Early Warning System for Douglas-Fir Tussock Moth Outbreaks in the Western United States

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ABSTRACT: *The Early Warning System is a pheromone-based trapping system used to detect outbreaks of Douglas-fir tussock moth (DFTM,* Orgyia pseudotsugata*) in the western United States. Millions of acres are susceptible to DFTM defoliation, but Early Warning System monitoring focuses attention only on the relatively limited areas where outbreaks may be developing. During 20+ years of monitoring, the Early Warning System provided warnings of 1–3 years for seven of nine outbreaks. No warnings were provided for two outbreaks because of inadequate density and distribution of Early Warning System plots in those specific areas. Plots should be evenly distributed over host-type forests at a density of at least 1 Early Warning System plot per 3,000 ac. After potential outbreaks have been identified by the Early Warning System, ground sampling for egg masses and larvae is necessary to characterize local DFTM populations. West. J. Appl. For. 19(4):232–241.*

Key Words: Orgyia pseudotsugata, pheromones, trap-catches, defoliation, tussock moths.

The Douglas-fir tussock moth, *Orgyia pseudotsugata* (DFTM), is a severe defoliator of Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and true firs (*Abies* spp.) in the interior western United States and parts of the dry interior forests of southern British Columbia (Brookes et al. 1978).

NOTE Katharine A. Sheehan can be reached at (503) 808-2674; ksheehan@fs.fed.us. Our thanks go to the many people who have deployed, collected, and examined the quite sticky pheromone traps during the past 20+ years. We also thank our state and federal colleagues for implementing the Early Warning System for their agencies: Ladd Livingston and David Beckman (Idaho Department of Lands); Dave Overhulser (Oregon Department of Forestry); Karen Ripley, Bob Backman, Rick Johnsey, and David McComb (Washington Department of Natural Resources); Richard Hunt, Stephen Jones, Jose Medina, Don Owen, Jess Rios, and Frank Spandler (California Department of Forestry and Fire Protection); Steve Kohler (Montana Department of Natural Resources); Dan Marlatt (Bureau of Land Management); and Phil Mocettini, Leon Pettinger, Iral Ragenovich, Carol Randall, Bill Schaupp, Sheri Smith, Nancy Sturdevant, Ralph Thier, Julie Weatherby, and Jill Wilson (USDA Forest Service). An earlier version of this manuscript was reviewed by Mike Johnson (private entomologist), Dave Overhulser (Oregon Department of Forestry), Don Owen (California Department of Forestry and Fire Protection), Carol Randall (USDA Forest Service), Karen Ripley (Washington Department of Natural Resources), and Darrell Ross (Oregon State University).

DFTM populations can increase rapidly, leading to outbreaks that occur with little or no warning. Defoliation may cause top-kill, loss of increment growth, direct tree mortality, and indirect mortality due to increased susceptibility of defoliated trees to bark beetle attack. In addition to the loss of timber, DFTM also causes increased risk of wildfire due to increased fuels and fuel ladders, increased stream runoff and other hydrologic impacts that could influence fish habitat, and changes in vegetation structure that could influence the quality of wildlife habitat. DFTM larval hairs also may cause severe allergic responses for some people and domestic animals. This can be a significant problem when DFTM outbreaks occur near campgrounds or other forest sites frequented by the public.

Effective management to mitigate undesirable impacts of DFTM outbreaks is difficult because of the abrupt nature of outbreak occurrence. Aerial surveys are helpful in detecting defoliation; however, in the case of DFTM, aerial detection usually occurs after the outbreak is in progress and substantial defoliation has already taken place. Tussock moth populations also have a strong tendency to aggregate (Shepherd et al. 1985, Mason 1996) due in part to the flightless nature of adult females, so locating increasing populations on a landscape by using traditional ground-based sampling techniques requires intensive fieldwork.

The identification of the sex attractant pheromone for DFTM (Smith et al. 1975) led to the development of a system for monitoring DFTM population changes by tracking the number of flying male moths caught annually in pheromone-baited traps (Daterman et al. 1979). These traps survey a much larger area than ground-based sampling of less mobile life stages; for example, pheromone traps have caught substantial numbers of male moths in areas devoid of host trees and up to 2.5 miles distant from the nearest infestation (Daterman 1980).

Since 1979–1980, the Early Warning System, based on standardized pheromone-baited traps, has been used in most western states. The objective of this monitoring system is to identify areas with increasing DFTM populations 1–2 years prior to visible defoliation, thus providing an early warning that allows forest managers to focus on areas where DFTM populations are building toward outbreak densities (Daterman et al. 1979). This article evaluates the effectiveness of the Early Warning System based on case studies of outbreaks that occurred in Oregon, Washington, California, and Idaho from 1979 to 2001. Recommendations for improving the Early Warning System also are presented.

Methods

About 800 Early Warning System plots are currently maintained throughout host forests of Arizona, California, Colorado, Idaho, Montana, Oregon, Utah, and Washington (Table 1). See Daterman et al. (1979) for a more detailed description of the Early Warning System, which is summarized below.

Each Early Warning System plot has five traps placed along a line at 75-ft intervals (and at least 75-ft away from roads) in stands with DFTM host trees. Traps are placed near the ends of branches about 6 ft above ground on relatively open-grown host trees. Each trap is a modified half-gallon milk carton cut to a delta-shape with interiors lined with adhesive; within the trap, a small pellet containing the synthetic pheromone is suspended above the adhesive via a long pin. Traps are set out by state and federal cooperators from late July to mid-Aug. and picked up in mid-Oct. to early Nov. of each year.

