PATTERNS OF STRUCTURAL FAILURE IN MONTEREY PINE

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Abstract. The California Tree Failure Report Program database was established in 1987 to collect data on tree branch, trunk, and root breakage or uprooting. The database for the CTFRP is compiled from failure evaluation reports filled out by statewide cooperating arborists, tree assessors, and other horticultural professionals. Compilation of 186 reports for Monterey pine (Pinus radiata) has permitted development of a "failure profile" -a characterization of failure location, structural defects, decay, climatic conditions, and other factors associated with structural failure of Monterey pine. Monterey pine was found to be particularly failure prone compared to other tree species in Golden Gate Park, San Francisco, CA. Close to 60% of Monterey pine failures reported in the CTFRP database were limb failures, rather than trunk or root failures, and most of these were considered to be heavy lateral limbs - a structural defect. The majority of limb breakage occurred away from, rather than at the point of attachment, suggesting a wood strength problem. Decay was not frequently associated with Monterey pine failures at any location on the tree. Tree spacing, nutrition, and genetic strain are likely to be major factors influencing heavy lateral limb development. Closer tree spacing, low nitrogen input, and genetic selection offer hope for reducing Monterey pine branch failure.

The California Tree Failure Report Program (CTFRP) was established in 1987 to collect reliable data on tree branch, trunk and root breakage or uprooting. The ultimate goal of this program is to provide systematic information that will aid in more accurately assessing tree hazard potential in the landscape, and will improve management practices to prevent failures in the future (5). The database for the CTFRP originates from failure evaluation reports filled out by statewide cooperating arborists, tree assessors, and other horticultural professionals who deal with tree failures as part of their work. The failure report form deals with structural aspects of the failure, site conditions, damage resulting from the failure, and the costs of the damage and tree cleanup (see reference 5 for a copy of the report form).

One valuable way the data may be used is to develop "failure profiles" for urban tree species - that is, the most common patterns of tree failure for a given species, including site conditions and structural problems associated with the failure patterns. The purpose of this paper is to present a failure profile for Monterey pine (*Pinus radiata*). This is the first profile of this type to be assembled. In addition to having direct value for tree care professionals in California, this profile is an example of what is possible using a database approach to failure assessment for an individual species. The methods presented here may therefore be applicable in other regions and for other common species.

Monterey pine is a commonly planted landscape tree in California (9,11). It is also the single most frequently reported tree in the CTFRP database. These trees may live up to 150 years and may reach over 100 feet in hospitable climates. Monterey pine is native to the slopes and bluffs along the central California coastline in closed cone pine forests below 1000 feet (10). This climate is highly ocean influenced. Winters are cool, mild, and wet, averaging 50°F, with 12-20 inches of rain. Summers are cool, windy and foggy, with high temperatures reaching an average of 60-70°F and rainfall averaging 2" a month, supplemented by fog drip (8).

In the planted landscape of coastal California, Monterey pine is popular due to its impressive stature and rapid establishment. Sapling growth may be 4-8 feet a year under good conditions with trees reaching over 50 feet by age 15 (8). Monterey pine is often planted in climates where it is not well adapted, such as in California's interior valleys. In these regions, the summers are dry and daily high temperatures may range from 90-110°F. Growth may be rapid initially but tree size and lifespan are greatly reduced. Trees here will often decline after 20-30 years, resulting in major landscape disruption and removal costs. Monterey pine is an important commercial timber tree in New Zealand, Australia, and Africa. Although the wood is described as generally inferior, it provides domestic wood in these countries for quality pulp, plywood, particleboard, and adequate structural timber (2).

Methods

The California Tree Failure Report Program survey form and the data categories were described previously (5). The data were compiled with dBaseIV database software. Monterey pine failure reports were analyzed using dBStats and SPSS statistical packages. Missing information was screened from individual fields and removed from statistical analysis. For general data descriptions, frequency tables (% of population) were used directly or in combination with sorting features to establish additional categories (examples: height classes; or "all other conifers"; etc.). Crosstabulation of fields (i.e. windspeed vs. failure location) was analyzed using the chi-squared test.

