Monterey Pine (*Pinus radiata*) in California: Variation Among Native Forests and Health as a Predictor of Tree Removal in an Urban Forest

By

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This thesis, “Monterey Pine (*Pinus radiata*) in California: Variation among native forests and health as a predictor of tree removal in an urban forest”, is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN FORESTRY.

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Thesis Abstract

Three native Monterey pine (*Pinus radiata* D. Don) populations occur along the central coast of California and cover a total area of approximately 5,330 hectares. The goals of this research were 1) to provide a contemporary characterization of the three native populations and 2) to determine which biological and environmental factors were predictive of Monterey pine street tree removal in an urban forest. For the natural forests, forest heath, stand structure and understory plant communities were compared between six stands, four on the Monterey Peninsula and one each at Año Nuevo and Cambria. On the Monterey Peninsula, coastal stands had higher incidence of pitch canker, a disease caused by the exotic pathogen *Fusarium circinatum* (Nirenberg & O'Donnell) and abundance of red turpentine beetle (Coleoptera: Scolytidae). Regeneration rates and recruitment success was also greater in the coastal stands. The richness of shrub species was lower in the inland stands and there was a negative correlation between poison oak percent cover and seedling regeneration. For the urban forest of Carmel-by-the-Sea, the height and diameter in 1988 of trees that had been removed by 2005 were significantly greater than trees not removed and the presence of red turpentine beetles (Coleoptera: Scolytidae) in 1992 was a significant indicator of tree removal. Trees that develop pitch canker by 2005 were shorter in 1988, were more likely to have pitch moth and had a greater number of pitch moth attacks in 1988, than were trees which did not develop pitch canker by 2005.

Chapter 1

Forest health, stand structure and understory plant communities of three native Monterey pine (*Pinus radiata* D. Don) forests.

(Formatted for "Forest Ecology and Management")

Abstract

Three native Monterey pine (*Pinus radiata* D. Don) populations occur along the central coast of California and cover a total area of approximately 5,330 hectares. These populations are economic, ecological and recreational resources for California and an important genetic resource for the international Monterey pine timber trade. The introduction of the exotic pathogen pitch canker (*Fusarium circinatum* Nirenberg & O'Donnell) has altered the forest health and stand ecology of all three native populations. This study compared stand structure, understory plant communities and forest health between six native Monterey pine stands; four on the Monterey Peninsula and one each at Año Nuevo and Cambria. Coastal stands had higher incidence of pitch canker and abundance of red turpentine beetle (Coleoptera: Scolytidae) on the Monterey Peninsula. Regeneration rates and recruitment success were also greater in the coastal stands. Pitch canker may have opened the forest for natural regeneration in the coastal stands, while shrubs intercept the increased light environment of the inland stands and out-compete regeneration. The richness of shrub species is lower in the inland stands and the negative correlation of poison oak percent cover to seedling regeneration suggests that poison oak is dominating the understory and reducing Monterey pine regeneration in the inland stands.

Introduction

The native range of Monterey pine (*Pinus radiata* D. Don) is limited to only five locations worldwide. Año Nuevo (600 ha), the Monterey Peninsula (3,800 ha) and Cambria (930 ha) are the three mainland populations located on the central coast of California (Huffman, 1994) (Figure 1.1). The other two locations are off the coast of northern Mexico on the Pacific islands of Guadalupe and Cedros. The island populations have two needles per fascicle rather than three and are considered relictual variants of Monterey pine (Axelrod, 1980; Millar, 1986). Although the genetically distinct ecology of the island populations is of interest, this study focuses on the three mainland populations.

The range of Monterey pine is reportedly limited by the inland reach of summer fog (Roy, 1966; Vogl, 1977) and sandy loam soils overlying shallow marine sediments (Lindsay, 1932; Roy, 1966). In all three mainland populations, Monterey pine grows from just above sea level to upper elevations of about 200 to 300 meters (Libby, 1997). Genetic studies of the three populations revealed a high interpopulation genetic differentiation with a very low level of genetic differentiation within each population (Moran et al., 1988). Cone morphology is one of the visible genetic differences between the three populations (Eldridge, 1997). The Cambria population has the largest mean cone size, followed by the Año Nuevo and Monterey Peninsula populations. (Lindsay 1932; Forde, 1964).

