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FACTORS ASSOCIATED WITH WETWOOD INTENSITY OF *POPULUS FREMONTII* (FREMONT COTTONWOOD) IN ARIZONA

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ABSTRACT.—Wetwood is a condition of *Populus fremontii* and other tree species characterized by staining and water soaking in the heartwood, bleeding from wounds and stem junctions, and leaf and branch dieback. A field survey indicated that wetwood symptoms were present in populations of *Populus fremontii* at all 17 riparian sites surveyed in Arizona. However, incidence and severity of bleeding symptoms varied within and among sites. Within sites, incidence and severity increased with tree size. In the smallest size class of trees (1–32 cm dbh), incidence (% of trees with wetwood bleeding symptoms) ranged among sites from 14% to 83%, and mean severity ranged from 1.1 to 2.6 (on a 5-point scale). Closer host spacing (i.e., greater density), more homogeneous stand composition, finer substrate texture, and channel instability all were significantly correlated with increased expression of wetwood symptoms. Bleeding symptoms also were significantly correlated with canopy effects. As the severity of bleeding symptoms increased, so did canopy decline independent of changes in host density.

Key words: wetwood, Populus fremontii, *disease severity, riparian habitat, bacteria, canopy decline.*

Wetwood occurs in the heartwood of *Populus fremontii* Wats (Fremont cottonwood) and other tree species and is characterized by dark brown staining and infusion of water (Ward and Pong 1980, Murdoch and Campana 1981). High internal pressures develop in trees with internal wetwood symptoms resulting in the bleeding or "fluxing" of liquid from wounds and stem junctions. When contaminated with bacteria, yeasts, and other fungi, the liquid forms a fetid, foaming mass known as slime flux. Profuse bleeding can cause liquid to flow down bark, forming a light gray or white incrustation on the bark when dried. Branch dieback may occur, and the entire crown can decline over several years.

Several aerobic bacteria (Carter 1945, Teidemann et al. 1977, Murdoch and Campana 1983) or anaerobic bacteria (Shigo et al. 1971, Zeikus and Ward 1974, Zeikus and Henning 1975, Teidemann et al. 1977, Schink et al. 1981) have been associated with wood in trees with wetwood symptoms, but the pathogenicity of these bacterial isolates has not been proven. Some investigators have suggested that causes of wetwood are physiological and result in changes in wood that promote bacterial growth (Knutson 1973, Bauch et al. 1975, Teidemann et al. 1977, Ward and Pong 1980). Bacteria are directly involved in the production of external symptoms associated with internal wetwood symptoms (Rasmussen-Dykes and Jacobi 1995)

Regardless of causative factors, biotic and abiotic environmental conditions are known to influence the development of wetwood in tree species. Wetwood symptoms have been shown to increase with host age, but symptoms do occur in very young trees (Hartley et al. 1961, Ward and Pong 1980). In some cases moist or swampy sites are associated with high incidences of wetwood (Ward and Pong 1980). External wetwood symptoms have been associated with insect attacks (Hartley et al. 1961), stem cankers of dwarf mistletoe (Wilcox et al. 1973), and physical wounding including broken branches, pruning cuts, and systemic pesticide injection holes (Murdoch and Campana 1980, Ward and Pong 1980). Wetwood symptoms are prevalent in many ornamental shade trees including elm, cottonwood, aspen, and willow (Horne 1983, Rasmussen-Dykes and Jacobi 1995). In landscapes stress conditions including drought increase problems associated with wetwood (Rasmussen-Dykes and Jacobi 1995).

Populations of *P. fremontii*, a dominant tree species in riparian ecosystems of the U.S. Southwest, were observed with bleeding or fluxing

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symptoms and canopy dieback. Bleeding was observed from all woody plant parts including roots and the entire length of stems. Sources of bleeding included branch junctions, ends of broken limbs, insect bore holes, frost ribs, and other wounds of undetermined nature. Examination of cores from trunks of trees with these external symptoms revealed darkly discolored, water-soaked wood. The objectives of this investigation were to ascertain the extent of wetwood symptoms in *P. fremontii* populations in Arizona and to determine some host and environmental factors associated with high incidences and severity of wetwood symptoms.

MATERIALS AND METHODS

Wetwood Symptoms

We quantified severity and incidence of wetwood symptoms and extent of canopy dieback for *P. fremontii* at 17 riparian sites in Arizona (Fig. 1). Sites were chosen to encompass a range of environmental conditions in which *P. fremontii* occur. At sites with narrow riparian corridors, we randomly selected 50 *P. fremontii* trees. At sites with wide flood plains, the 50 trees were selected in stratified random fashion by dividing the flood plain into lateral strips of varying distances from the active channel. This insured the sampling of trees in the range of size classes present.