Plots averaging 25 or more moths per trap signal DFTM populations potentially capable of causing visible defoliation within 1–2 years (Daterman et al. 1979, Shepherd et al. 1985). Once trap captures reach these threshold levels, ground sampling for larvae or egg masses in the general area of the plot becomes necessary to locate the infestation more precisely and evaluate its status.

Annual trap catches, plot locations, and annual defoliation maps were provided by USDA Forest Service cooperators from the Intermountain, Northern, Pacific Northwest, Pacific Southwest, Rocky Mountain, and Southwestern Regions, other federal agencies (Bureau of Land Management, Bureau of Indian Affairs), and by state and private cooperators from California, Idaho, Montana, Oregon, and Washington. A downloadable database containing the annual trap catches and plot locations is available on the USDA Forest Service, Pacific Northwest Region, Forest Health Protection website (www.fs.fed.us/r6/nr/fid/data.shtml#dftm, Dec. 2, 2002).

Through case studies of specific outbreaks, we examined the relationship between the pattern of annual number of moths caught per plot (or per group of plots) and outbreak timing and spatial location (Table 1, Figure 1). For this article, an outbreak is defined as those years when DFTM populations cause defoliation visible from the air over specific geographic areas. Data were also pooled across outbreaks to examine the relation between numbers of moths caught in individual plots during the years of outbreak initiation (defined as the first 2 years of an outbreak in a geographic subregion plus the 2 prior years) and subsequent defoliation.

Results and Discussion

Individual Plots

From 1979 to 2001, trap catches were reported for 4,332 plot-years during outbreak initiation years and for 8,958 plot-years during nonoutbreak initiation years. About 15.2% of the outbreak initiation plot-years exceeded the 25-moth threshold, while 3.4% exceeded the threshold in nonoutbreak initiation plot-years. The large proportion of traps that remained below threshold during outbreak years reflects the highly aggregated distribution of DFTM populations (Shepherd et al. 1985, Mason 1996).

Table 1. Number of DFTM Early Warning System plots maintained annually, by state.

State	Years covered	Mean no. plots/yr (all years[a])	Mean no. plots/yr (1991–2000[a])	Maximum no. plots	Minimum no. plots
Arizona	1992–2000	9.8	9.8	15	6
California	1980–2000	126.9	155.6	183	65
Colorado	1986–1999[b]	33.4	8.8	60	7
Idaho	1979–2000	128.9	186.4	200	12
Montana	1979–2000	28.9	32.9	33	8
Nevada	1991–2000	6.6	6.6	10	5
Oregon	1979–2000	188.3	179.4	343	48
Utah	1991–2000	6.6	6.6	7	5
Washington	1980–2000	188.2	223.7	319	53
	Sum of mean plots:	717.6	809.8		

[a] Excludes years when no plots were monitored.
[b] Plots were not monitored from 1991 through 1994.

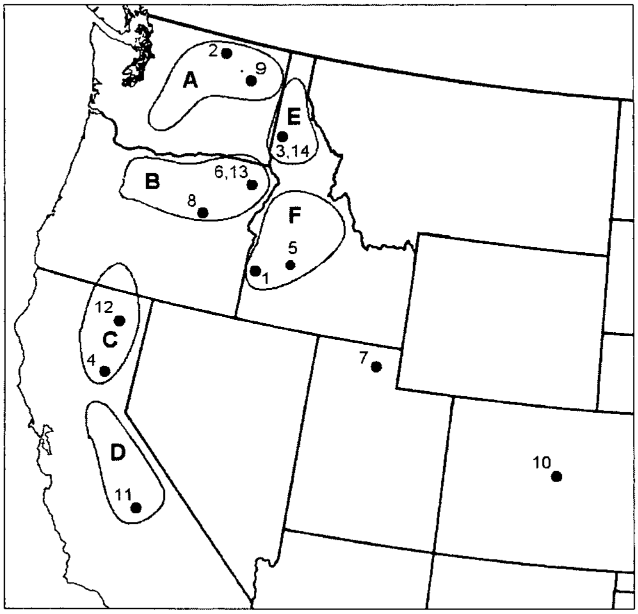

Figure 1. Geographic distribution of subregions in the western United States: A, northeastern and central Washington; B, Blue Mountains and central Oregon; C, South central Oregon and northern California; D, central California; E, northern Idaho; and F, southern Idaho. Dots indicate general locations of outbreaks as numbered in Table 2.

Several factors should be taken into account when interpreting individual plot catch results. First, consider the time elapsed since the last outbreak occurred in the general area. Because outbreaks tend to occur at 7- to 14-year intervals (Shepherd et al. 1988, see also Figure 2), high trap catches toward the end of this interval may be more indicative of an impending outbreak than high catches earlier in the interval.

Second, the history of catches for a particular plot or small number of plots may be useful. Some plots may prove to be consistent predictors of impending outbreaks, while others may consistently yield above-threshold catches that are not followed by outbreaks, and still others may always capture low numbers of moths even during outbreak years. Plots that have been monitored during several outbreaks should be evaluated in the context of their historical relation to outbreaks, with some considered for relocation depending on their demonstrated utility for outbreak prediction.

Finally, both the general trend in plot catches and the distribution and density of plots in the area should be considered when interpreting results from an individual or small number of plots. Depending on individual plot history, high catches in one or very few plots may not be significant if other plots in the general area do not exhibit similar increasing trends.