Results

Reported Monterey pine failures were largely (95%) planted trees. Almost all of the failures reported were from three site categories: park failures accounted for 65%, residential tree failures made up 14%, and 14% occurred on school grounds. The mean tree height for all failures reported was 71 feet, and the mean dbh was 34". One hundred fifteen of the 186 Monterey pine failures in the database (62%) were reported from Golden Gate Park in San Francisco, where the tree has been heavily planted.

Failure rate in the landscape. The CTFRP has accumulated 1216 failure reports on urban landscape species including 144 different species (September, 1993). Monterey pine was reported the most frequently, accounting for 15% of all failures. The next three most frequent species, *Cupressus macrocarpa*, *Quercus agrifolia*, and *Quercus lobata*, made up 12%, 9%, and 5% of the database, respectively. The remaining 140 species contributed less than 4% of the total each.

The high percentage of Monterey pine in the database prompted us to ask whether this was a failure prone tree, or whether this was simply a reflection of the popularity of Monterey pine in the landscape. To judge the failure susceptibility of a tree, its percentage occurring in the failure database may be compared to its percentage occurring in the population. We would expect the species mix of a region reporting failures to be reflected in the species mix for that region in the failure database. If tree X made up 30% of the landscape, for example, and failed at an average rate, then tree X should also make up 30% of the species in the failure database for that landscape. A general species population survey is necessary to determine if a particular tree is failing at a rate above, below, or equal to that present in the landscape. San Francisco's Golden Gate Park maintains inventory records of tree species in the park, and using this information, we were able to compare the failure rate of Monterey pine to its population percentage within that system.

Monterey pines made up 23% of the Golden Gate Park tree population (1980 survey), yet 44% of all reported failures from Golden Gate Park were Monterey pine, substantially higher than the percentage in the park population (Fig. 1). Monterey cypress (*Cupressus macrocarpa*) failed at a rate somewhat higher than its percentage in the park population, while eucalyptus and oak species were reported to fail at a rate approximately equal to, or below their percentage in the population. When additional categories were created, i.e. "other conifers" (all conifers excluding

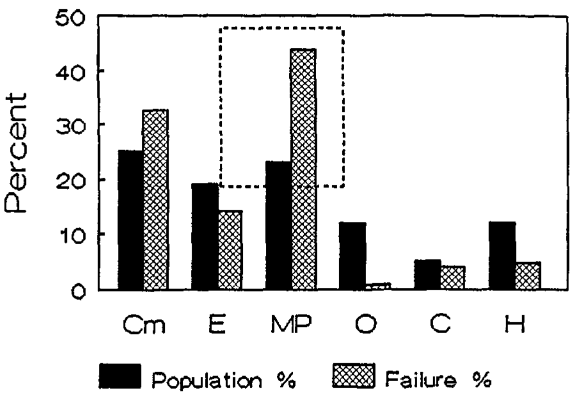

Figure 1. Comparison of tree failure frequency and population composition in Golden Gate Park, San Francisco, CA (CM = *Cupressus macrocarpa*, E = Eucalyptus species, MP = Monterey pine, O = oak species, C = conifers, H = other hardwoods).

Monterey pine and *Cupressus macrocarpa*) and "other hardwoods" (all hardwoods excluding eucalyptus and oaks), failures also occurred in proportion to their population.

Characteristics of failure - branch. Monterey pine failures (Golden Gate Park and other combined) occurred most frequently at the branch (59%; Figure 2). Branch failures also form the largest category for all other species ("all other"). However, the frequency of branch failure for Monterey pine is significantly greater than for other species (chi-squared, P=.00). The sample population was greatly influenced by the predominance of reports from Golden Gate Park trees. Still, the branch failure rate for Monterey pine trees reported from other areas outside the park was significantly higher than that for all other trees in the database grouped together (51% vs 42%, chi-squared, P=.03)(Table 1).

Tree structural defects are potentially important factors contributing to a failure event. The California Tree Failure Report form includes a category for recording up to three structural defects noted for the failed tree (Figure 3). If more than one structural defect is associated with a failure, they are recorded in order of importance. The following results involve the primary structural defect (listed as most important by failure reporter).