Monterey pine is a fire-adapted species (McDonald and Laacke, 1990). The fire-return frequency of prehuman lightning fires on the Monterey Peninsula is estimated to have been in the range of 30 to 135 years (Greenlee and Langenheim, 1990). Native Americans lived among all three mainland Monterey pine populations in some areas for at least 3,000 years and other areas as long as 10,000 years or more (Libby, 1997). Native Americans used fire to flush wildlife, harass enemies, remove vegetation to make travel easier, and to encourage the growth of certain plants such as hazel (*Corylus cornuta* Marsh. var. *californica* (A. DC.) Sharp) (Gordon, 1979). These anthropogenic uses of fire reduced the fire-return frequency to approximately 15 years (Greenlee and Langenheim, 1990). Adaptations such as the serotinous cones, thicker bark, and an intermediate shade tolerance may have been selected for as a result of the more frequent use of fire by Native Americans.

In California, Monterey pine is widely used as a landscape tree and provides a unique backdrop for recreational activities in the native stands along the coast. However, the value provided to California is far outweighed by the global importance of the species. Monterey pine is the most widely planted pine in the world (McDonald and Laacke, 1990; Deghi et al., 1995). Seed collection from the native forests has formed the basis of timber plantations in Australia, Chile, New Zealand, Spain, South Africa and other countries (Rogers, 2002). Maintenance of a stock of genetically diverse Monterey pine is essential to ensure the continuance of genetic combinations that may not be found in cultivated trees (Deghi et al., 1995).

Change in land use has increased development, which has fragmented and reduced the area covered by native Monterey pine forests. Large portions of forest are under private ownership, and the native forests on the Monterey Peninsula and Cambria have become increasingly urbanized (Deghi et al., 1995). This development may expose the fragmented Monterey pine forest to edge characteristics (Cancino, 2005), which can include susceptibility to exotic species, stress, disease and pests (Oliver and Larson, 1990).

Pitch canker is caused by the exotic pathogen, *Fusarium circinatum* Nirenberg & O'Donnell [=*F. subglutinans* (Wollenw and Reinking) Nelson et al. f.sp. *pini* (Correll et al.)], and was first identified in the native population located on the Monterey Peninsula in 1992 (Storer et al., 1994). Pitch canker is now prevalent in each of the three native California populations (Gordon et al., 1996, 1997; Storer et al., 2001). The disease is both associated with and vectored by an array of native insects (Fox et al., 1991; Hoover et al., 1996; Storer et al., 1998). Once the pathogen is vectored into branch tips, a girdling lesion develops which kills the branch distal to the infection. Eventually the needles fall from the tree leaving bare branch tips. As the disease progresses, infections on the main stem become common, and in response the tree produces profuse amounts of resin. Trees can be killed directly by the pathogen or left susceptible to mortality by native bark beetles (Wikler et al., 2003). Progression of pitch canker has been characterized in planted stands (Storer et al., 2002) and in the Monterey Peninsula population (Wikler et al., 2003). In the Monterey Peninsula populations there is evidence that disease progression and severity is greater in coastal areas than inland areas (Wikler et al., 2003). Pitch canker causes concern for the long-term viability of infected Monterey pine stands (Hilyard, 1997).

In addition to fragmentation and pitch canker, fire suppression is another threat to the native Monterey pine forests. The heat from fire stimulates Monterey pines to shed a heavy seed rain onto bare mineral soil, increasing seedling germination and survival rates. The suppression of fire has allowed for the increased abundance of coast live oak (*Quercus agrifolia* Nee) in some areas. Data collected during the early summers of 1965 and 1966, in 38 stands of native Monterey pine on the Monterey Peninsula, were compared with data collected in 1994 and showed an increase of coast live oak saplings over the 29 year period (White, 1999). The absence of fire has possibly allowed for the gradual shift towards oak-dominated forests in some areas.

There has been very little research performed comparing the stand structure, forest health or understory plant communities of the three California native populations. The goal of this research was to provide a contemporary characterization of the three native populations.