Geographic Subregions

Interpreting trapping results in the context of geographic subregions may provide additional predictive capability that complements individual plot histories. Figure 2 displays mean annual trap catches for all monitoring plots grouped within six different geographic subregions. Note that mean trap catch numbers are generally lower for these broad-scale illustrations of DFTM populations than is the case for finer spatial scales in which monitoring traps were all in closer proximity to a developing outbreak (Figure 3). In most geographic subregions, trap catches generally increased at 7- to 14-year intervals, and remained quite low during the intervening years. DFTM populations in South central Oregon and northeastern California (Figure 2, group C) exhibited somewhat more irregular cycles. In most cases, defoliation occurred somewhere within the subregion soon after threshold trap captures were recorded. These findings support previous reports that DFTM outbreaks occurred at intervals of 8 to 14 years in British Columbia (Shepherd and Otvos 1986), and that DFTM population cycles throughout western North America averaged 9 years between peaks (Shepherd et al. 1988).

For most outbreaks, pheromone trap catches progressively increased for 1–3 years prior to defoliation then declined during the peak years of high population levels and defoliation. During peak population years, the correspondingly high amounts of pheromone emitted by the numerous females may overwhelm the relatively small amounts of pheromone present in the traps. In addition, the pheromone produced by female tussock moths has at least two components and is inherently more attractive to male moths than the single component used in the pheromone traps (Gries et al. 1997). At high population levels, most male moths would be attracted to females rather than the traps. The timing of tussock moth mortality may also contribute to the trap catch decline in years of heavy defoliation. In the latter stages of an outbreak, high initial populations of eggs and larvae often decline rapidly due to natural factors including a disease caused by a nucleopolyhedrosis virus, thus leaving relatively few adults to be captured in monitoring traps during the late summer and fall of that same year.

Outbreak Case Studies

From 1979 through 2000, 14 DFTM outbreaks have occurred in the western United States (Table 2, Figure 1). For the 10 outbreaks reviewed below, the Early Warning System was installed in the general area prior to the outbreak. An additional outbreak that was detected early even though the nearest traps were about 60 miles away (the Sequoia/Kings Canyon National Parks outbreak of 1997–1999) also is reviewed. See the Early Warning System website on the USDA Forest Service, Pacific Northwest Region, Forest Health Protection website (www.fs.fed.us/r6/nr/fid/dftmweb/ews/; Dec. 2, 2002) for more details on each case study.

Owyhee Mountains, Idaho (1981–1983)

Two plots in the Owyhee Mountains of southern Idaho were monitored in 1980 (mean = 27.8 moths per trap), and three plots were monitored in 1981 (mean = 44.9 moths per trap). The Early Warning System was then discontinued until 1984. Approximately 160 ac of defoliation were recorded during the 1981 aerial survey, followed by ~4,000 ac of defoliation in 1982 and a peak of ~14,200 ac defoliated in 1983. Although the trap catch record is limited for this outbreak, trap catches were elevated starting at least 1

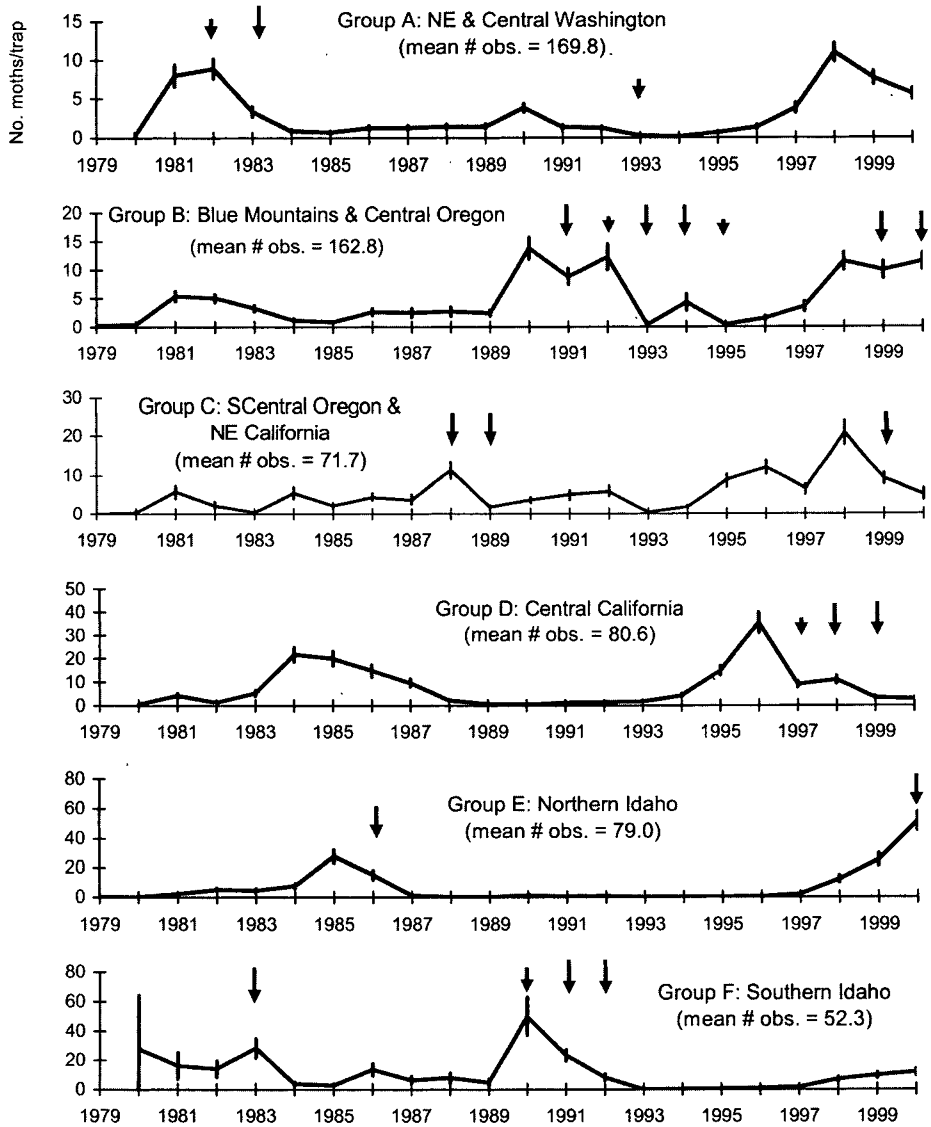

Figure 2. Annual mean trap catches by geographic subregions. Vertical arrows indicate years when defoliation by DFTM was detected during aerial surveys, and the length of those arrows reflects the relative amount of defoliation within a given outbreak. For Group B, defoliation during 1991–1995 occurred in two distinct areas: in the Pine Ranger District in 1991, and near Burns, OR in 1992–95. The y-axis scales vary to facilitate comparison of the relative trend in trap catches.