Heavy lateral limbs (HLL) were associated with 75% of all Monterey pine branch failures (MP, in Figure 4). This is nearly double the rate of association of heavy lateral limbs with branch failures for all other species as a group, excluding Monterey pine (43%, A-MP). Other pine species (P-MP) and other conifers in general as a group (C-MP) also had lower rates of association (47% and 61% respectively). The high association of heavy lateral limbs with Monterey pine branch failure was consistent for failure reports from Golden Gate Park, and from other locations (Table 1). Surprisingly, the average branch diameter for HLL-associated failures was only 12". Long branches, branches with a heavy foliage load, and branches with a heavy cone load may have been included in this category for Monterey pine.

The second most frequently reported structural defect (10% of all branch failures) was that of multiple trunks/codominant stems. The average diameter of branch failures associated with this structural defect was 19", considerably larger than the HLL-associated branch diameter. Tree professionals familiar with Monterey pine in the landscape report that large codominant stems or branches are characteristic of mature trees of this

Table 1. Comparison of location of failure and structural defects associated with branch failure for urban Monterey pines within and from ourside Golden Gate Park.

	Inside park	Outside park
Location of failure		
Trunk	24%	18%
Branch	64%	51%
Root	12%	31%
Structural defect		
Heavy lateral limbs	72%	81%

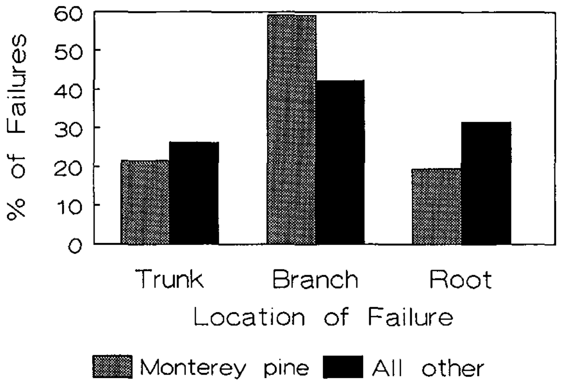

Figure 2. Type of failure by location on the tree (trunk, branch, or root). Comparison of Monterey pine and all other trees in the database.

TREE STRUCTURAL DEFECTS

___ (7) Choose up to three, in the order of importance
___
___

1-Failed portion dead	8-Embedded bark in crotch
2-Multiple trunks/stems	9-Crook or sweep
3-Dense crown	10-Leaning trunk
4-Heavy lateral limbs	11-Cracks or splits (describe p. 2)
5-Uneven branch distribution: onesidedness	12-Kinked or girdling roots
6-Uneven branch distribution: top-heavy	13-None apparent
7-Branches at same point	14-Other (describe p. 2)

Figure 3. Structural defect categories included in the California Tree Failure Report Program form.

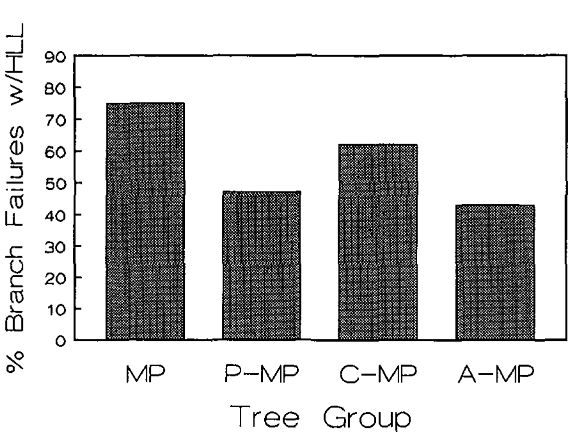

Figure 4. Heavy lateral limbs (HLL) as a structural defect associated with failure. Comparison of Monterey pine (MP) with other pines (P-MP), all conifers except Monterey pine (C-MP), and all other trees in the database (A-MP).