There were three objectives of this research; 1) to characterize stand structure and regeneration in large (>80 ha) stands within three native populations, 2) to compare the stand structure, understory vegetation and forest health of the three native populations, and between the coastal and inland stands of the Monterey Peninsula, and 3) to assess the development of the Monterey Peninsula population over time by comparing stand structure and understory vegetation to data collected in 1965-1966 published by White (1999).

Methods

Six natural stands of the native populations were selected for this study; four on the Monterey Peninsula, one in Año Nuevo and one in Cambria. The criteria for selection were that the stand be of natural origin and greater than 80 ha in size. The four stands selected on the Monterey Peninsula were the largest stands reported (Huffman, 1994) and were located at Huckleberry Hill (Monterey coastal 1 stand; 108 ha), PQR (Monterey coastal 2 stand; 98 ha), Jack's Peak County Park (Monterey inland 1 stand; 254 ha) and Aguajito (Monterey inland 2 stand; 289 ha). The stand selected in Año Nuevo was the Scotts Creek stand (106 ha) on the California Polytechnic University School Forest at Swanton Pacific Ranch. The stand selected in Cambria was located at the Kenneth S. Norris Rancho Marino Reserve (91 ha).

For the 2005 data collection, the six stands were delineated using ArcMap 8.0, and transect locations were created by overlaying a grid on the map of the stands either manually (1999 data) or electronically (2005 data). Randomly generated numbers created the coordinates for the starting point and azimuth of ten 100m transects within each stand.

1999 Data Collection

In November 1999 the starting points of 10 transects for the four stands on the Monterey Peninsula were established. Every 5m along the 100m transect a 1m x 1m quadrat was placed on the ground to the left of the transect line. Seedlings (alive and dead) within the quadrat were counted. In addition, all trees 0.15m and above within 2.5m on each side of the transect line were counted. The trees were placed in height classes of 0.15m - 0.6m, 0.6m - 1.8m, 1.8m - 3.6m, understory greater than 3.6m, and overstory.

2005 Data Collection

In the summer of 2005 ten new transects within each stand were established. The stands at Año Nuevo and Cambria were included in the study. The start of each transect was located in the field with a handheld GPS unit. A metal rod was used to monument the start of each transect and a tape was used to lay out the 100m transect line.

To assess forest health and structure, one 0.04ha plot was placed at the start, middle and end of each transect (Figure 2.2). In each plot the species was recorded for every tree with a diameter at breast height (DBH, 1.37m) greater than 7.6cm. Height of each tree was measured using a clinometer. Live crown ratio (LCR) was calculated for each tree by visually estimating the percentage of tree height composed of live crown. The percent canopy closure was measured using a convex spherical densiometer. Four readings were taken at plot center and at the edge of the plot in the four cardinal directions. The readings were then averaged to represent the percent canopy closure of the plot (Lemmon, 1957).

Every tree in the 0.04-ha plot was visually assessed for symptoms and signs of disease and pests. Presence and absence of each forest health agent was recorded for each tree in order that the percet of trees with each condition could be compared between stands. The number of new and old symptomatic tips of pitch canker were counted, and the tree was categorized as having 0, 1-10, or >10 symptomatic tips. Stem cankers on each tree were also counted, and then categorized as 0, 1-3, or >3.

Pitch canker symptomatic tip and stem data were combined to give each tree a disease severity rating. 1-10 tips counted as 1 point; over 10 symptomatic tips counted as two points; 1-3 stem cankers counted as 1 point; and over 3 stem cankers counted as 2 points. Disease severity in each plot was calculated as a percentage of the maximum severity possible in the plot (Wikler et al., 2003):

$$\text{plot severity (\%)} = \left(\frac{\sum_{i=0}^{n} R_i}{nx4} \right) 100$$

where R_i is the tree disease severity rating of the *i*th tree within the plot, and *n* is the total number of trees rated in each plot.