year prior to the first year of defoliation and 3 years before the peak of defoliation.

Northeastern Washington (1982–1983)

About 3,000 ac were defoliated in northeastern Washington in 1982, and 17,000 ac were defoliated in 1983. Early Warning System plots were established in the general area of this outbreak in 1981. For plots in or within 1 mile of the defoliated area, elevated trap catches were observed 1 year prior to the first year of defoliation and 2 years prior to peak defoliation (Figure 3).

Northern Idaho-1 (1986)

Trap catches near Potlatch in northern Idaho increased from 1983 through 1985 (Figure 3). Acting on this early warning, State of Idaho pest managers conducted additional sampling to delineate areas likely to be heavily defoliated and to plan a suppression treatment for 1986. Approximately 1,930 ac were sprayed in 1986 with a nucleopolyhedrosis virus. Scheduled spraying of additional acreage was cancelled due to a widespread decline in DFTM populations caused by natural mortality factors during the egg mass stage. Approximately 3,400 ac were defoliated in 1986.

Plumas-Lassen National Forests (1987–1989)

This northeastern California outbreak resulted in 105,000 ac of defoliation at its peak in 1988–1989. This outbreak was first detected by aerial observation of defoliation in several discrete areas ranging from about 25 to 200 ac that totaled approximately 7,500 ac. Some of the defoliated areas had no record of previous defoliation by tussock moth. Only three Early Warning System plots were located in or

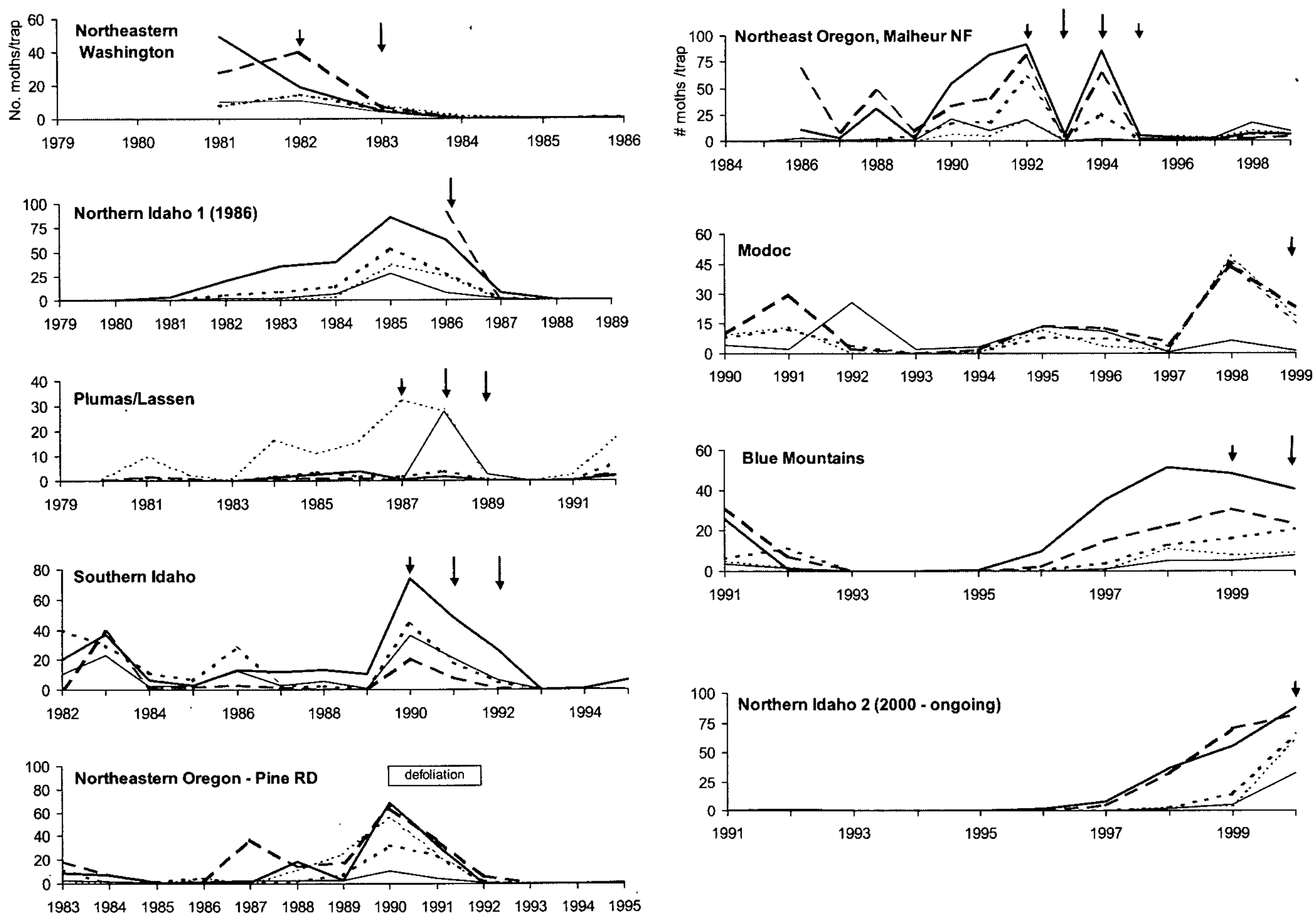

Figure 3. Trap catches for nine DFTM outbreaks, categorized by distance from the defoliated area. Thick solid lines, within the defoliated area; thick long dashes, 0.1–1.0 mi from the defoliated area; thick short dashes, 1.1–5 mi from the defoliated area; thin short dashes, 5.1–10 mi from the defoliated area; and thin solid lines, greater than 10 mi from the defoliated area.