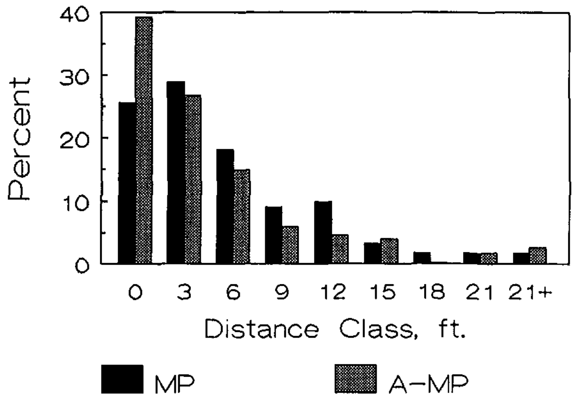

Figure 5. Branch failures: Distance of break site from point of attachment to trunk (attachment = 0 ft., 1-3 ft. class = 3, 4-6 ft class = 6, etc.). Frequency of branch failures per distance class for Monterey pine (MP) and all other species combined (A-MP).

species.

The location of branch failure ranged from the point of attachment with the main trunk to 25 feet out on the branch (Figure 5). Failure occurred flush with the trunk in 26% of all Monterey pine (MP) branch failure reports, while 74% occurred away from the point of attachment. This pattern suggests that most Monterey pine branch failures are not the result of a weak attachment but rather arise from some problem with wood strength or load distribution. Branch failures for all other species (A-MP) in the database grouped together occurred at the attachment in 39% of the reports and out on the branch 61% of the time. A cross-tabulation of branch failures at the attachment or not between Monterey pine and all other species as a group results in a chi-squared probability of .05.

Root failures. Root failures made up 20% of Monterey pine reports. Decay was reported to be associated with only 25% of root failures. By comparison, hardwoods as a class had a significantly higher incidence of decay associated with root failures, 74% (P chi-squared =.000). Leaning trunks were associated with 28% of root failures. By comparison, a leaning trunk was associated with 20% of other pine root failures, 7% of other conifer root failures, and 10% of root failures for hardwoods in the database.

Trunk failures. Monterey pine trunk failures occurred relatively higher on the trunk than was typical for other trees in the database. The ratio of the height of trunk failure to the height of the tree for Monterey pine (.30) was greater than the mean for all other species combined as a group (.22, Figure 6). The ratio of the height of trunk failure to the height of the tree was used rather than failure height alone to compensate for the fact that Monterey pine is, on the average, a taller tree than most other landscape species in the database. The difference was significant at the 5% level for Monterey pine vs. all other species in an unpaired t-test.

Dense crowns were the most frequent structural defect associated with trunk failure in Monterey pine at 19% (of all trunk failures). For other pines, a dense crown was associated with trunk failure in 14% of reports; for conifers and hardwoods, 7%. Crooks and sweeps were the next most frequently reported defect associated with Monterey pine trunk failure at 17%. This type of structural defect was unusually common in Monterey pine, with other pines having 5%, other conifers having 0%, and hardwoods reporting 3% crooks and sweeps associated with trunk failure. Multiple trunks/stems and leaning trunks were other major structural defects associated with trunk failure at 14% and 12% respectively.

Leaning trunks were frequently associated with

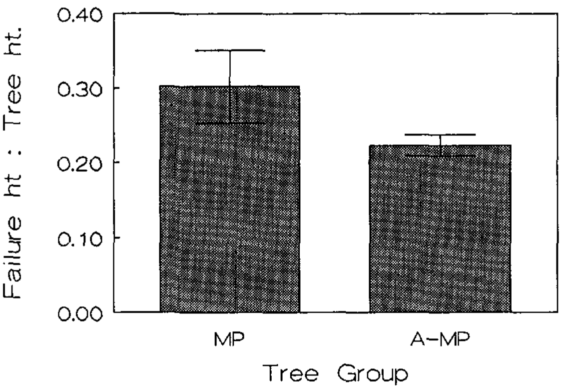

Figure 6. Ratio of trunk failure height (height above ground where failure occurred) to total height of tree. Comparison of Monterey pine (MP) with all other trees in the database (A-MP).

trunk and root failure in Monterey pine, and in other pines as well: some 12% of Monterey pine failures and 14% of other *Pinus* species trunk failures were associated with a leaning trunk as the primary structural defect noted. This was not a structural defect reported as frequently for other conifers (8%), or for the entire database excluding pines (7%).