Sequoia pitch moth (Lepidoptera: Sesiidae) attacks were characterized by reddish brown frass pellets incorporated in a pitchy mass on the trunk and branches of the tree and were categorized as 0, 1-10 or >10 per tree. Red turpentine beetle (Coleoptera: Scolytidae) attacks were characterized by pitch masses 2-5cm wide on the lower 3m of the trunk and earlier attacks were characterized by small gray granules of crystallized resin and frass on the soil. The total number of red turpentine beetle attacks were counted and characterized as 0, 1-10, or >10 per tree. Dwarf mistletoe (*Arceuthobium* spp.) infection was characterized by small, leafless, yellow-green shoots, 2.5-25cm long, in tufts or scattered along the branches or trunk and assessed using the Hawksworth Mistletoe Rating Scale. The Hawksworth Mistletoe Rating Scale divides the live crown into horizontal thirds and each third is given an infection rating of 0-2 for a maximum severity rating of 6 per tree (Hawksworth, 1977). Western gall rust (*Peridermium harknessii*) was characterized by round to pear-shaped woody outgrowths on the trunk or branches of the tree. The number of galls on the trunk or branches were categorized separately as having 0, 1-10 or >10 galls per tree. Forest health signs and symptoms were based on Wood et al. (2003).

Every 5m along each transect a 1m x 1m quadrat was placed on the ground to the left of the transect line to quantify herbaceous and shrub species. Visual estimates of ground cover percentage for each plant species were estimated in 5% categories within each quadrat, and the number of herbaceous and shrub species individuals rooted within the quadrat were counted. Nomenclature of herbaceous and shrub species followed Matthews (1997).

Two diversity indices were calculated for the following three types of understory plants; all understory species, herbaceous species and shrub species. Taxonomic richness was the total number of species rooted within quadrats of the transect and the Shannon-Wiener Diversity (*H'*) was calculated per quadrat using the following equation;

$$H' = -\sum (p_i)(\ln p_i)$$

where p_i = the proportion of individuals belonging to the *i*th species of each quadrat. Mean *H'* was then calculated for each transect (Krebs, 1999).

The Monterey Peninsula stands were revisited in November 2005, to count seedlings in quadrats at the same time of year as the 1999 data was collected. Monterey pine seedlings (alive and dead) within the quadrat were counted. In addition, all trees 0.15m and above within 2.5m on each side of the transect line were counted and placed in the height classes of the 1999 data collection.

Data Analysis

In all analyses the stands were regarded as treatments, such that for the 1999 data there were four treatments and for 2005 data there were six treatments. Comparisons between stands for vegetation data and forest health severity values were made using one-way ANOVA. Data were transformed where necessary to ensure homogeneity of the variances. Understory plant abundance for each of the 10 transects (replicates) was the number of quadrats in which the plant species was present. For quadrat seedling data, the mean number of seedlings in the twenty quadrats along each transect was calculated for a total of 10 replicates per stand. For the 0.04ha plots, each plot was regarded as an independent replicate due to the spacing of the plot locations over 25m from one another for a total of 30 replicates per stand. Comparison between stands for percent of trees with different forest health attributes were made using *G*-tests to test the differences in the proportion of trees in each stand that had symptoms or signs of each forest health condition. In this case, data from all thirty plots in each stand were pooled.

Following testing of differences among the six stands, a. priori orthogonal contrasts were performed using Student's t-test following the ANOVA or *G*-tests for the data showing percent of trees affected.. Orthogonal contrasts were performed to allow comparison between the the Monterey Peninsula and the other two populations, and comparison between the Año Nuevo and Cambria stands. In addition, the Monterey coastal stands were compared with the Monterey inland stands as a greater incidence and severity of pitch canker along the coast has been reported (Wikler et al., 2003). For the 2005 data, five orthogonal contrasts tested differences between 1) the four Monterey Peninsula stands combined and the Año Nuevo and Cambria stands combined, 2) the Año Nuevo stand and the Cambria stand, 3) the two Monterey coastal stands combined and the two Monterey inland stands combined, 4) the Monterey coastal 1 stand and the Monterey coastal 2 stand, and 5) the Monterey inland 1 stand and the Monterey inland 2 stand. For the 1999 data, the three orthogonal contrasts tested differences between 1) the two coastal stands combined and the two inland stands combined, 2) Monterey coastal 1 stand and Monterey coastal 2 stand, and 3) Monterey inland 1 stand against Monterey inland 2 stand.

Differences in the number of seedlings per hectare and the number of recruits in the 0.15m-0.60m height class between the 1999 and 2005 data were tested using a two way ANOVA. The data from the two years were regarded as independent since none of the seedlings present in 2005 would have been present in 1999, and none of the recruits from 1999 would still be in the recruit size class in 2005.