We used a 5-point scale (Table 1) to quantify severity of wetwood symptoms for each tree. Severity was assessed based on quantity and size of bleeding sources (including branch junctions, branch stubs, cracks, and other wounds) per tree. Bleeding sources were divided into minor and major sources based on size, flow rate, and presence of bark incrustation. The severity scale had greatest sensitivity at the low end of the scale and lost sensitivity at the top end in that all trees receiving a rank of 5 did not have equivalent amounts of wetwood symptoms. We defined incidence in a binary fashion based on presence or absence of wetwood symptoms. All trees scoring a rank of 1 on the severity scale were considered to be free of wetwood symptoms. Incidence was calculated as the percentage of trees with symptoms relative to the total sample of trees. These methods may underestimate incidence because not all individuals that show internal wetwood symptoms also express bleeding symptoms (Toole 1968). The percent of maximum canopy (PMC) present was estimated for each tree, taking into consideration the presence of broken, missing, or otherwise damaged limbs and trunks, branch dieback, and wilting. Maximum canopy was defined as the maximum canopy development that would occur under ideal growing conditions.

Host and Environmental Conditions

We measured each *P. fremontii* tree for trunk diameter at 1.5 m above ground level (dbh), distance (m) from the trunk to the edge of the nearest channel, and distance to the nearest adjacent *P. fremontii*. Because willows (*Salix* spp.) were observed also to have wetwood symptoms, we recorded distance to the nearest willow tree. Elevation (m) above the channel thalweg was estimated for each tree. Height of flooding debris was recorded as an indication of magnitude of the most recent flood (statewide flooding occurred in winter 1995). Each tree was inspected for the presence of wounds, mistletoe, tent caterpillars, and bark beetle damage.

For each site we visually characterized tree species composition as *P. fremontii* dominated, *P. fremontii–Salix* dominated, or "mixed" (vegetated by a mixture of *P. fremontii, Salix* sp., *Juniperus* sp., *Quercus* sp., *Platanus wrightii, Fraxinus* sp., and/or *Alnus* sp.). Surface flow frequency was characterized as either ephemeral or perennial, based on literature review, conversations with site managers, or review of USGS stream gage data. Channel morphology was described as either multichanneled (i.e., braided) or confined to a well-defined single channel; this variable was designated as channel stability. Predominant substrate particle size was visually classified as silt, sand, gravel, or cobbles. Information on site elevation (as a surrogate for site temperature) and stream gradient was obtained from topographical maps.

Statistical Analysis

Within sites, Pearson correlation analysis was used to examine the relationship of wetwood severity with tree size, distance to the stream channel and above the thalweg, and distance to nearest neighbors. Correlation analysis also was used to assess the relationship between individual severity of wetwood bleeding symptoms and dbh, using data pooled across sites.