Native Monterey Pine Stand Architecture

The native stands of Monterey pine in the City of Monterey Forest Preserve system and in other areas outlying the city were studied in order to determine the unmanipulated structure of this tree. These trees have not been pruned, irrigated, or fertilized. The soils in most of these native stand regions are shallow, over a sandstone or shale base. Photographs and observations of the architecture of trees in these stands were compared with similar observations of managed trees in Golden Gate Park.

Canopies with branches high on the trunk were common to both groups. Branches of trees in native stands had typical upper canopy branch diameters approximately one-half that of the trunk (Figure 7). In contrast, park trees commonly had

Figure 7. Typical limb architecture of Monterey pine from native stand in Monterey, CA.

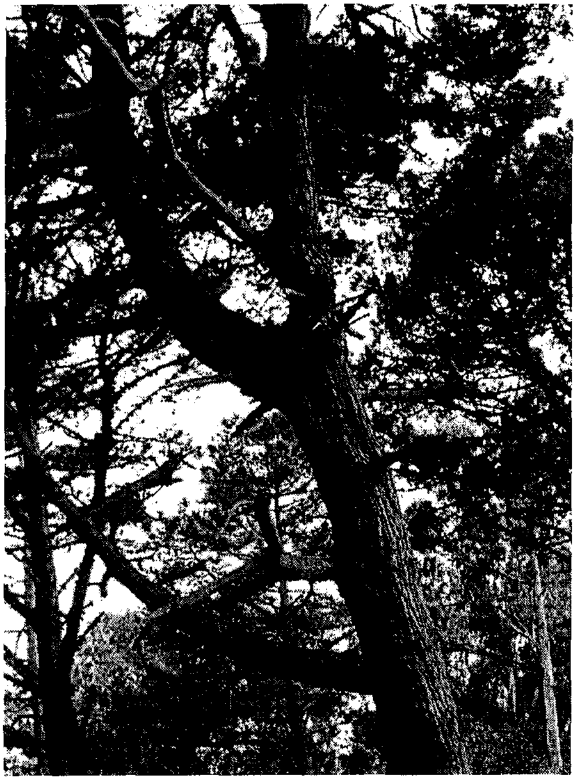

Figure 8. Heavy lateral limb of Monterey pine from Golden Gate Park, CA.

one to several lateral limbs (or codominant stems) whose diameter approached or exceeded that of the trunk diameter (Figure 8). The foliage appeared to be less dense in the native stands, possibly due to the shallow soil system, intermittent drought, and less nutrient availability. In both native stands and urban plantings, branch breakage seemed to occur most often out on the limb rather than at the trunk. Stubs left along the trunk were plentiful in both groups, generally 1 to 4 feet long. Several of those examined were broken at a dead secondary branch insertion point.

The lower trunk of the native Monterey pines had few branches (Figure 7), apparently as a result of shading out from earlier high stand densities. Park trees often had large diameter scaffold limbs (Figure 8) originating along the lower trunk (or pruning wounds indicating their previous presence).

Discussion

Analysis of the Monterey pine failures reported to the California Tree Failure Report Program revealed the most common failure to be breakage of "heavy lateral limbs", usually at some distance from the branch-trunk junction. The location of the breaks away from the point of branch attachment, and the fact that average branch diameter for this class of failures was relatively small, suggest that the main source of branch failure in Monterey pine is some problem with wood strength or branch architecture. Visual observation of limb breakage in both native stands and park plantings often showed stubs of long, horizontal type branches. It was noted in several failure reports that a common point for branch failure was where one or several old, dead secondary branch stubs remained embedded in the limb wood and created a weak point. It was also noted in failure reports that HLL branch failure often occurred at a point where an arching limb became horizontal. Branching architecture, as well as branch strength, apparently contribute to failure potential. Changes in wood structure or grain along the length of large or failed branches of urban Monterey pines would be useful to document.