Differences in the occurence of understory species in quadrats between the 1965-1966 data and the 2005 data were tested using G-tests. Data from all quadrats in all stands were pooled within each sampling time period.

Relationships between percent cover of understory shrub species and the number of Monterey pine seedlings were tested by calculating the Pearson correlation coefficient (r) between the mean number of Monterey pine seedlings along each transect and the mean percent cover of each understory shrub species along each transect. All statistical analyses were completed using Statistix 8.0 (Analytical Software, 2003) and Microsoft Excel.

Results

Stand structure

The Monterey coastal 1 stand had the highest number of Monterey pine per hectare (354 trees per hectare). There were more Monterey pines per hectare in the four Monterey Peninsula stands combined than the Cambria and Año Nuevo stands combined ($t = 2.46$, $P = 0.0149$). There were more Monterey pines per hectare in the Cambria stand than the Año Nuevo stand ($t = 4.35$, $P < 0.0001$), and the two Monterey coastal stands combined had more Monterey pines per hectare than the two Monterey inland stands combined ($t = 3.30$, $P = 0.0012$). The Cambria stand consisted of 29% (147/506) coast live oak, and resulted in the most trees per hectare of all species (including Monterey pine), which was higher than the Año Nuevo stand ($t = 4.71$, $P < 0.0001$). The Monterey coastal 1 stand had the most Monterey pine snags (72 snags per hectare). The two coastal Monterey stands combined had more Monterey pine snags than the two inland Monterey stands combined ($t = 3.05$, $P = 0.0027$) (Figure 1.3).

The Monterey pine basal area did not significantly differ among the six stands. The basal area of all species was the greatest at the Año Nuevo stand (34.1 m^2 per hectare) and was higher than the Cambria stand ($t = 2.08$, $P = 0.0387$) (Figure 1.4). The lowest canopy closure percentage was the Monterey inland 1 stand (21.7%), which was lower than the Monterey inland 2 stand ($t = 3.92$, $P = 0.0001$) (Figure 1.5).

The Monterey coastal 2 stand had the highest mean height (19.9m). The mean height of the Monterey inland 2 stand was higher than the Monterey inland 1 stand (t = 2.53, *P* = 0.0122). The four Monterey Peninsula stands combined had a higher mean height and a lower LCR when compared to the Cambria and Año Nuevo stands combined (t = 3.43, *P* = 0.0007; t = 3.68, *P* = 0.0003, respectively). The two Monterey coastal stands combined had a lower LCR than the two Monterey inland stands combined (t = 3.63, *P* = 0.0004). The Año Nuevo stand had the highest mean DBH (45.3cm) and was greater than the Cambria stand (t = 4.13, *P* = 0.0001) (Figure 6). None of the other contrasts between stands for each stand structure attribute were significant.

Frequency of native understory species

When the four Monterey Peninsula stands combined were compared with the Cambria and Año Nuevo stands combined, frequency in the Monterey Peninsula stands was higher for Hooker's manzanita (*Arctostaphylos hookeri* G. Don) (t= 2.26, *P* = 0.0276), shaggy-barked manzanita (*Arctostaphylos tomentosa* (Pursh) Lindl.) (t = 3.85, *P* = 0.0003) evergreen huckleberry (*Vaccinium ovatum* Pursh) (t = 2.54, *P* = 0.0141), sticky monkey flower (*Mimulus aurantiacus* Curt.) (t = 2.3, *P* = 0.0256) and creeping snowberry (*Symphoricarpos mollis* Nutt.) (t = 2.16, *P* = 0.0355) and lower for grass species (*Poaceae*) (t = 2.01, *P* = 0.0496), horsemint (*Agastache urticifolia* (Benth.) Kuntze) (t = 3.11, *P* = 0.003), poison oak (*Toxicodendron diversilobum* (T.&G.) Greene) (t = 3.05, *P* = 0.0035), and California blackberry (*Rubus ursinus* Cham. & Schlecht.) (t = 5.17, *P* < 0.0001) (Tables 1.1-1.3).

