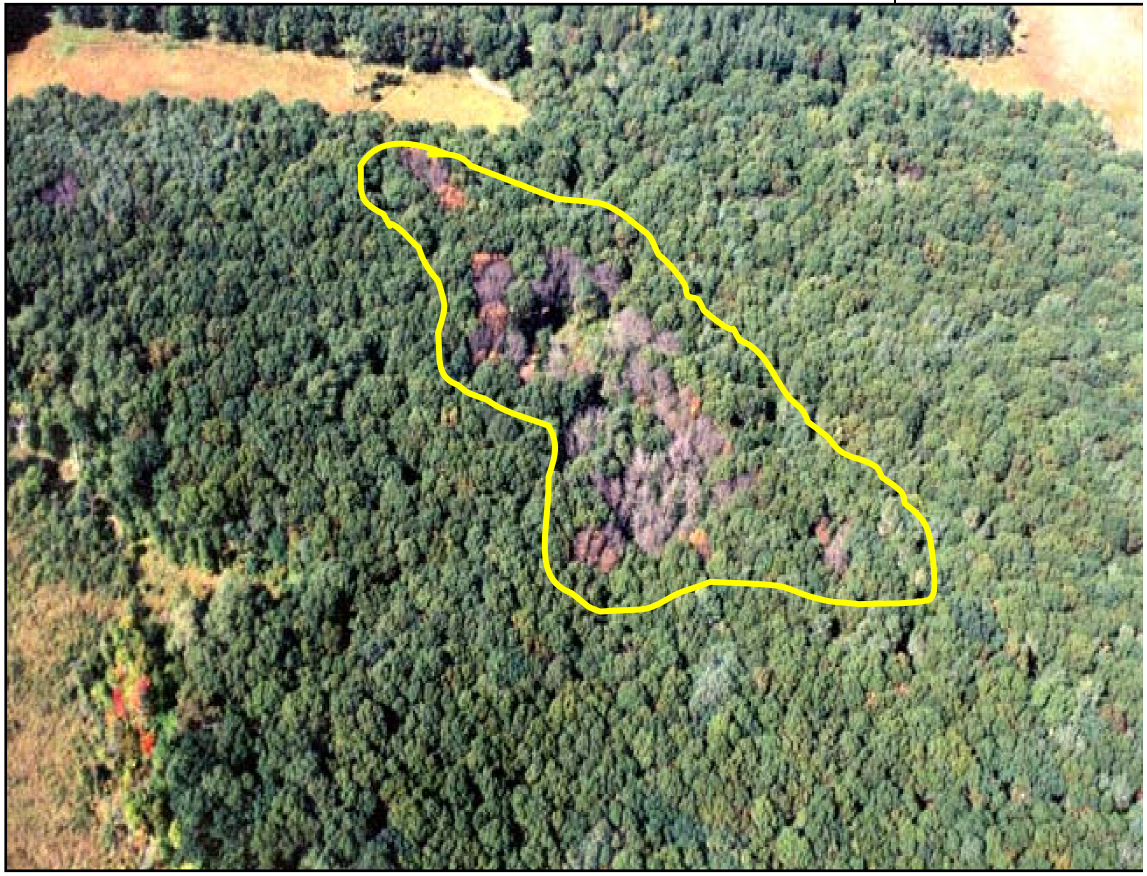
Disease Cycle

- Oak wilt has both an overland and an underground cycle
- Pockets form via beetles
- Pockets expand via root grafts



Oak Wilt Treatment

- Remove infected trees and healthy trees within 500 m
- Plow perimeter to break root grafts



Sampling Strategies for Established Pests

- Haight, Mehta, Homans, and Venette 2007
  - You own a forest that is free of infection
  - You have estimates of pest arrival and growth
  - You sample “sentinel trees” each year to find out if they are infected.
  - If pest infects a non-sentinel tree, it establishes a pocket and grows exponentially.
  - If pest infects a sentinel tree
    - pest is immediately detected
    - undetected infestations are removed
  - How many sentinel trees should you sample?

Optimal Sampling Model

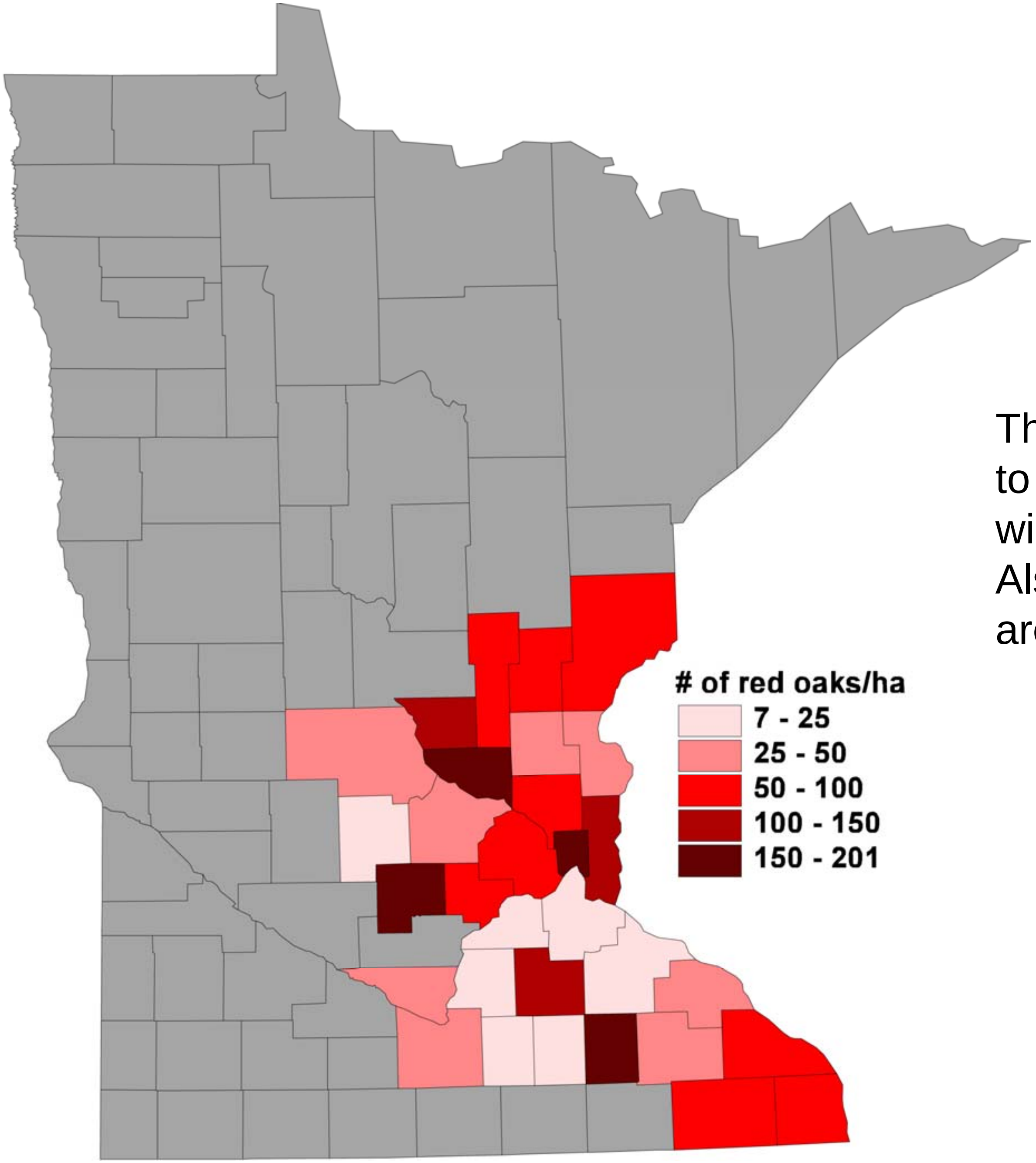
- Renewal-Reward Model
- Minimize Annualized Cost comprising:
  - Cost of search before detection as a function of sample proportion.
  - Cost of search to find all infected trees once an infection is detected.
  - Cost of eradicating all infected trees

Model components

- Unit of analysis
  - 10 hectare wood lot
- Choice variable
  - search proportion, s
- Parameters
  - Arrival rate per woodlot, r.
  - Growth rate, g.
  - Discount rate, δ.
  - Cost of searching entire woodlot, c_1.
  - Cost of removal per tree, c_2.