The second most frequently reported branch failure type was breakage of a multiple trunk or codominant stem of a larger diameter than the HLLs. Monterey pine is known to grow vigorously and rapidly, and is often fertilized in the landscape to enhance growth. Vigorous growth may produce heavy lateral limbs and codominant stems, and may result in decreased wood strength relative to weight for all types of branches - both HLL and codominant stems (2,6).

Trunk failures occurred relatively high in the tree in Monterey pine. The nature of crown development in the urban population, where trees are not usually planted in close stands, may contribute to this pattern: mature trees tend to produce large, codominant laterals with a resulting high canopy structure. Branches with a diameter approaching that of the trunk may be insufficiently supported by trunk wood surrounding the branch base (13). If such large, codominant stems occur in the mid to upper regions of the trunk, a weak zone would be created there with resulting failure potential. In addition, wood lignin content has been reported to vary with tree height in Monterey pine, being lowest at 30-40% of trunk height (7).

It is clear that Monterey pine has a high failure rate compared to its population percentage in Golden Gate Park. The park has a climate similar to that of the native range of Monterey pine, which should provide an adequate environment for the tree. Soils in the park are different compared with native stand locations (deep sand vs. shallow soil overlying shale or sandstone). The high failure rate under suitable conditions in the park suggests either that Monterey pine is a failure prone tree, that soil type is an important factor in crown development, and/or that the standard management techniques used for this tree are not appropriate. While conclusions based on comparisons made at one location should be interpreted with some caution, our data are consistent for all regions reporting to the CTFRP with respect to the higher than average proportion of branch failures and the frequent association of heavy lateral limbs with branch failure that characterize the main failure profile for Monterey pine.

An Evaluation of Monterey Pine Management in the Urban Landscape

Findings from this study, together with results from research conducted by forestry institutions in Australia, New Zealand, and South Africa, point to the need for changes in management practices that may reduce the frequency of failure in Monterey pine. Management begins by recognizing climatic, soil, and stand density influences on performance in the landscape. Fertilization and pruning practices may also play an important role in the development of tree structure and wood strength.

Stand characteristics. The spacing of Monterey pine in the urban landscape may be a factor influencing the likelihood of branch failure. Wide spacing of this species has been shown to increase branch diameter by as much as 46% (2). Closer tree spacing, even in an open woodland, can result in shading, higher competition among trees, slower growth, and consequently a reduced proportion of juvenile or weak wood core in the trunk (2). Use of Monterey pine as a specimen tree may therefore encourage large limbs and weaker wood, especially if fertilization is present for turf or other ground covers.

Fertilization. Fertilization or rich soil results in vigorous growth of Monterey pine, an increased tendency to produce large branches (2), and several other factors influencing wood strength. Trees growing on fertile ex-pasture sites in Australia had a high incidence of stem deformation and thick, heavy branching in the juvenile (6 years) stage. Forest plantations on poorer soil did not show the same tendency (1). Fertile ex-pasture sites were associated with trunk sweeps, heavy branching, multiple leaders, and numerous forks in 90% of the plantation trees in another Australian study. A high level of nitrogen and possibly boron deficiency were suspected factors for development of poor form (3). High nitrogen levels and copper deficiency in sandy soils with high organic matter content have also been linked to stem deformation, reduced cell lignification, and tracheal collapse (7). The lignin content varied most in the earlywood formed on fertile sites, and was lowest at 30-40% of tree height (7). The decrease in lignin content at this height correlates well with reported height of trunk failure in the California Tree Failure database (30% of tree height). Finally, nitrogen fertilization has been reported to decrease wood density from 3 - 17%, directly influencing wood strength (2,6).

Arborists may reduce the incidence of heavy lateral limbs, codominant stems, and deformed trunks through careful attention to soil nutrition, particularly avoidance of excessive nitrogen (12). Interestingly, during the early years of tree establishment in Golden Gate Park, situated on a sand dune based soil, there was extensive use of "street sweepings" — including manure from the horse population in San Francisco at the time -as a soil amendment (4). This may have created site conditions conducive to development of large limbs and weak wood.