near the affected area, and those were all near the extreme northern edge. Other plots were located 2.5, 5.5, and 7.0 miles away from the defoliated area. Only the trap locations 5.5 and 7.0 mi distant provided any indication of increasing DFTM populations (Figure 3), presumably because local wind conditions were not favorable for moving male moths, either passively or actively, to the vicinity of the few trap locations located near the northern edge of the affected area, whereas air movement was favorable for moving male moths into proximity of the more distant trap locations that captured significant numbers. Even distribution of additional monitoring plots over the affected area might have provided more timely information of the impending outbreak.

Southern Idaho (1990–1992)

This outbreak appeared suddenly, with ~51,000 ac of defoliation first detected in 1990 (including 35% recorded as heavy defoliation). By 1992, 418,000 ac had been defoliated on the Boise, Payette, and Sawtooth National Forests and in the Owyhee Mountains. Only three plots were located within the area of initial defoliation (~17,000 ac per plot). Trap catches rose sharply in 1990 (Figure 3), providing no warning for the initial 1990 defoliation but 1–2 years warning for the majority of the defoliation in this outbreak. As in the prior example, too few monitoring plots inadequately distributed over the affected area run the risk of missing the opportunity for early prediction.

Northeast Oregon—Pine Ranger District (1990–1992)

DFTM activity was noted on the Pine Ranger District of the Wallowa-Whitman National Forest in 1990 through 1992, and trap catches peaked in 1990 (Figure 3). Both aerial and ground estimates of defoliation by DFTM were impaired by concurrent heavy defoliation caused by western spruce budworm (*Choristoneura occidentalis*). Approximately 116,000 ac were treated with a microbial insecticide (*Bacillus thuringiensis* var. *kurstaki*) in 1991 to reduce populations of both tussock moth and budworm. Because of the spray application and presence of a second defoliator species, the effectiveness of the Early Warning System cannot be evaluated for this outbreak.

Northeast Oregon—Malheur National Forest (1992–1995)

Trap catches increased dramatically in 1990 and 1991 (Figure 3), triggering larval sampling in 1992 through 1995 (see Mason et al. 1998 for a comprehensive case history of this outbreak). Trap catches continued to rise in 1992, when defoliation was first detected over ~6,600 ac. Most of the defoliation occurred in 1993 and 1994, 3 to 4 years after the

Table 2. Summary of recent Douglas-fir tussock moth outbreaks in the western United States.

No.	Outbreak name	State	Starting year[b]	Ending year[c]	Acres defoliated: Initial year	Acres defoliated: Maximum area	No. nearby plots[a]: Initial defoliation	No. nearby plots[a]: Maximum area	Plot density (ac/plot): Initial defoliation	Plot density (ac/plot): Maximum area
1	Owyhees	ID	1981	1983	160	14,200	1	2.5	160	5,680
2	NE Washington	WA	1982	1983	3,030	20,300	1.5	3.5	2,020	5,800
3	Northern Idaho-1	ID	1986	1986	3,390	3,390	3.7	3.7	916	916
4	Plumas/Lassen	CA	1987	1989	7,500	105,000	None	3.0	n/a	35,000
5	Southern Idaho	ID	1990	1992	50,800	418,000	3.0	10.0	16,933	41,800
6	NE Oregon-Pine RD	OR	1990	1992	w/wsb[d]	w/wsb[d]	n/a	n/a	n/a	n/a
7	Wasatch-Cache[e]	UT	1990	1992	2,900	4,900+(?)	None	None	n/a	n/a
8	NE Oregon-Malheur NF	OR	1992	1995	6,630	62,400	2.0	5.0	3,315	12,480
9	Keller's Ferry[e]	WA	1993	1993	278	278	None	None	n/a	n/a
10	Pike NF[e]	CO	1993	1995	250	6,100+(?)	None	None	n/a	n/a
11	Sequoia/Kings Cyn NPs[e]	CA	1997	1999	3,500	5,800	None	None	n/a	n/a
12	Modoc	CA	1999	1999	2,200	2,200	3.0	3.0	733	733
13	Blue Mountains	OR/WA	1999	2001	21,000	220,000	8.0	10.7	2,625	20,561
14	Northern Idaho-2	ID	2000	?[f]	54,700	n/a[f]	31.0	n/a[f]	1,765	n/a[f]

[a] Mean number of plots within 1 mi of the initial defoliated area for the 3 years prior to the starting year (exceptions: for outbreaks 1 and 2, the mean for the 2 years prior to the first year of the outbreak is listed).
[b] First year that defoliation was detected by aerial surveys. Sources: annual Forest Service insect and disease conditions reports and digital files; on file at Forest Health Protection, Natural Resources, Pacific Northwest Region, USDA Forest Service, P.O. Box 3623, Portland, OR 97208.
[c] Last year that defoliation was detected by aerial surveys.
[d] Defoliation by both tussock moth and western spruce budworm occurred in the same stands; aerial surveyors generally could not determine which insect was responsible for the observed defoliation.
[e] Early warning system not monitored within 10 mi of the defoliated area prior to these outbreaks.
[f] Outbreak ongoing at the time this manuscript was written.

initial increase in trap catches. Although trap catches commonly decrease after defoliation becomes evident, in this case, the numbers of captured males sharply decreased in 1993 but then increased again the following year. We cannot explain this apparent anomaly in trap data. Of most significance, however, was the early warning evidenced by high trap catches in 1990 and 1991, 2 years prior to visible defoliation.