Data for Minnesota Oak Stands

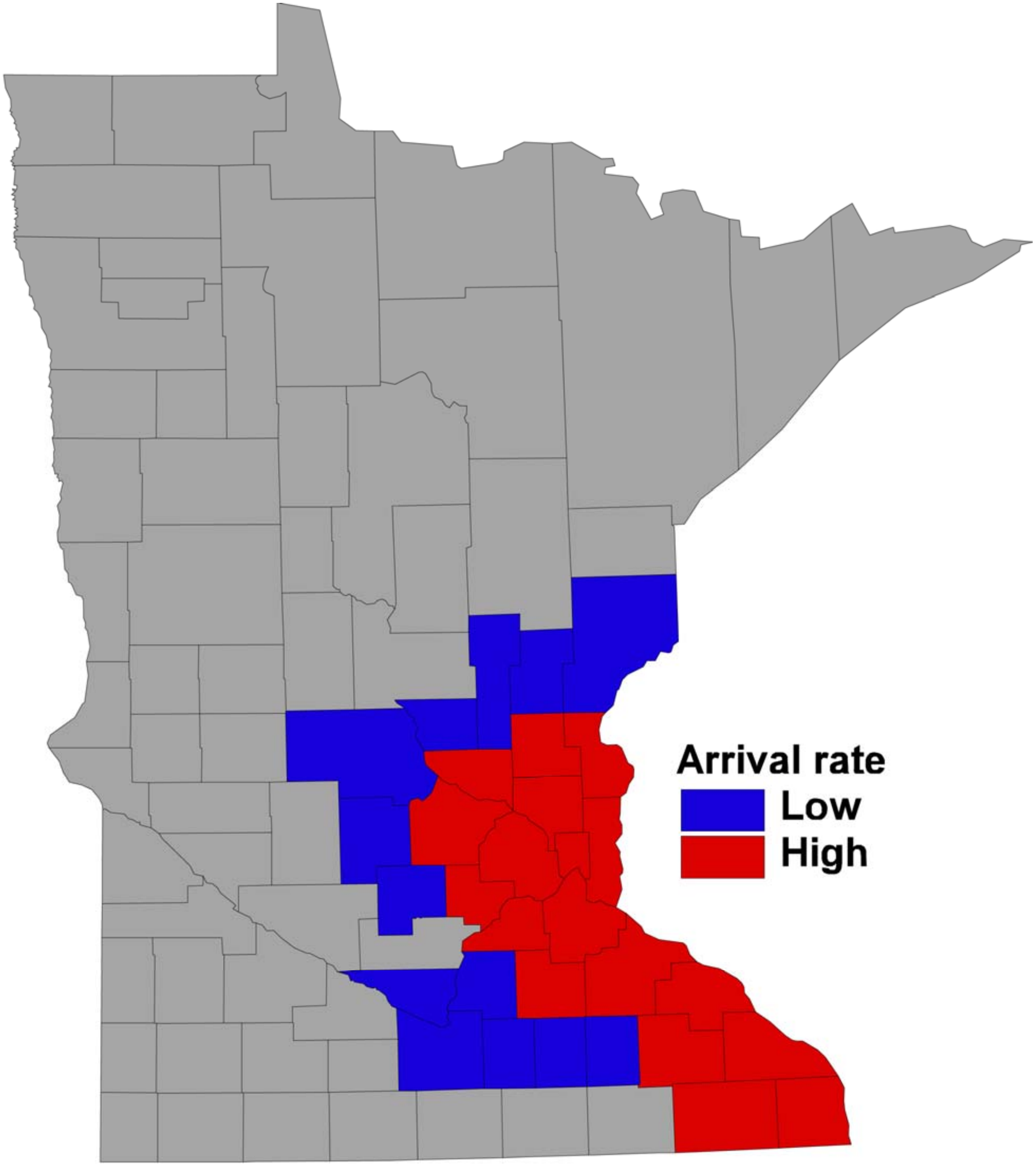
- Forest Inventory and Analysis (FIA) Database
  - Forested hectares per county
  - Number of red oaks per county
- Converted into: density of red oaks per hectare

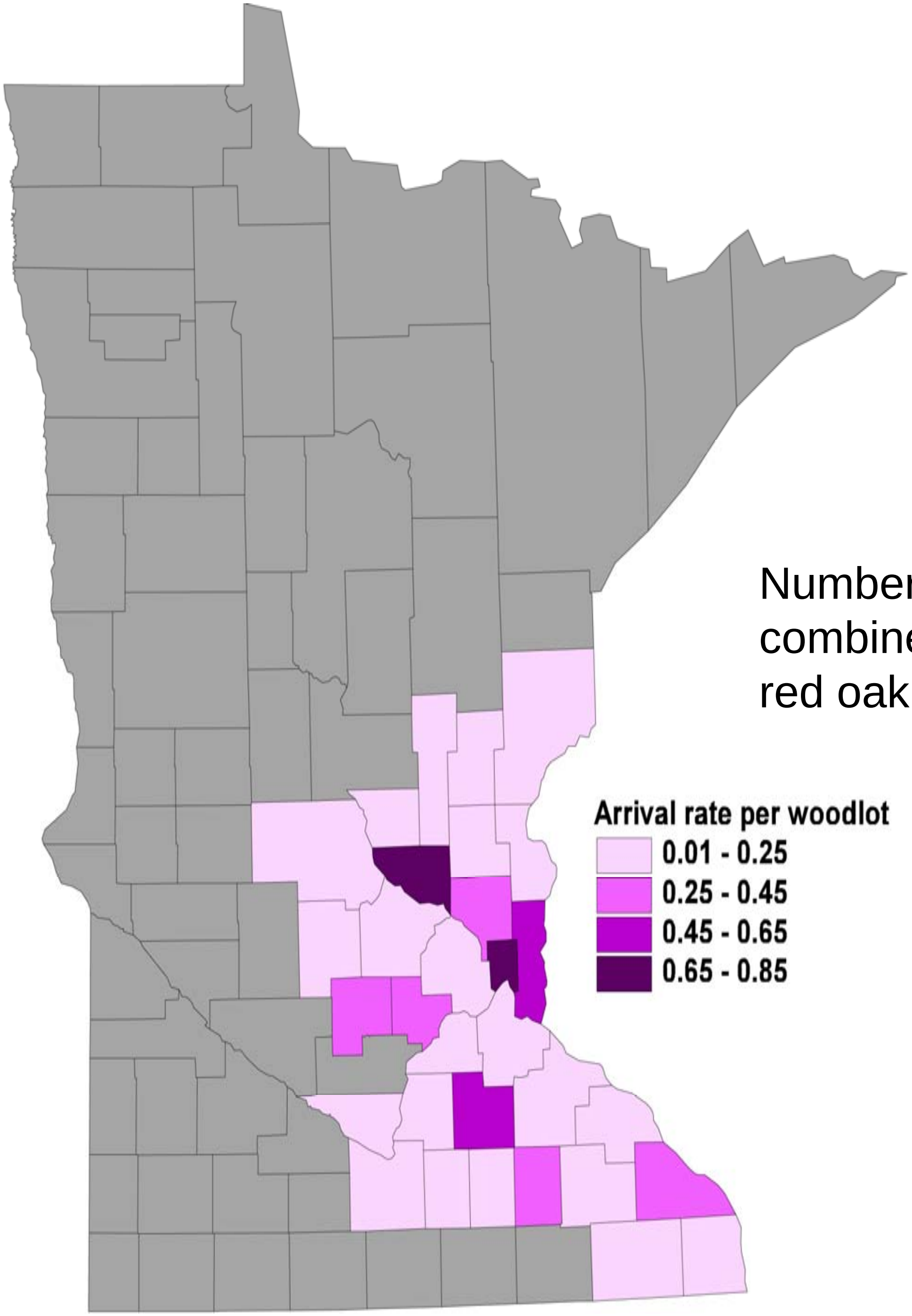


This is the study area due to the presence of the oak wilt fungus. Red oaks are Also present outside this area.