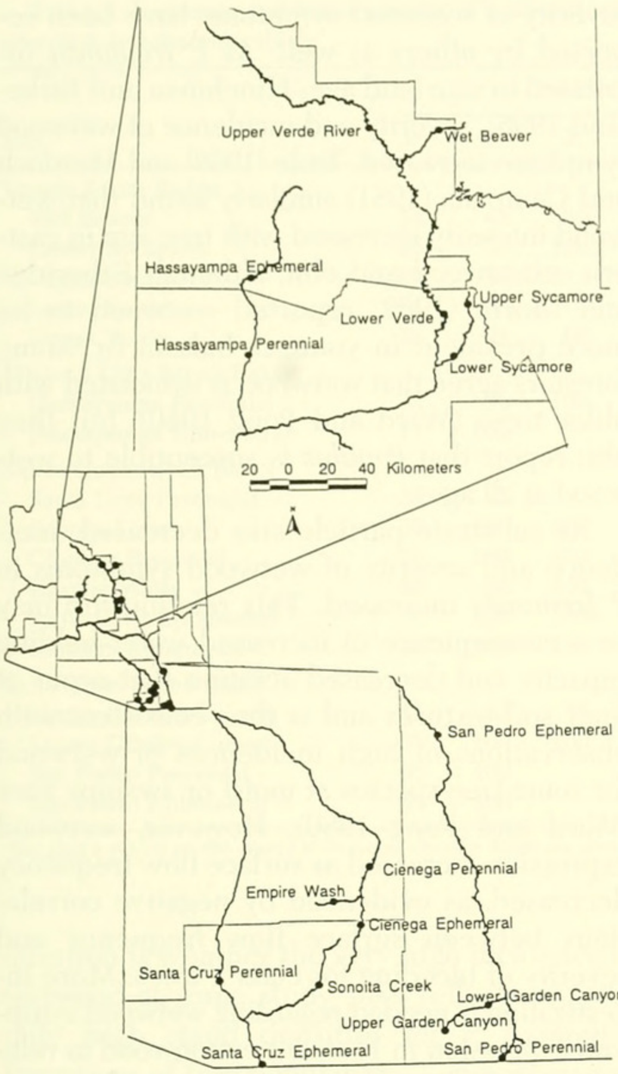

Fig. 1. Locations of the 17 study sites found in riparian areas in Arizona where wetwood incidence and severity were assessed.

To facilitate among-site analysis, we assigned trees to 1 of 6 size (dbh) classes (1–32 cm, 33–64 cm, 65–96 cm, 97–128 cm, 129–160 cm, 161–192 cm). Incidence and mean severity were compiled by size class for each site. Relationships between incidence and mean severity values for size classes 1 and 2 (the only size classes present at all 17 sites) and mean site values for host and environmental conditions (using a mix of cardinal and ordinal variables) were analyzed with Pearson correlation analysis and forward stepwise multiple regression analysis (SPSS). Correlation analysis also was used to examine interrelationships of site variables. Average site value for percent maximum canopy (PMC) was correlated with site averages for incidence and severity of wetwood symptoms and other site and host variables.

RESULTS

We observed wetwood bleeding symptoms on *P. fremontii* at all 17 sampling sites. Incidence and mean severity of wetwood bleeding symptoms varied substantially within and among sites. Within sites, incidence and severity varied strongly with tree size. Incidence and mean severity increased from the smallest size class to the largest size class present (Table 2, Fig. 2), and individual severity of wetwood bleeding symptoms was significantly correlated with individual dbh ($P < 0.01$, $r = 0.55$, $n = 850$, data pooled across sites). Distance to channel and elevation above channel for each tree were also significantly correlated with severity at several sites; however, distance and elevation relative to channel were also significantly correlated with host dbh at $P < 0.05$.

For size class 1, incidence ranged among sites from 14% at Wet Beaver Creek to 80% at Empire Wash, and mean severity ranged from 1.1 at Wet Beaver Creek to 2.6 at the Santa Cruz Ephemeral site (Table 2). For size class 2, values for incidence ranged among sites from 43% to 87%, and mean severity ranged from 1.9 to 4.5. *Populus fremontii* spacing, stand composition, substrate texture, and channel stability were all significantly correlated (at $P < 0.05$) with incidence or severity of size class 1 or 2 (Fig. 3, Table 3). Stream flow frequency and bark beetle incidence were, respectively, negatively and positively correlated with wetwood incidence (at $P < 0.10$; Table 3). However, substrate texture and density-related variables (mean *P. fremontii* spacing, stand composition) were the only variables included in the multiple regression models (Table 4). Substrate texture was strongly correlated with several other site variables, including channel stability ($P < 0.01$, $r = 0.73$), stream gradient ($P < 0.01$, $r = 0.56$), stand composition ($P < 0.05$, $r = 0.50$), and site elevation ($P < 0.08$, $r = 0.44$). *Populus fremontii* spacing was significantly correlated among sites only with mean *P. fremontii* dbh ($P < 0.01$, $r = 0.65$; i.e., correlation between larger trees and lower density).

Site factors not significantly correlated with incidence and severity included site elevation, height of flooding, stream gradient, mean distance to nearest willow, physical wounding (primarily flood damage), and incidences of mistletoe and tent caterpillars. The incidences

TABLE 1. Severity scale and definitions used to quantify bleeding symptoms of wetwood.

Bleeding symptoms observed	Severity class
No bleeding sources	1
One minor bleeding source	2
Two minor bleeding sources, or one major bleeding source	3
Three to four minor bleeding sources, or two to three major bleeding sources	4
More than four minor bleeding sources, or more than three major bleeding sources	5

of mistletoe, tent caterpillar, and bark beetle damage were highly variable between sites. These organisms were not detected in trees at most sampling sites, but they occurred at higher incidences (>30%) at a few sites. For example, bark beetle infestation was detected at these levels at only 2 sites (Santa Cruz Ephemeral and Perennial).

Mean site value for the percentage of maximum canopy (PMC) was significantly correlated ($P < 0.01$, $r = -0.62$, $n = 17$) with mean site severity. As severity of bleeding symptoms increased, so did canopy decline. Natural pruning is common, especially in the lower canopy of dense stands; however, there was no significant correlation between PMC and stand density ($P > 0.10$, $r = 0.23$). Percent optimal canopy decreased significantly with increasing site elevation, but not with other measured factors.