Sequoia/Kings Canyon National Parks (1997–1999)

No plots were located within about 60 air miles of this outbreak; however, consistently increasing captures in 1995 and 1996 in distant pheromone traps within the central California geographic subregion (Figure 2D) played a role in its detection. Forest health specialists alerted forest managers in this subregion to watch for indications of tussock moth activity throughout the host type, particularly in areas of special concern to management. Forest workers observed late-instar larvae and light defoliation in late-July and Aug. 1997. In 1998, ~44,000 ac had at least light larval feeding injury (not always visible from the air), including 5,800 ac (13.2%) with moderate to heavy defoliation. Virus was found in about 22% of the larvae reared from 1998–1999 overwintering egg masses and populations collapsed due to natural factors, including virus, in 1999.

Modoc National Forest (1999)

Defoliation from this outbreak in northeastern California was detected from the air on 2,200 ac in 1999 (Table 2). All nine plots located near the outbreak recorded sharp increases in moth captures in 1998 (Figure 3), and eight of the nine plots exceeded the 25 moths per trap threshold. No new egg masses were found in the fall of 1999, and no additional defoliation occurred in 2000.

Blue Mountains (1999–2001)

Trap catches throughout much of the Blue Mountains of northeastern Oregon and southeastern Washington began increasing in 1997, and nearly all of those areas had elevated trap catches in 1998. Aerial surveyors observed ~21,000 ac of defoliation in the Blue Mountains in 1999 and 220,000 ac in 2000. Approximately 40,000 ac were treated with virus (TM BioControl-1) in 2000. Plots within 5 miles of the areas defoliated in 1999 showed elevated trap catches for at least 2 years prior to the defoliation (Figure 3).

Northern Idaho-2 (2000–in progress)

Approximately 54,700 ac were defoliated by DFTM in 2000 near Potlatch in northern Idaho (Randall 2001). Trap catches within 1 mi of the defoliated area began increasing in 1997 (Figure 3), averaging 34.6 moths per trap in 1998 and 61.8 moths per trap in 1999, thus providing a 2-year early warning of the impending outbreak that first became apparent in 2000.

Case History Summary

For one of the 10 outbreaks that occurred in areas where the Early Warning System was in place, the effectiveness of the system could not be evaluated because of the confounding influences of another defoliator and a suppression project (Northeastern Oregon—Pine Ranger District 1990–1992). For seven of the other nine outbreaks, trap catches provided early warnings of 1–3 years in advance of the occurrence of visible defoliation (Table 2, Figure 3). Trap catches averaging more than 25 moths per plot provided an early warning 1 year prior to defoliation on the Modoc National Forest 1999 and northeastern Washington 1982–1983 outbreaks, 2 years prior to defoliation for Owyhees 1981–1983, Malheur 1992–1995, Blue Mountains 1999–2000, and Northern Idaho-2 2,000+ outbreaks, and 3 years prior to defoliation for the Northern Idaho-1 1985–1986 outbreak. The early warning traps did not provide an alert for the remaining two outbreaks, Plumas/Lassen (1987–1989) and southern Idaho (1990–1992), presumably because of low plot density (Table 2) and inadequate distribution of the plots over the host type.

Factors Influencing System Efficacy

Plot Density and Distribution

For the seven case studies in which a 1- to 3-year early warning was provided, plot density based on initial year of defoliation averaged 1,648 ac per plot (range: 160–3,315 ac per plot) (Table 2). Plot densities based on maximum defoliation (total area defoliated during outbreak) for those seven outbreaks ranged from 733 to 20,561 ac per plot, with a mean of 7,695 ac per plot. Conversely, no early warning was provided in the two cases (Plumas/Lassen 1987–1989, and southern Idaho 1990–1992) where plot density was low: no plots or 17,000 ac per plot for the area of initial defoliation, and 35,000–41,800 ac per plot for the total area defoliated. Furthermore, in these two cases, the few plots present were clustered at one edge or within a limited section of the much larger areas that were subsequently defoliated.

The results of the case studies strongly suggest that areas selected for DFTM monitoring should be supplied with a plot density of at least one plot per 3,000 ac, based on acres defoliated in the initial year. This density is about one plot per five sections (5 mi^2) or about eight plots per township. Additionally, the plots should be distributed proportionately across the area to be monitored, and not clustered along edges or in a limited sector.

Selection of Areas to be Monitored

Most plots are located in areas with a recorded history of DFTM outbreaks. During the past two decades, however, two outbreaks have occurred in areas with little or no recorded history of DFTM outbreaks (Plumas-Lassen and Sequoia-Kings Canyon outbreaks, Table 2). In addition, the amount of DFTM-susceptible host type has increased over the last several decades due to past management practices and fire suppression (Wickman 1992, Hessburg et al. 1994, Campbell et al. 1996). Thus, while plots in areas with a known history of DFTM outbreaks should be maintained, plots also may be warranted in other areas of potential susceptibility.