Selection. There are five natural populations of Monterey pine. Three are from the mainland northern California coast (Monterey, Año Nuevo, and Cambria) and two from islands off the coast of California and Baja California (Guadalupe and Cedros). Early California landscape plantings were generally propagated from wild collected mainland seed. Monterey pine seed from Monterey and Año Nuevo populations was also exported to New Zealand in the late 1800's. A "land race" was developed in New Zealand from this parentage. Seed from various stages in the development of New Zealand timber and pulp selections began to return to California around 1940. This seed was intended for christmas tree growers and was either unselected, collected from obsolete selections, or from culled trees of undesirable form. However, trees grown from this seed found their way into forestry and landscape use. The current California landscape population then, consists of native trees, displaced native trees, various by-products in the development of New Zealand land race trees, and intermediate hybrids. Growers and urban foresters are beginning to emphasize native seed purity as well as the use of a positively selected New Zealand land race selection GF17. Further improvements in the selection of Monterey pine for desirable crown architectures and wood properties have been made by forestry institutes in Australia and New Zealand, and this genetic material offers the potential to reduce poor tree structure. In cases where stem deforming crooks or sweeps, codominant leaders, and heavy branching were linked to fertile ex-pasture sites for example, certain genetic selections were substantially less affected (1,12). Thus, selections with improved crown architecture (i.e. smaller branch diameter), especially under conditions of relatively high soil fertility may result in fewer failures in an urban setting as well.

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Résumé. La banque de référence de données sur le Programme de recherche sur la chute d'arbres de la Californie a été établie en 1987 pour emmagasiner des données sur les bris de branches, de troncs ou de racines et sur les déracinements. La banque de données est alimentée par les rapports d'évaluation de chutes en provenance d'arboriculteurs, d'évaluateurs et d'autres professionnels du domaine horticole à la grandeur de l'état. La compilation de 186 rapports concernant le pin de Monterey (*Pinus radiata*) a permis de développer un «profil de chute», c'est-à-dire une caractérisation du site de chute, des défauts structuraux, de la carie présente, des conditions climatiques et d'autres facteurs associés avec la faiblesse structurale du pin de Monterey. Près de 60% des cas de chutes pour le pin de Monterey sont attribuables aux branches, plutôt qu'à une faiblesse structurale du tronc ou des racines, et la plupart de ces cas de branches étaient généralement associés à de grosses branches latérales comportant des défauts structuraux. La majorité des bris de branches se produisaient au-delà du point d'attache de celles-ci avec le tronc, laissant supposer dès lors à des problèmes de résistance du bois. La carie n'était pas fréquemment mentionnée dans les rapports de chutes sur le pin de Monterey.

Zusammenfassung. Die Datenbank des kalifornischen Programms zur Aufzeichnung von Baumversagen wurde 1987 eingerichtet, um Daten zu sammeln über Bruchschäden von Ästen, Stämmen und Wurzeln, sowie Entwurzelung. Die Datenbank ist zusammengetratgen aus Bewertungsberichten über Baumversagen, die von bundesweit kooperierenden Arboristen, Baumgutachtern und anderen Gartenbaufachleuten ausgefüllt wurden. Die Zusammenstellung von 186 Berichten über die Monterey-Kiefer (*Pinus radiata*) hat zur Entwicklung eines Versagenprofils beigetragen - eine Charakterisierung des örtlichen Auftretens von Versagen, strukturellen Defekten, Fäulnis, klimatische Bedingungen und andere Faktoren, die mit dem strukturellen Versagen der Monterey-Kiefer in Verbindung gebracht werden. Nahezu 60% der Fehler der Monterey-Kiefer waren eher Astbruch als Stamm- oder Wurzelversagen und die meisten dieser Äste waren schwere laterale Äste - ein strukureller Defekt. Die Mehrheit der Astbrüche traten eher am äußeren Ende als am Anfang auf, was auf ein Holzstärkeproblem hindeutet. Fäulnis wurde gewöhnlich nicht in Verbindung gebracht mit dem Versagen der Monterey-Kiefer.