DISCUSSION

We found wetwood symptoms to be widespread in *P. fremontii* populations at riparian ecosystems in Arizona. It is likely that values for wetwood incidence were greater than this investigation reports because incidence calculations were based on external symptoms only. Toole (1968) reported that liquid flowed from core wounds in only 30% of affected cottonwood trees. In addition, Murdoch and Campana (1981) report that elm trees in the western U.S. show more variability in internal disease development and significantly less bleeding and symptom expression than those in the eastern U.S.

Certain host and site characteristics found to be associated with higher incidences and severity of wetwood symptoms have been reported by others as well. As *P. fremontii* increased in size (and age; Hinchman and Birkeland 1995), severity and incidence of wetwood symptoms increased. Toole (1968) and Murdoch and Campana (1981) similarly found that wetwood intensity increased with tree age in eastern cottonwood and elm, although Etheridge and Morin (1962) reported wetwood to be more prevalent in younger balsam fir. Many foresters agree that wetwood is associated with older trees (Ward and Pong 1980), but they also report that *Populus* is susceptible to wetwood at all ages.

As substrate particle size decreased, incidence and severity of wetwood symptoms in *P. fremontii* increased. This relationship may be a consequence of increased water-holding capacity and decreased aeration that occur at finer soil textures and is thus consistent with observations of high incidences of wetwood for some tree species at moist or swampy sites (Ward and Pong 1980). However, wetwood expression increased as surface flow frequency decreased, as evidenced by negative correlations between surface flow frequency and severity of bleeding for class 1 trees. More investigation is needed regarding wetwood symptom expression in Fremont cottonwood in relation to soil moisture.

Similar to other studies (Hartley et al. 1961, Bauch et al. 1975), we found some correlation between wounding (i.e., bark beetle damage) and the occurrence of wetwood symptoms. Lack of significant relationships for other types of wounding may have resulted from the highly variable nature of wounds between sites, as well as from an inability to detect and accurately quantify wounding. For example, flood-related wounds located near the root crown could be buried at some sites under a meter or more of sediment (Stromberg et al. 1991).

Relationship between density-related variables (mean tree spacing, stand composition) and wetwood incidence and severity has received little research attention. High stand densities may affect wetwood incidence and severity by increasing competition for nutrients and water and affecting growth rates of individual cottonwood trees. Density also affects the microenvironment of a stand, leading to changes in light intensity, temperatures, and relative humidity, all of which may affect wetwood incidence and severity. An intriguing

TABLE 2. Incidence and mean severity of wetwood symptoms on *Populus fremontii* by size (dbh) class for 17 riparian sites in 4 Arizona watersheds.

Site	Incidence (%)						Severity					
	1[a]	2	3	4	5	6	1	2	3	4	5	6
VERDE RIVER BASIN												
Wet Beaver	14	43	50				1.2	1.9	1.7			
Lower Sycamore	26	53	100				1.4	1.9	3.0			
Upper Sycamore	29	69					1.4	1.9				
Lower Verde	64	86					1.9	2.6				
Upper Verde	48	94	60	100			1.9	3.3	3.2	5.0		
MIDDLE GILA RIVER BASIN												
Hassayampa Perennial	35	96	100				1.5	3.2	3.0			
Hassayampa Ephemeral	77	100					2.3	4.0				
SANTA CRUZ RIVER BASIN												
Santa Cruz Perennial	35	75					1.5	2.8				
Sonoita Creek	30	100	100	100			1.4	3.5	4.2	5.0		
Cienega Perennial	76	100	100				2.2	2.8	2.0			
Empire Wash	80	80	100	100			2.5	2.8	5.0	5.0		
Santa Cruz Ephemeral	76	100	100	100	100		2.6	3.7	5.0	5.0	5.0	
Cienega Ephemeral	55	100	100	100	100	100	2.1	4.5	4.5	5.0	5.0	5.0
SAN PEDRO RIVER BASIN												
Upper Garden Canyon	41	83	75				1.5	2.3	2.3			
Lower Garden Canyon	33	100	100				1.4	2.7	3.0			
San Pedro Perennial	66	100					2.1	3.3				
San Pedro Ephemeral	83	100					2.2	2.5				