In general, plots should be evenly distributed throughout the host type at a density of about 1 plot per 3,000 ac. Plot density might be increased for areas with high relative value in terms of stakeholder concerns and management objectives—that is, specific areas where the short- or long-term effects of defoliation might lead managers to realistically consider direct suppression. This criterion is relevant regardless of the recorded history of DFTM outbreak for a specific area and could be used as an initial screen to help determine the distribution of early warning plots. One approach would be to allocate a higher density of early warning plots on those lands for which natural resource managers assign a higher priority for protection, while meeting the minimum density and distribution guidelines on other lands.

Moth Capture Thresholds

The trap threshold of 25 moths per trap detects increasing, but suboutbreak, DFTM populations, thus triggering the need for follow-up ground sampling (Daterman et al. 1979, Shepherd et al. 1985). As shown in Figure 3, trap catch levels that signal an outbreak may vary for different outbreaks, but generally, traps in the outbreak area rise above the 25-moth threshold for 1–3 years prior to visible defoliation. A comparison of trap catch patterns within geographic subregions (Figure 2) with the occurrence of specific outbreaks within those subregions (Figure 3) demonstrates that increasing trap catches at the broader scale generally signal that an outbreak will soon occur somewhere within that subregion. Average trap numbers across the broader scale may not be large, however. For example, in the Blue Mountains and central Oregon (Group B, Figure 2), average trap catches for all plots reached only about 15 moths per trap during periods of outbreak. In the vicinity of the defoliated area within the subregion, however, average trap captures were well above the 25-moth per trap threshold for up to 3 years prior to defoliation (Figure 3, Northeastern Oregon—Malheur National Forest and Blue Mountains).

Due to within-plot and among-plot variation in trapped numbers of moths, the effective threshold will actually encompass a range of trap-catch levels, rather than the specific single value of 25 moths per trap. Shepherd et al. (1985), for example, reported that using six traps per plot would reflect a variation of plus or minus 30%, or a range of 17–33 moths per trap around an estimated threshold of 25 moths per trap. Because the Early Warning System uses five traps per plot, at the very least those plots averaging 17 moths per trap or more should be considered as potentially above the threshold.

Supplementary Plots

When faced with increasing trap catches, some managers have opted to install additional plots to temporarily supplement the information provided by the permanent plots. Although in some cases the Early Warning System triggered alerts up to 3 years prior to defoliation, in other situations the warning came only 1 year prior to defoliation. In the latter situation, a manager who waits 1 year pending the results from supplemental plots loses any timing benefits from the early warning. Supplemental plots do not replace the need for timely follow-up egg mass/ larval sampling. A more effective approach for improving early warning predictions of outbreaks would be to improve the density and distribution of permanent plots that are maintained annually.

Pheromone Components

The discovery of the new dienone pheromone component (Gries et al. 1997) raises the question of whether this new compound should be incorporated into the pheromone lures used in the Early Warning System. Addition of the

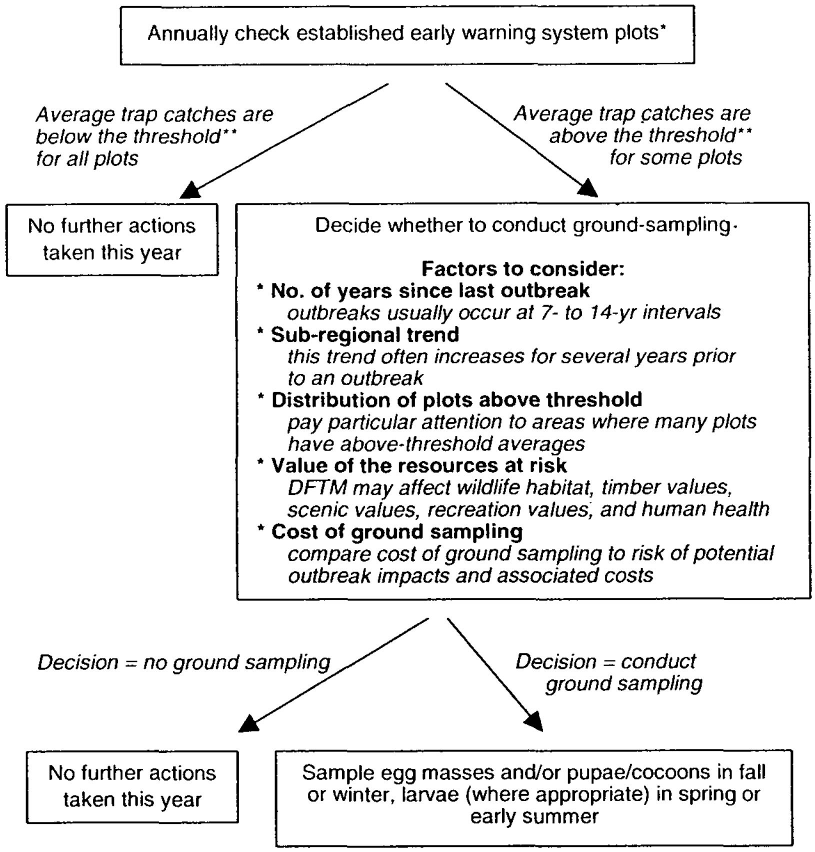

Figure 4. Overview of the use of the DFTM Early Warning System in conjunction with other monitoring tools. *Maintain at least 1 plot for every 3,000 ac, evenly distributed throughout host-type forests. **The individual trap threshold is 25 moths per trap, ±30%, so that any traps averaging >17 moths per trap should merit attention.

dienone component would significantly increase attractiveness (Gries et al. 1997), even at the lower release rates calibrated for the early warning trap lures. However, Early Warning System lures were intended to have relatively low attractiveness so that traps would not become saturated at lower DFTM densities. Significant changes in the attractiveness of the standard lure for the early warning monitoring traps would make meaningful comparisons with historic data difficult without extensive trap catch calibration studies. Furthermore, the case study results clearly show that the existing lure is effective for providing timely early warning of impending outbreaks when adequate numbers of plots are appropriately distributed across the areas selected for monitoring. Consequently, there appears to be no reason to incorporate the new compound into the monitoring trap lures.