When the Año Nuevo stand was compared to the Cambria stand, frequency in the Año Nuevo stand was higher for daisy species (*Erigeron* L.) ($t = 3.28$, $P = 0.0018$), poison oak ($t = 2.33$, $P = 0.0237$), California blackberry ($t = 4.42$, $P < 0.0001$), and sedge species (*Cyperaceae*) ($t = 3.58$, $P = 0.0007$) and lower for common yarrow (*Achillea millefolium* L.) ($t = 2.25$, $P = 0.0283$), tiny bedstraw (*Galium murale* (L.) All.) ($t = 2.12$, $P = 0.0387$), wood strawberry (*Fragaria vesca* L.) ($t = 2.25$, $P = 0.0288$), yerba buena (*Satureja douglasii* (Benth.) Briq.) ($t = 2.16$, $P = 0.0352$), California coffeeberry (*Rhamnus californica* Eschs.) ($t = 3.46$, $P = 0.0011$) and sticky monkey flower ($t = 3.67$, $P = 0.0006$).

When the two Monterey coastal stands combined were compared to the two Monterey inland stands combined, frequency in the two Monterey coastal stands combined was higher for common yarrow ($t = 2.18$, $P = 0.0336$), blue-eyed grass (*Sisyrinchium bellum* Wats.) ($t = 2.14$, $P = 0.0365$), horkelia species (*Horkelia* Cham. & Schlecht.) ($t = 3.36$, $P = 0.0015$), Douglas iris (*Iris douglasiana* Herb.) ($t = 2.51$, $P = 0.0151$), California bedstraw (*Galium californicum* H.& A.) ($t = 2.62$, $P = 0.0115$), daisy species ($t = 4.71$, $P < 0.0001$), Hooker's manzanita ($t = 3.5$, $P = 0.0009$), evergreen huckleberry ($t = 4.4$, $P = 0.0001$) and sedge species ($t = 2.62$, $P = 0.0115$) and lower for horsemint ($t = 3.44$, $P = 0.0011$) poison oak ($t = 5.35$, $P <0.0001$) and California coffeeberry ($t = 2.51$, $P = 0.015$).

When the Monterey coastal 1 stand was compared to the Monterey coastal 2 stand, frequency in the Monterey coastal 1 stand was higher for California blackberry ($t = 3.12$, $P = 0.0029$), shaggy-barked manzanita ($t = 3.27$, $P = 0.0019$) and evergreen huckleberry ($t = 6.22$, $P < 0.0001$) and lower for grass species ($t = 2.59$, $P = 0.0123$), blue-eyed grass (t = 3.41, $P = 0.0012$), horkelia species (t = 2.60, $P = 0.012$), wood strawberry (t = 2.17, $P = 0.0342$), sticky monkey flower (t = 2.52, $P = 0.0148$) and creeping snowberry (t = 2.36, $P = 0.0218$).

When the Monterey inland 1 stand was compared to the Monterey inland 2 stand, frequency was higher in the Monterey inland 1 stand for poison oak (t = 3.27, $P = 0.0019$) and California coffeeberry (t = 2.33, $P = 0.0235$) and lower for shaggy-barked manzanita (t = 2.59, $P = 0.0122$). None of the other contrasts between stands for native understory vegetation were significant.

Frequency of exotic understory species

When the four Monterey Peninsula stands combined were compared with the Cambria and Año Nuevo stands combined, frequency in the Monterey Peninsula stands was higher for French broom (*Genista monspessulana* (L.) L. Johnson) (t = 2.01, $P = 0.0496$) and lower for rattlesnake grass (*Briza maxima* L.) (t = 8.37, $P < 0.0001$) (Table 1.4).

When the Año Nuevo stand was compared to the Cambria stand, frequency in the Año Nuevo stand was lower for rattlesnake grass (t = 10.79, $P < 0.0001$).

When the Monterey coastal 1 stand was compared to the Monterey coastal 2 stand, frequency in the Monterey coastal 1 stand was lower for French broom (t = 2.59, $P = 0.0123$).

When the Monterey inland 1 stand was compared to the Monterey inland 2 stand, frequency was higher in the Monterey inland 1 stand for pampas grass

(*Cortaderia jubata* (Lemoine) Stapf) (t = 2.08, $P = 0.0422$). None of the other contrasts between stands for exotic understory vegetation were significant.