[a]Size class 1 = 1–32 cm dbh, class 2 = 33–64 cm, class 3 = 65–96 cm, class 4 = 97–128 cm, class 5 = 129–160 cm, class 6 = 161–192 cm

question is whether the very high incidence of wetwood at some study sites reflects unnaturally high stand densities for *P. fremontii*. Irruptions of tree populations—and associated irruptions of disease or insect outbreaks—can be an indicator of reduced ecosystem integrity (Costanza et al. 1992). Such irruptions can result from human management practices that diverge from evolutionary history of a population or ecosystem (Covington and Moore 1994). Presently, conditions along some rivers in this study contrast with historical descriptions. For example, historical descriptions of the San Pedro refer to a mosaic of forest and marshland rather than to corridors of high-density forest stands. Changes in tree density may be a response to local extirpation of beaver, an agent of geomorphic and biological change that historically served to create a more patchy, heterogeneous flood plain community.

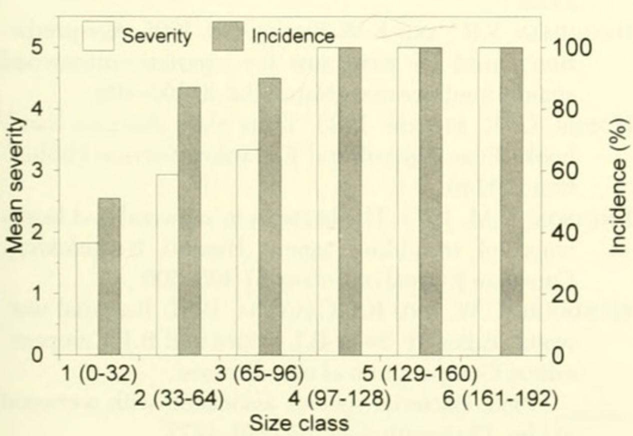

Fig. 2. Mean severity and incidence of wetwood bleeding symptoms observed for 6 stem diameter (cm) size classes of *Populus fremontii* for all sites sampled in Arizona.

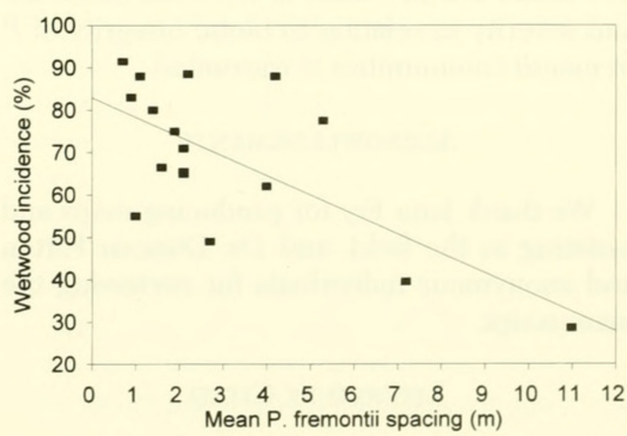

Fig. 3. Mean site incidence of wetwood symptoms in *Populus fremontii* (values averaged for size class 1 and 2 trees, dbh 1–64 cm) in relation to mean host spacing (i.e., density).

TABLE 3. Correlation coefficients between site variables and wetwood incidence and severity values for 2 size classes of *Populus fremontii* (see Table 2).

	Incidence class 1	Incidence class 2	Severity class 1	Severity class 2
Mean spacing of *P. fremontii*	–0.52**	–0.71**	–0.41*	NS
Substrate texture	–0.64**	NS	–0.65**	–0.46*
Channel stability	–0.52**	NS	–0.60**	NS
Stream flow frequency	NS	NS	–0.47*	NS
Stand composition	NS	–0.42*	NS	–0.58**
Bark beetle incidence	NS	NS	0.43*	NS

**$P < 0.05$
*$P < 0.10$
NS = $P > 0.10$

TABLE 4. Multiple regression coefficients between site variables and wetwood incidence and severity values for 2 size classes of *Populus fremontii* (see Table 2).

Dependent variable	Independent variables	r^2
Incidence, class 1	Substrate texture	0.42
Severity, class 1	Substrate texture	0.44
Incidence, class 2	*P. fremontii* spacing	0.48
	P. fremontii spacing + stand composition	0.58
Severity, class 2	Stand composition	0.30

Given the quantitative relationship expressed between wetwood symptom bleeding severity and canopy decline, wetwood is ecologically significant for *P. fremontii* riparian communities. Such a relationship has not been previously reported for any host species and has potential consequences (positive and negative) for insect and bird species that variously depend on live or dead cottonwood canopy for habitat. Canopy decline may ultimately lead to tree death. Further study of wetwood incidence and severity in relation to biotic integrity of *P. fremontii* communities is warranted.

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