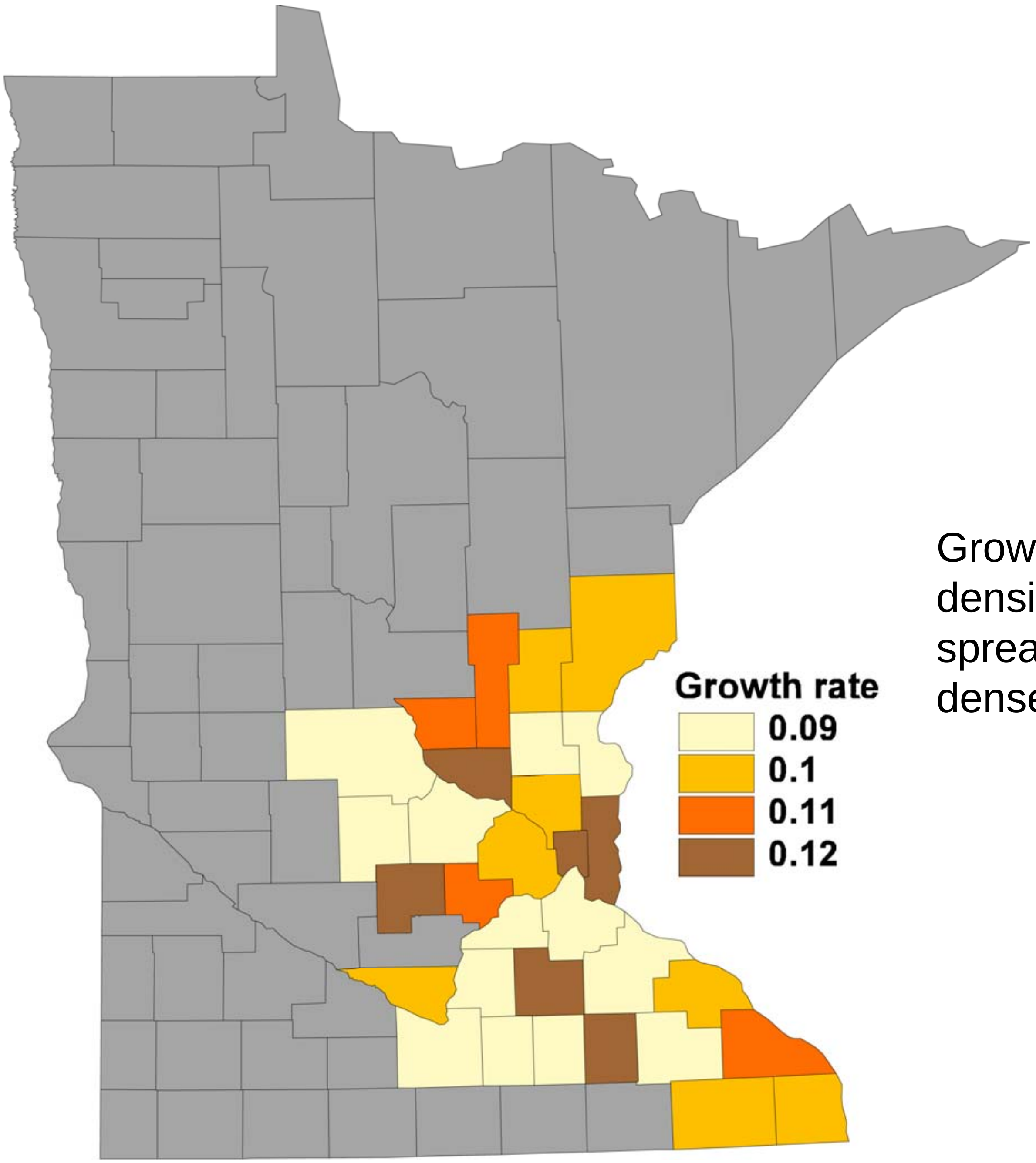
Published Literature

- Arrival Rate per hectare (*r*)
  - 100 red oaks/hectare: Menges
  - Converted to a density-dependent arrival rate
- Growth Rate (*g*)
  - Radial growth rate via root grafts: 3.47 meters/year: Shelstad *et al*., 1991
  - 40 year mortality results: Menges, 1984.
  - Converted to a density-dependent mortality rate