Diversity indices

When the four Monterey Peninsula stands combined were compared to the Año Nuevo and Cambria stands combined, the understory species richness (t = 13.96, $P > 0.0001$) and herbaceous species richness (t = 5.08, $P > 0.0001$) of the four Monterey Peninsula stands were higher and the shrub species richness (t = 3.60, $P = 0.0007$) and shrub species Shannon-Wiener diversity (t = 2.19, $P = 0.0331$) were lower (Figure 1.7).

When the Año Nuevo and Cambria stands were compared, the understory species richness (t = 3.04, $P = 0.0036$), herbaceous species richness (t = 4.18, $P = 0.0001$), understory species Shannon-Wiener diversity (t = 2.18, $P = 0.0340$) and shrub species Shannon-Wiener diversity (t = 2.36, $P = 0.0218$) of the Año Nuevo stand were higher.

When the two Monterey coastal stands combined were compared to the two Monterey inland stands combined, the shrub richness of the Monterey coastal stands was higher (t = 3.12, $P = 0.0029$).

When the Monterey coastal 1 stand was compared to the Monterey coastal 2 stand, the understory species richness (t = 2.85, $P = 0.0062$) and herbaceous species richness (t = 3.06, $P = 0.0035$) were higher at the Monterey coastal 1 stand and the shrub species richness (t = 2.39, $P = 0.0204$) and herbaceous species Shannon-Wiener diversity were lower (t = 2.55, $P = 0.0136$). None of the other contrasts between stands for diversity indices were significant.

Forest health

When the four Monterey Peninsula stands combined were compared to the Año Nuevo and Cambria stands combined, signs and symptoms of pitch canker ($G = 10.57$, $P = 0.0011$), sequoia pitch moth ($G = 119.57$, $P < 0.0001$), red turpentine beetle ($G = 5.80$, $P = 0.016$), dwarf mistletoe ($G = 129.76$, $P < 0.0001$), dwarf mistletoe on the main stem ($G = 108.28$, $P < 0.0001$) and western gall rust ($G = 5.76$, $P = 0.0164$) were greater in the four Monterey Peninsula stands (Table 1.5).

When the Año Nuevo and Cambria stands were compared, the signs and symptoms of pitch canker ($G = 60.39$, $P < 0.0001$) and red turpentine beetle ($G = 35.49$, $P < 0.0001$) were greater and sequoia pitch moth ($G = 34.28$, $P < 0.0001$), dwarf mistletoe ($G = 6.72$, $P = 0.0095$) and dwarf mistletoe on the main stem ($G = 6.70$, $P = 0.0096$) were lower in the Año Nuevo stand.

When the two Monterey coastal stands combined were compared to the two Monterey inland stands combined, signs and symptoms of pitch canker ($G = 17.47$, $P < 0.0001$), red turpentine beetle ($G = 35.49$, $P < 0.0001$), dwarf mistletoe ($G = 5.57$, $P = 0.0183$), and dwarf mistletoe on the main stem ($G = 8.26$, $P = 0.0041$) were greater in the two Monterey coastal stands combined.

When the Monterey coastal 1 stand was compared to the Monterey coastal 2 stand, signs and symptoms of pitch canker ($G = 18.34$, $P < 0.0001$), sequoia pitch moth ($G = 73.65$, $P < 0.0001$), red turpentine beetle ($G = 17.03$, $P < 0.0001$), dwarf mistletoe ($G = 85.17$, $P < 0.0001$), dwarf mistletoe on the main stem ($G = 81.76$, $P < 0.0001$) and western gall rust ($G = 14.16$, $P = 0.0002$) were lower in the Monterey coastal 1 stand.

When the Monterey inland 1 stand was compared to the Monterey inland 2 stand, signs and symptoms of pitch canker ($G = 6.07$, $P = 0.0137$), dwarf mistletoe ($G = 23.73$, $P < 0.0001$), dwarf mistletoe on the main stem ($G = 19.74$, $P < 0.0001$) and western gall rust ($G = 23.38$, $P < 0.0001$) were greater in the Monterey inland 1 stand. None of the other contrasts between stands for signs and symptoms of forest health issues were significant.