Permanent Cocoon and Egg Mass Sampling Devices

Artificial shelters (often referred to as "cryptic shelters") have been developed as permanently installed sampling devices for collecting DFTM cocoons and egg masses (Dahlsten et al. 1992, Sower et al. 1990). Late instar DFTM larvae readily spin cocoons and pupate in these shelters. The egg masses deposited by the flightless adult females can then be counted to measure population density and collected to determine egg mass viability.

The Early Warning System may be augmented in specific high-value locations by use of these shelters. These passive sampling devices may provide site-specific indications of cocoon and egg mass densities as well as indications of associated natural enemy activity and other mortality factors. When maintained annually, the artificial shelters can give managers a timely, low-cost estimate of DFTM activity in high-value locations such as campgrounds or habitat for threatened or endangered species. If implemented on a plot, the artificial shelters may provide supplementary information on DFTM populations in the immediate area, in contrast to the information provided by the Early Warning System, which is representative of a much larger area.

Follow-up Ground Sampling

Follow-up ground sampling for DFTM pupae, cocoons, egg masses, and/or larvae is a labor-intensive and time-consuming activity necessary for obtaining more accurate site-specific population density and natural mortality information, and for delineating the outbreak areas (areas of potential defoliation). Several ground-sampling techniques are available (Dahlsten et al. 1992, Mason et al. 1993, Fettig et al. 2001). Because tussock moth populations are highly aggregated (Shepherd et al. 1985, Mason 1996) and the pheromone traps may contain moths originating from distances of up to 4 mi distant, (Daterman 1980, Shepherd et al. 1985), it is not uncommon for follow-up ground sampling to find low to very low DFTM population levels in the immediate area surrounding an Early Warning System plot with elevated trap catches. Consequently, to effectively assess the status of tussock moth populations, it is necessary to sample the general area (approximately 1- to 2-km radius) around plots and not just in the immediate area of the traps. It may also be appropriate to conduct initial ground sampling in areas of high management value, especially those near plots with elevated trap catches.

Conclusions and Recommendations

The Early Warning System has been used throughout the range of DFTM in the western United States for over 20 years. The system provided a 1–3 years early warning for seven of nine outbreaks in which pheromone plot data could be evaluated. The remaining two outbreaks might also have received timely warnings of impending outbreak had adequate numbers of monitoring plots been distributed over the affected areas. Once the early warning trapping system has alerted resource managers to the potential for DFTM outbreak, they can focus their attention on those limited areas where direct treatments may be warranted. Figure 4 summarizes key steps in the Early Warning System and follow-up ground sampling. Following are recommendations for applying the Early Warning System:

In most areas, permanent plots should be evenly distributed throughout host-type forests at a density of at least one plot for every 3,000 ac

Host-type includes forests with significant amounts of Douglas-fir or true firs, excluding coastal forests. Susceptible forests may include areas with no recorded history of DFTM defoliation. The recommended plot density can also be described as eight plots per township (36 mi^2).

Additional permanent plots may be warranted in high-value areas

As shown in the northern Idaho case studies, higher plot densities generally provide earlier alerts to potential defoliation. Additionally, establishing artificial shelters may be a cost-effective method for ground sampling pupae, cocoons, and/or egg masses in localized high-value areas.

Supplementary plots should not be used to augment permanent plots after the latter have indicated population increases

Past applications of such temporary, supplementary traps have resulted in less time to conduct ground sampling and plan management options. A better approach is to have a higher density of appropriately distributed permanent plots in areas of interest.

Rising trap catches should be evaluated in the context of several factors

First, consider the time elapsed since the last outbreak occurred, and be especially watchful if seven or more years have elapsed. Second, the subregional average catch levels associated with outbreaks may vary among subregions (Figure 2), so consider the historic subregional trends in numbers of moths caught in relation to subsequent outbreaks. Third, consider the distribution of those plots with trap catches above the 25-moth threshold, paying particular attention to those areas with many plots above the threshold; in addition, bear in mind that due to within- and among-plot variation, average trap catches of 17 moths or more should also initiate some concern. Fourth, the value of the resources at risk if heavy defoliation occurs should be balanced with the costs of ground sampling to measure DFTM populations in specific locations. For example, if the cost of ground sampling in a critical wildlife habitat area is minor compared to the change in habitat suitability that would follow if extensive tree mortality occurred, then managers may be more willing to conduct ground sampling—even though ground sampling may reveal low DFTM populations that are not likely to cause serious damage.

When localized trap catches in a geographic subregion rise above the 25-moth threshold, conduct ground sampling in areas of concern

Within a subregion with rising trap catches, the general location for an outbreak is signaled by individual plots with catches near or above the 25-moth threshold. If there are areas of concern to managers within that general area, ground sampling for larvae and egg masses (Mason 1979, Shepherd et al. 1985, Mason and Paul 1994, Mason et al. 1998) becomes necessary to locate patches of high DFTM populations. Ground sampling can be focused on specific locations such as campgrounds, parks, and administrative sites where high DFTM populations could be particularly damaging.

Millions of acres of western coniferous forests are at risk to DFTM outbreaks that may develop within a very short time. When plots are adequately distributed, the Early Warning System has been successful in identifying the relatively few areas where DFTM populations are increasing. Follow-up ground sampling is then needed to delineate and evaluate outbreak areas, thus providing information needed by managers to develop treatment options.

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