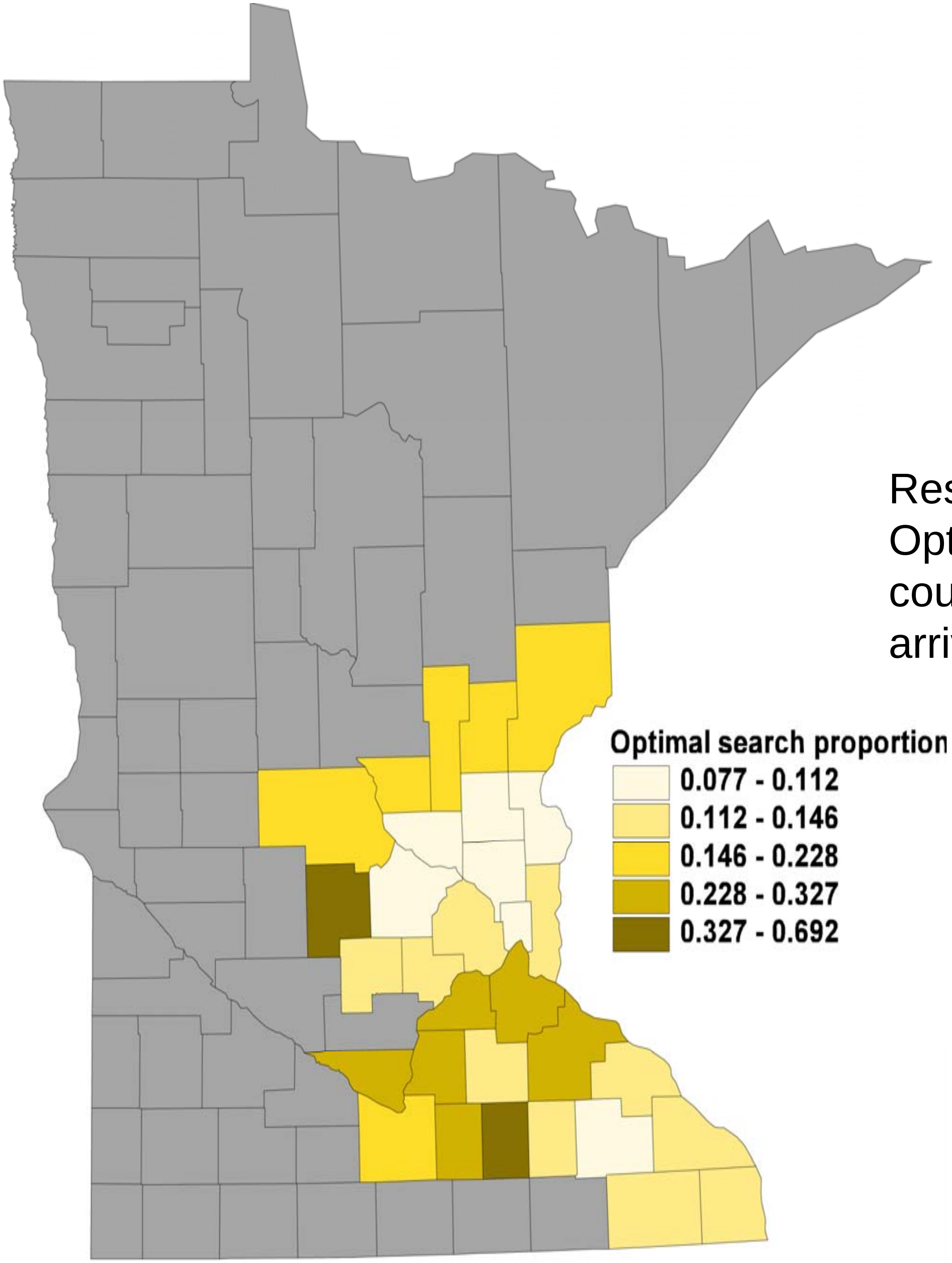

Arrival rate
🟦 Low
🟥 High



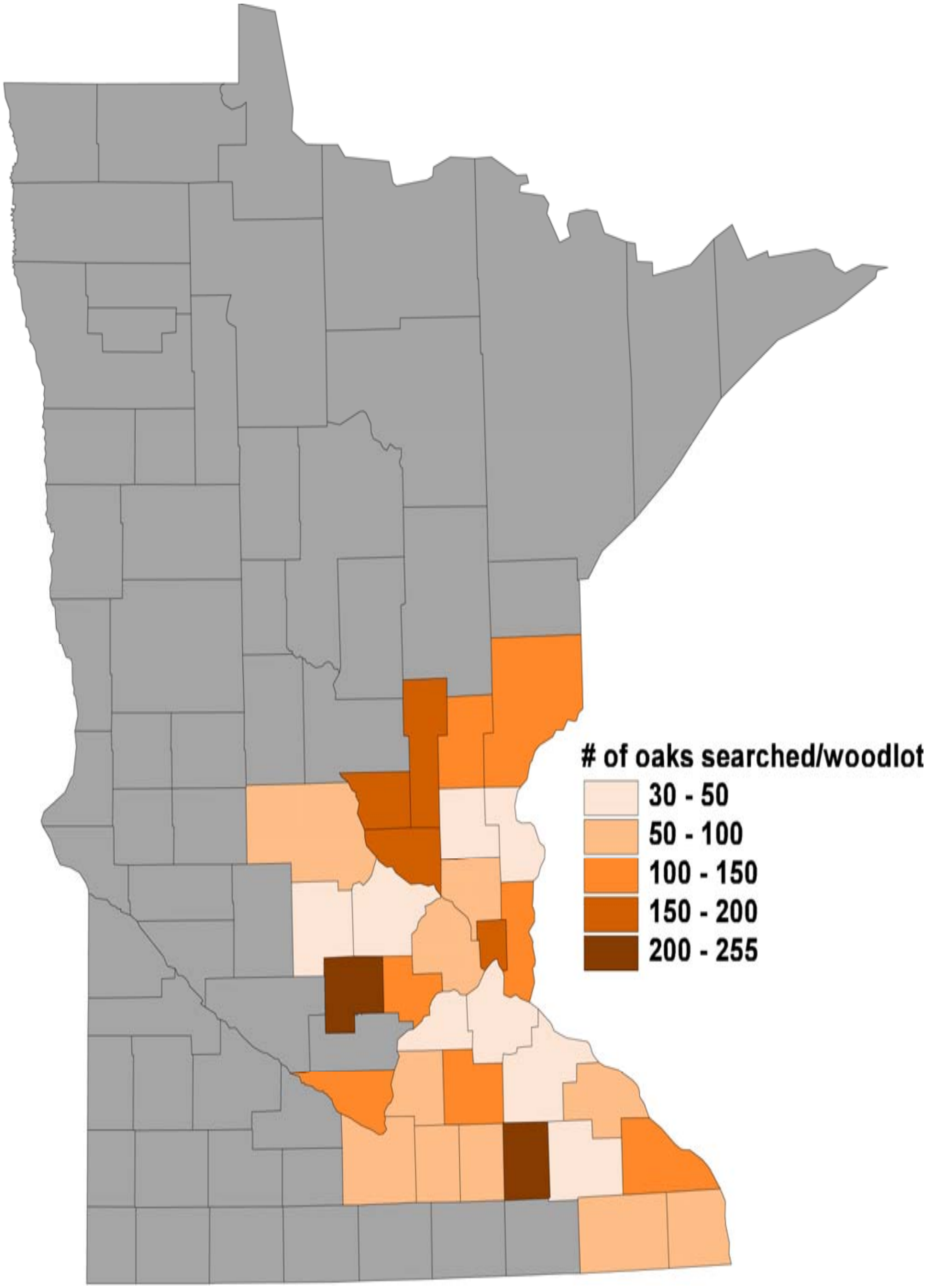
Number of new pockets per woodlot per year:
combines overall arrival rate with
red oak density



Growth rate depends on density of red oaks: a given radial spread infects more oaks if more densely packed.



Results of cost minimization problem. Optimal search proportions vary by county due to differences in arrival rates and red oak density



Results reflect number of red oaks per 10 hectare woodlot

Alternative Model

- Minimize sum of second stage search cost and eradication cost, subject to a constraint on first stage search cost
- May apply if government agencies search, land-owners eradicate
- Results:
  - Low search levels impose high costs on landowners.
  - Without some minimum level of search, landowners are likely to assume responsibility for first stage search.

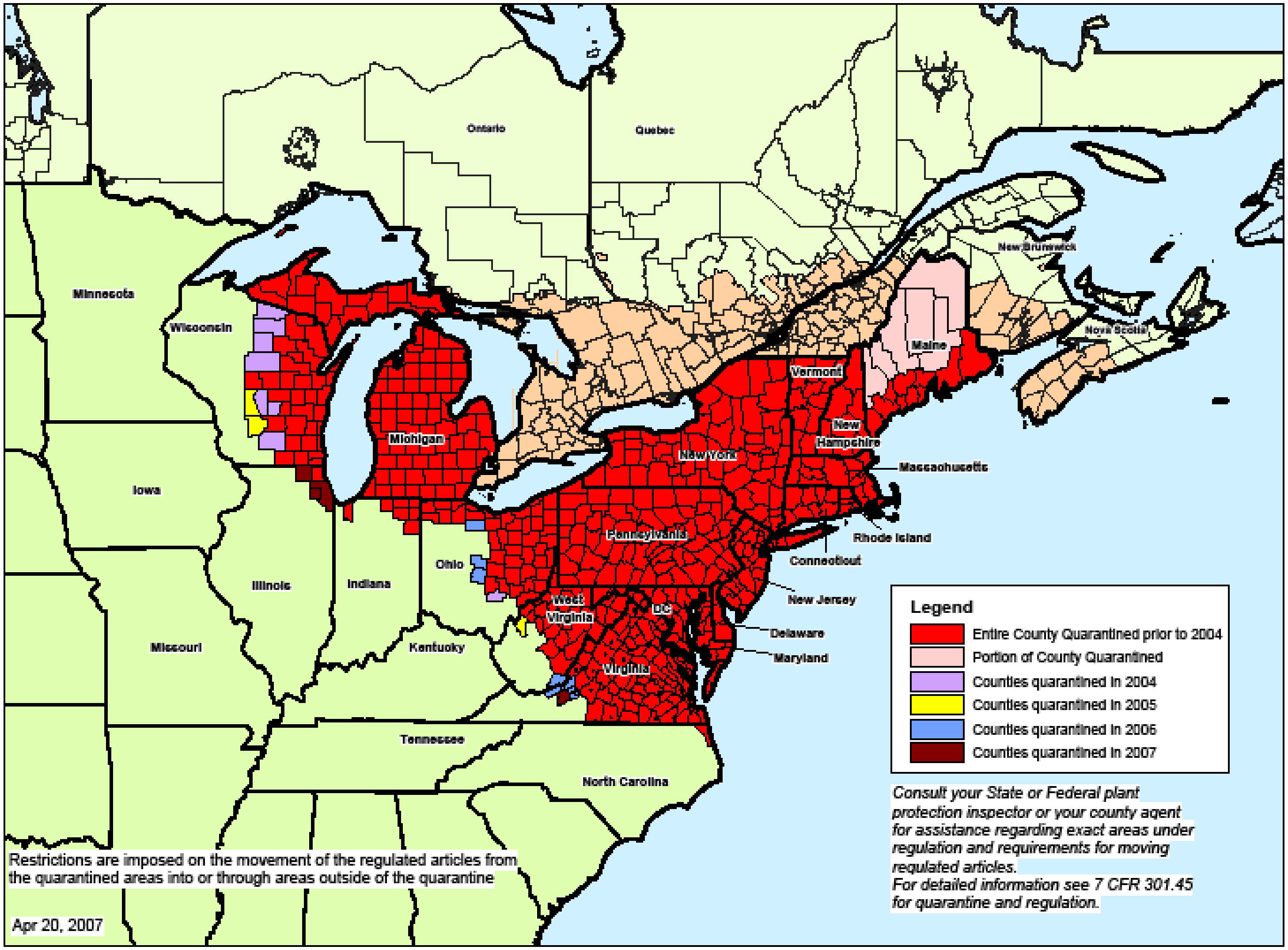
How do constraints on search affect landowners' costs?

	Stage 1 Cost Constraint	Stage 2 Costs	Eradication Costs	Sum of Landowner Costs	Total Costs
Minimum search	$ 6,250,000	$ 1,062,096	$ 27,549,854	$ 28,611,950	$ 34,861,950
	$ 6,500,000	$ 1,125,819	$ 15,126,435	$ 16,252,254	$ 22,752,254
	$ 6,600,000	$ 1,118,982	$ 14,093,225	$ 15,212,208	$ 21,812,208
	$ 6,650,000	$ 1,136,104	$ 11,624,339	$ 12,760,443	$ 19,410,443
	$ 6,700,000	$ 1,140,807	$ 11,165,357	$ 12,306,164	$ 19,006,164
	$ 6,800,000	$ 1,158,645	$ 9,716,063	$ 10,874,707	$ 17,674,707
	$ 6,900,000	$ 1,175,921	$ 8,698,859	$ 9,874,780	$ 16,774,780
	$ 7,000,000	$ 1,192,999	$ 7,928,378	$ 9,121,377	$ 16,121,377
	$ 7,500,000	$ 1,272,900	$ 5,941,736	$ 7,214,636	$ 14,714,636
Unconstrained optimum	**$ 7,812,283**	**$ 1,322,214**	**$ 5,697,650**	**$ 7,019,864**	**$ 14,832,146**

Second Research Context

- Invader is not yet established in an area, but invasion is inevitable
    - Natural spread of front is unstoppable
    - Sub-populations erupt ahead of the front due to human-assisted dispersal. These populations are manageable.
    - How much effort should be devoted to detecting sub-populations ahead of the main front?
- Example: gypsy moth ahead of the front

Current Range



European Gypsy Moth (Lymantria dispar) Quarantine

Legend

- 🟥 Entire County Quarantined prior to 2004
- 🟥 Portion of County Quarantined
- 🟪 Counties quarantined in 2004
- 🟨 Counties quarantined in 2005
- 🟦 Counties quarantined in 2006
- 🟫 Counties quarantined in 2007

Consult your State or Federal plant protection inspector or your county agent for assistance regarding exact areas under regulation and requirements for moving regulated articles.
For detailed information see 7 CFR 301.45 for quarantine and regulation.

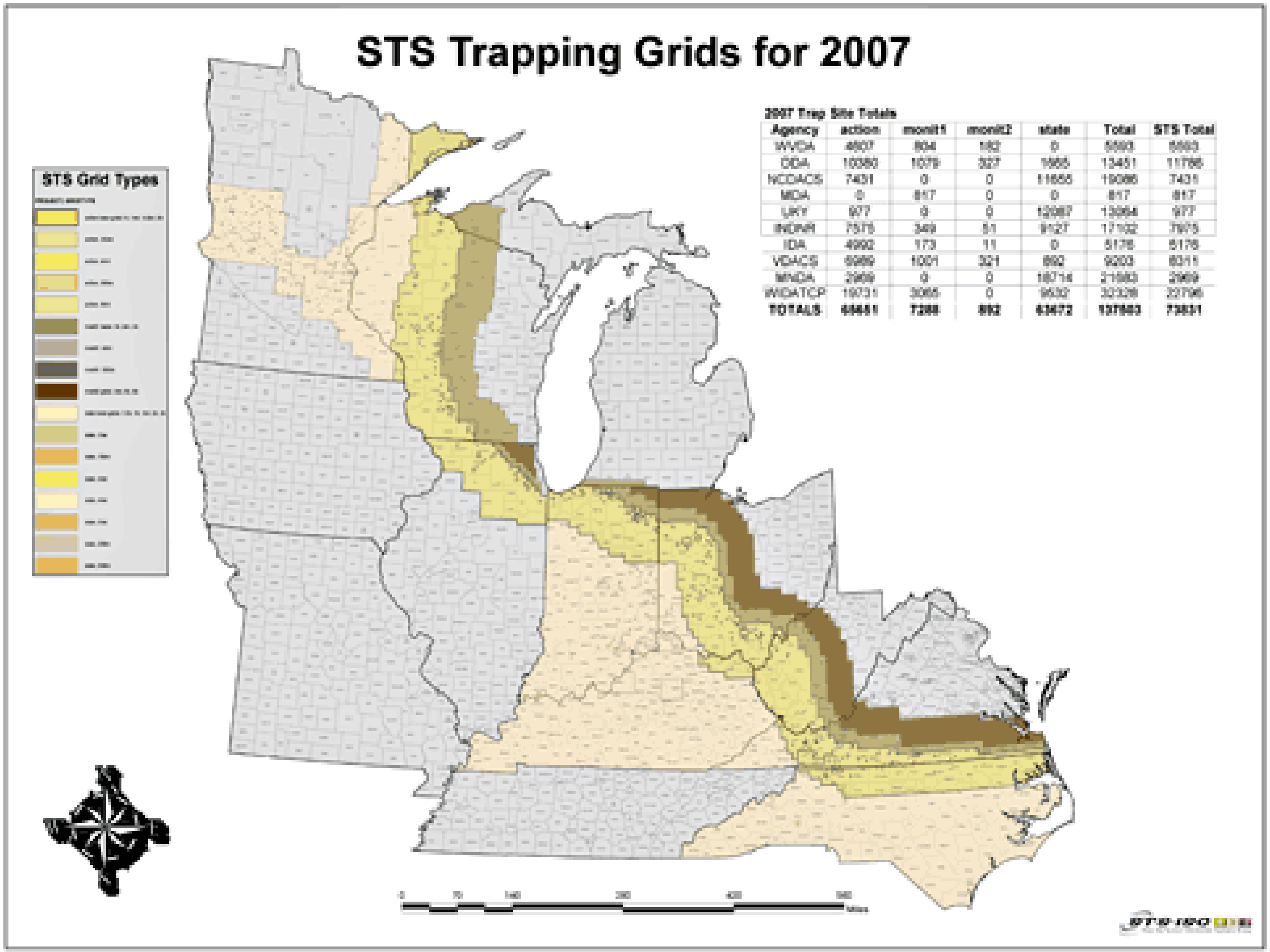
Restrictions are imposed on the movement of the regulated articles from the quarantined areas into or through areas outside of the quarantine

Apr 20, 2007

United States Department of Agriculture - Animal and Plant Health Inspection Service

http://www.aphis.usda.gov/ppq/maps/gypmoth.pdf

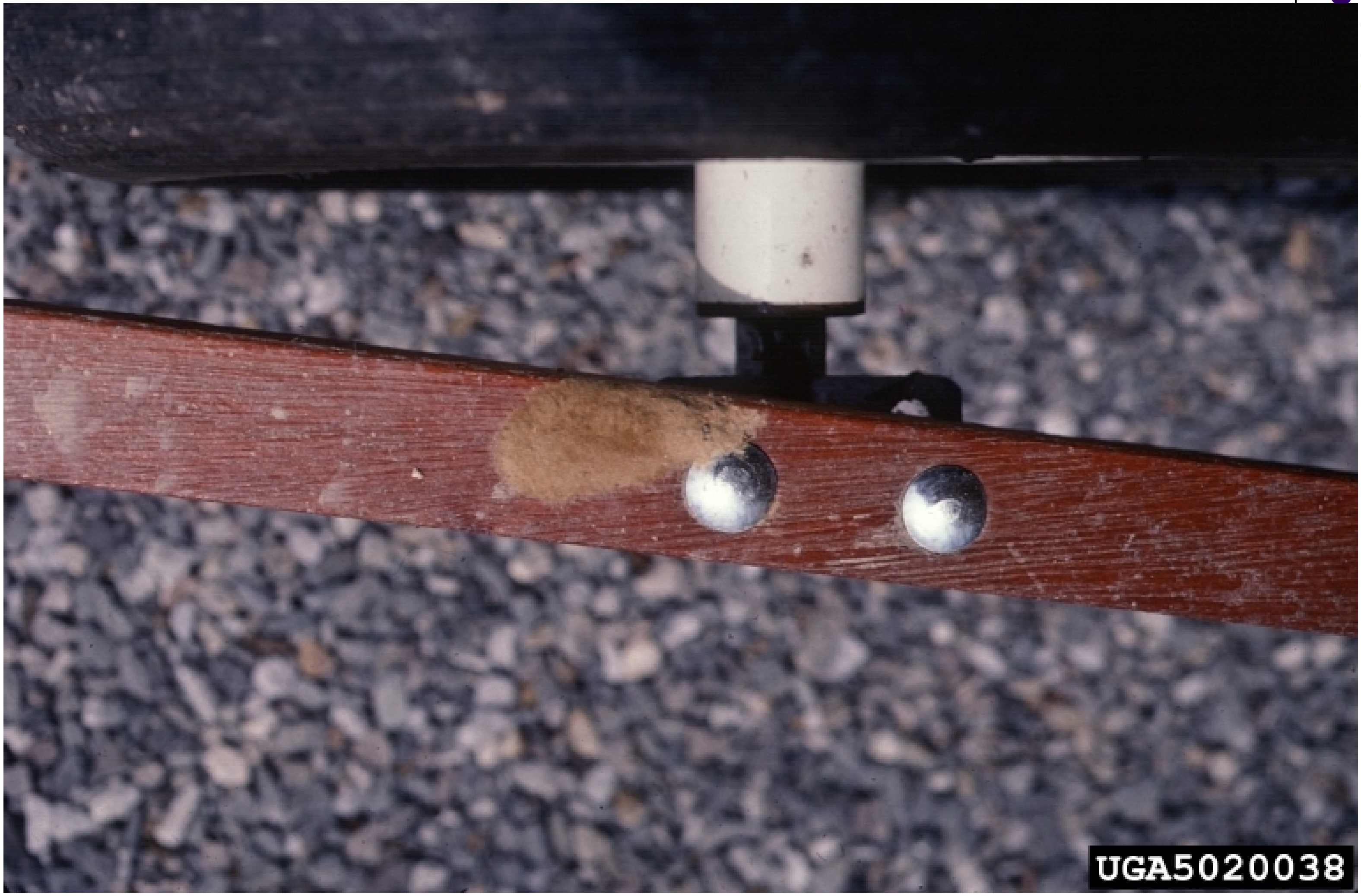
Slow the Spread of the Gypsy Moth Project
http://www.gmsts.org/operations/maps/



2007 Trap Site Totals

Agency	action	monit1	monit2	state	Total	STS Total
WVDA	4607	804	182	0	5593	5593
ODA	10380	1079	327	1665	13451	11786
NCDACS	7431	0	0	11655	19086	7431
MDA	0	817	0	0	817	817
UKY	977	0	0	12087	13064	977
INDNR	7575	349	51	9127	17102	7975
IDA	4992	173	11	0	5176	5176
VDACS	6989	1001	321	892	9203	8311
MNDA	2969	0	0	18714	21683	2969
WIDATCP	19731	3065	0	9532	32328	22796
TOTALS	**65651**	**7288**	**892**	**63672**	**137503**	**73831**

Human-assisted dispersal



Pennsylvania Department of Conservation and Natural Resources - Forestry Archives, Pennsylvania

Department of Conservation and Natural Resources, Bugwood.org

Literature: spatial distribution of trap density

- Sharov, Liebhold, Roberts, *Journal of Economic Entomology*, 1998
  - Optimal density of traps beyond the population front
  - Probability of eradication of small populations is equal to the probability of detection, which depends on the density of traps
  - Result – higher intensity of traps near the front is optimal
  - Focus on slowing the spread due to natural dispersal: range of possible locations of sub-populations is limited.

Optimal control of sub-population

- Sub-populations emerge beyond front—manage the population once you detect it. Detection at τ.
  - Derive optimal value function from:
    - min $$\int_{\tau}^{T} e^{-r(t-\tau)}\left(px(t)+cR(t)^{2}\right)dt$$
    - Subject to:

$$\dot{x}=ax-R, x(\tau)=x_{\tau}, T\leq T_{\max}, x(T)\geq 0$$

    - Get:

$$V(x_{\tau},(T-\tau))=\int_{\tau}^{T} e^{-r(t-\tau)}\left(px^{*}(t)+cR^{*}(t)^{2}\right)dt$$

Model of detection

- Value function $V(x(\tau),T-\tau)$
  - Cost is increasing in both arguments
- Search determines the date that the population is detected
  - Detection rate: (prob $(t=\tau)=kse^{(-ks\tau)}$)
  - Expected date of detection, $E(\tau)=1/(k\ s)$
  - k: detectability, s: search

Objective Function

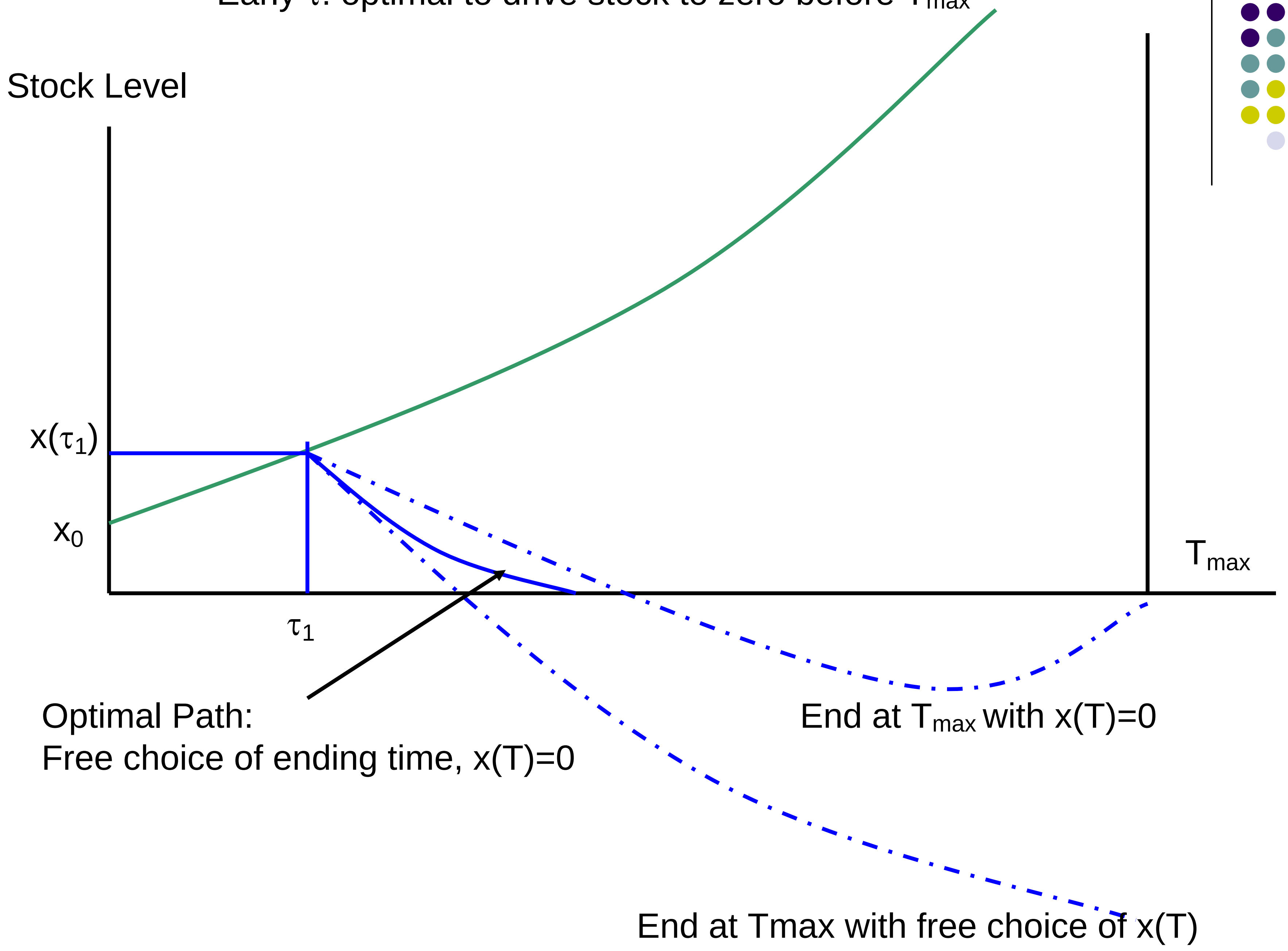
- Total Cost with Search (TCS)
  - Search cost = $bs^2(1-e^{-r\tau(s)})$
  - Damage before detection = $p^*x_0(e^{(a-r)\tau(s)}-1)$
  - Optimized cost after detection

    $= e^{-r\tau}V(x(\tau(s)),T-\tau(s))$
- Search enters through date of detection, τ.
- Minimize total costs with respect to s.

Solution Procedure

- Given T_{max}
- Given search level, and corresponding τ:
  - Find optimal removal path and value function.
  - For example:

Early τ: optimal to drive stock to zero before T_{max}



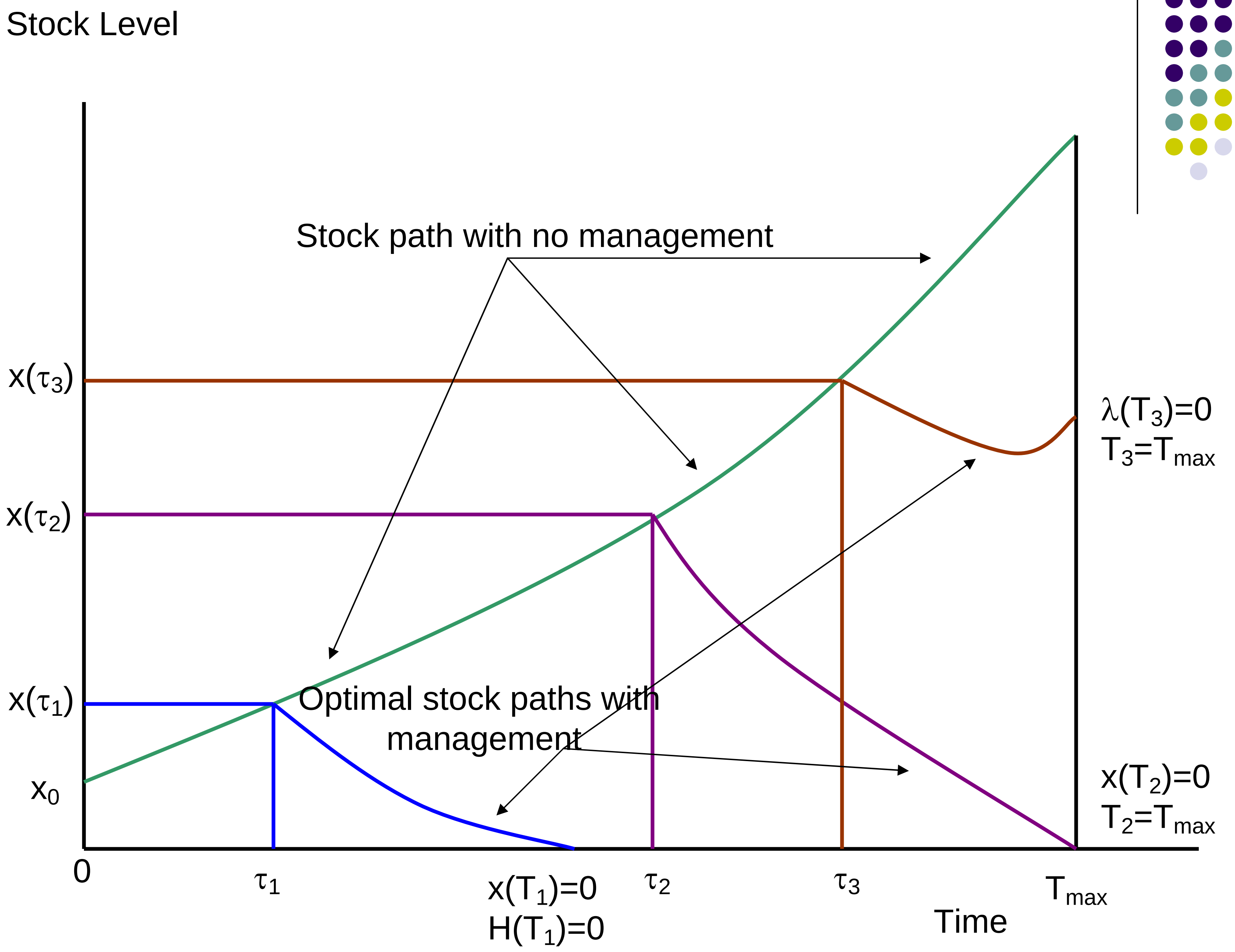
Optimal Path:
Free choice of ending time, $x(T)=0$

End at T_{max} with $x(T)=0$

End at Tmax with free choice of $x(T)$

Solution Procedure, continued

- Find optimal removal paths and value functions for each search level greater than $1/(kT_{max})$. This constraint ensures that the date of detection is before the front arrives ($\tau < T_{max}$).



Stock path with no management

Optimal stock paths with management

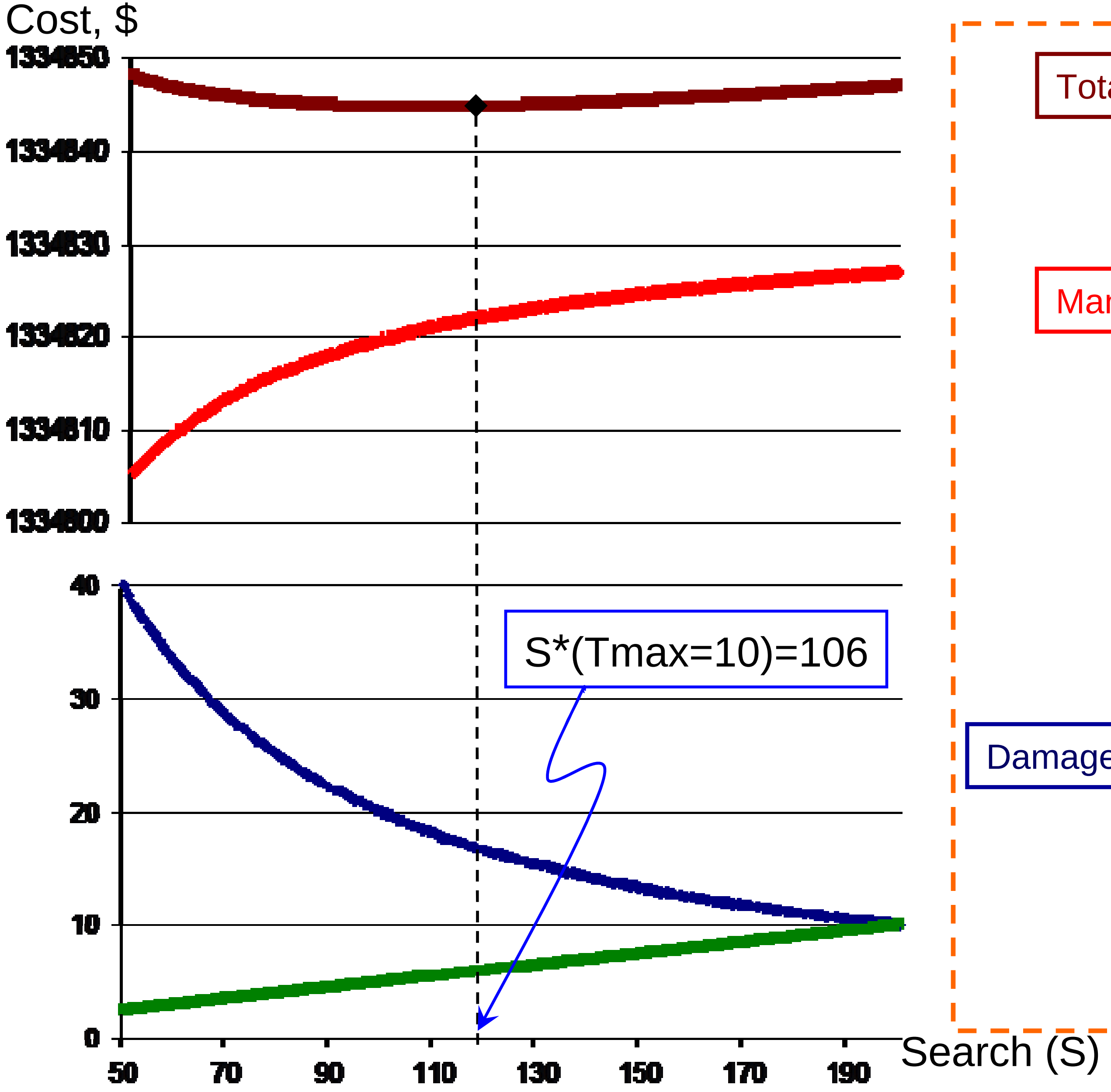
Solution Procedure, continued

- For each search level, calculate the sum of search costs, damage costs before detection, and optimized costs after detection.
- Find the search level that minimizes these costs.
- Repeat for different levels of T_{max} to see how optimal search varies over space.

Parameter Values

Parameter	Value
Growth rate, a	0.04
Cost of detection, b	5
Cost of treatment, c	1000
Discount rate, δ	0.1
Damages, p	2000
Starting stock level, x_0	100
Detectability, k	100

Example when ending date=10



S*(Tmax=10)=106

Total Costs (Tmax=10)

=

Management Cost (Tmax=10)

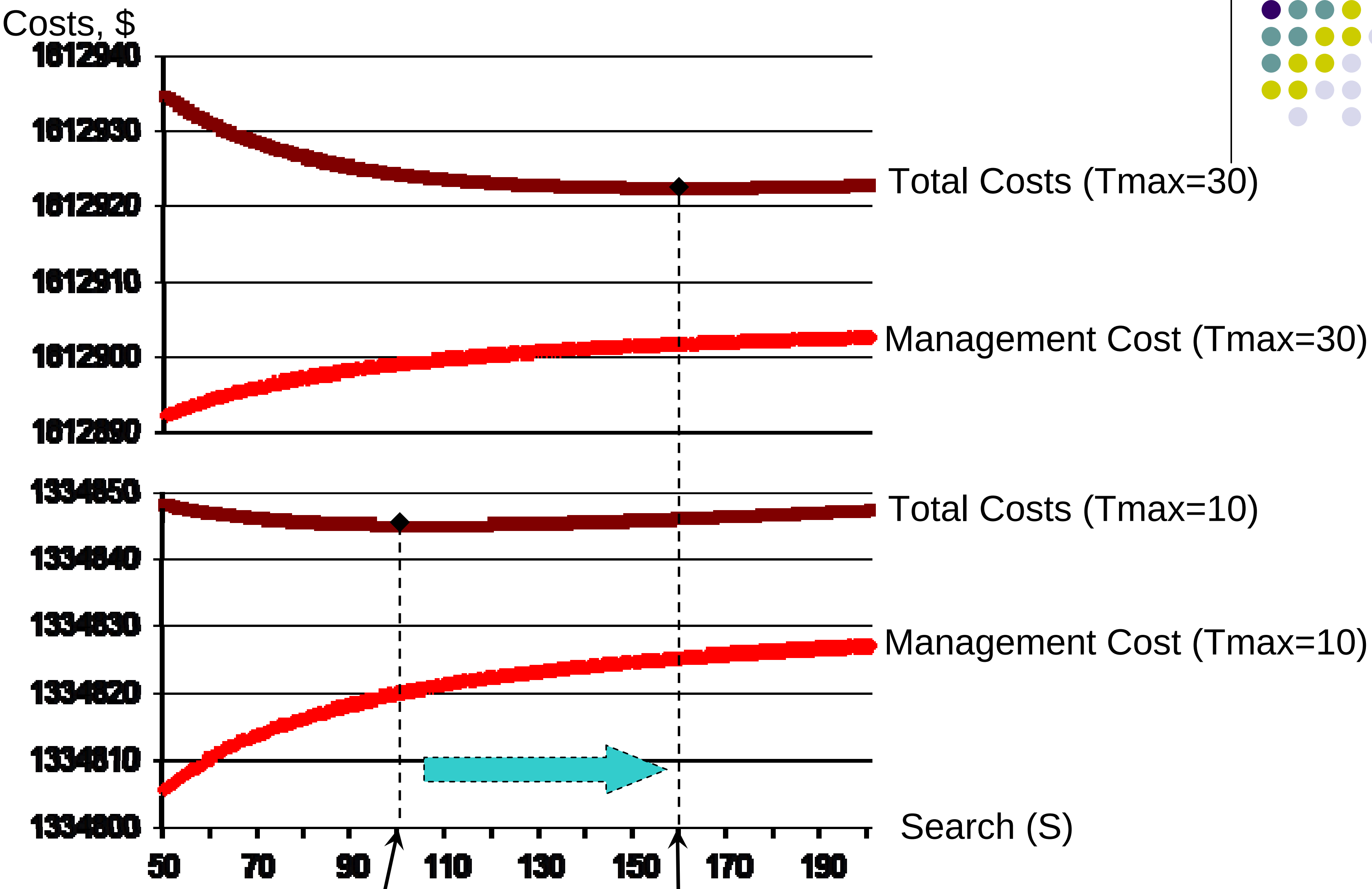
+

Damage before Detection (Tmax=10)

+

Search costs

Result 1: Optimal search levels increase with distance from the front.

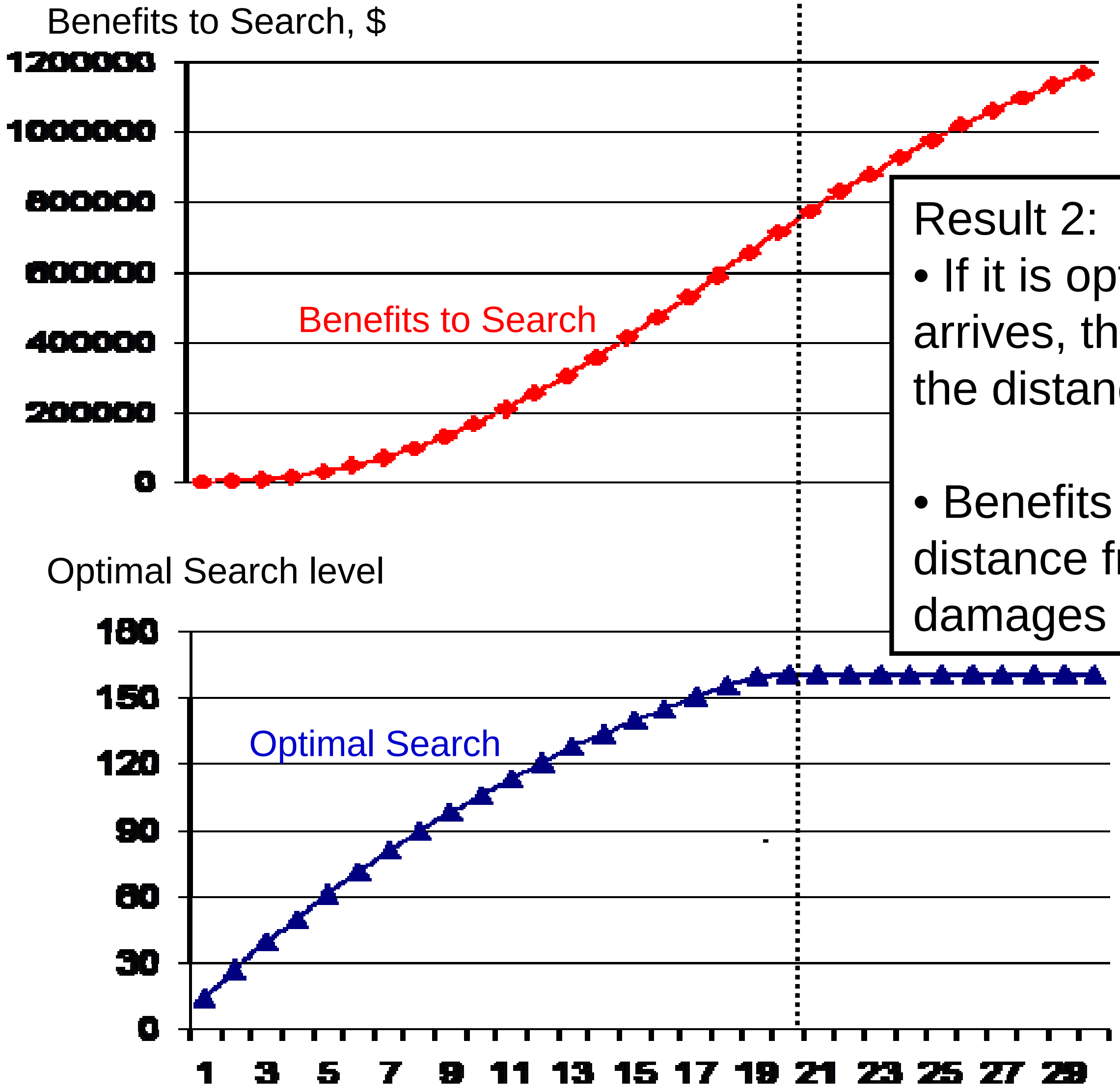


S*(Tmax=30)=106

S*(Tmax=30)=161

Suppression is Optimal

Eradication is Optimal



Result 2:

- If it is optimal to eradicate before the front arrives, the search level will be invariant to the distance from the front.

- Benefits to search will increase with distance from the front, as avoided damages are higher.

Benefits to Search
= (Damage costs if search is zero)
- (Costs with optimized search level)

Conclusions

- Optimal management depends on where you are relative to the front
- Optimal search strategy depends on optimal management upon detection
- Future work
  - Incorporate optimal determination of the rate of natural spread
  - Incorporate alternative starting stock levels at different distances from the front

Summary Remarks

- First model
  - Continuous random arrival of the pest, exponential growth
  - Monitoring of “sentinel trees”
  - Detection triggers local eradication
  - Results for a heterogeneous landscape
    - Overall cost minimization strategy
    - Budget constrained optimization across landscape

Summary Remarks

- Second Model
  - Sub-populations are established and grow ahead of the front
  - Management commences once detection occurs
  - Higher detection effort leads to earlier detection, implying a smaller population upon detection
  - Optimal detection and optimal management strategy depends on distance from the front because the ending date, T, depends on how long it takes the front to arrive.