When the four Monterey Peninsula stands combined were compared to the Año Nuevo and Cambria stands combined, the Hawksworth mistletoe rating was higher in the four Monterey Peninsula stands combined ($t = 5.25$, $P < 0.0001$) (Table 1.6).

When the Año Nuevo stand was compared to the Cambria stand, the pitch canker plot severity rating was higher ($t = 4.33$, $P < 0.0001$) and the number of sequoia pitch moth attacks per Monterey pine was lower ($t = 6.00$, $P < 0.0001$) at the Año Nuevo stand.

When the two Monterey coastal stands combined were compared to the two Monterey inland stands combined, the Hawksworth mistletoe rating ($t = 3.46$, $P = 0.0007$), pitch canker plot severity rating ($t = 2.72$, $P = 0.0073$) and number of red turpentine beetle attacks per Monterey pine ($t = 2.8$, $P = 0.0402$) were greater at the two Monterey coastal stands combined.

When the Monterey coastal 1 stand was compared to the Monterey coastal 2 stand, the Hawksworth mistletoe rating ($t = 3.78$, $P = 0.0002$), the pitch canker plot severity rating ($t = 3.57$, $P = 0.0005$), the number of sequoia pitch moth attacks per Monterey pine ($t = 4.59$, $P < 0.0001$) and the number of red turpentine beetle attacks per Monterey pine ($t = 2.07$, $P = 0.0402$) were lower in the Monterey coastal 1 stand.

When the Monterey inland 1 stand was compared to the Monterey inland 2 stand, the pitch canker plot severity rating was greater ($t = 2.38$, $P = 0.0185$) at the Monterey inland 1 stand. None of the other contrasts between stands for forest health severity were significant.

Regeneration

Comparing the 1999 regeneration data among the four stands on the Monterey Peninsula, the two Monterey coastal stands combined had more seedlings per hectare than the two Monterey inland stands combined ($t = 7.27$, $P < 0.0001$) (Table 1.7). The Monterey inland stand 1 had more seedlings per hectare than the Monterey inland 2 stand ($t = 3.31$, $P = 0.0024$). The Monterey coastal 2 stand had more recruits per hectare in the 0.15m-0.6m size class than the Monterey coastal 1 stand ($t = 2.34$, $P = 0.0261$). The Monterey inland 1 stand had more recruits per hectare in the 0.15m-0.6m size class than the Monterey inland 2 stand ($t = 3.14$, $P = 0.0037$). The two Monterey coastal stands combined had more trees >3.6m per hectare than the two Monterey inland stands combined ($t = 3.79$, $P = 0.0007$). None of the other contrasts between stands for 1999 regeneration were significant.

Comparing the 2005 seedling data among all six of the native stands, the four Monterey Peninsula stands combined had more seedlings per hectare than the Cambria and Año Nuevo stands combined ($t = 2.28$, $P = 0.0267$). The two Monterey coastal stands combined had more seedlings per hectare than the two Monterey inland stands combined ($t = 4.86$, $P < 0.0001$). The four Monterey Peninsula stands combined had more recruits in the 0.15m-0.6m size class per hectare than the Año Nuevo and Cambria stands combined ($t = 2.65$, $P = 0.0104$). The two Monterey coastal stands combined had more recruits in the 0.15m-0.60m size class per hectare than the two Monterey inland stands combined ($t = 4.87$, $P < 0.0001$). The number of recruits per hectare in the 0.6m-3.6m size class was greater at the Monterey coastal 2 stand than the Monterey coastal 1 stand ($t = 2.56$, $P = 0.0133$). The number of trees >3.6m per hectare was greater in the Cambria stand than the Año Nuevo stand ($t = 2.08$, $P = 0.0426$). All other of the standard set of contrasts between stands for 2005 regeneration were not significant.

Relationships among understory vegetation and regeneration

There were inverse correlations between poison oak and both Hooker's manzanita ($r = -0.3105$, 58 d.f., $P = 0.0157$) and shaggy-barked manzanita; ($r = -0.3022$, 58 d.f., $P = 0.0189$) and positive correlations between poison oak and both coffeeberry ($r = 0.3394$, 58 d.f., $P = 0.0080$) and California blackberry ($r = 0.3045$, 58 d.f., $P = 0.0180$). There was an inverse correlation between sticky monkey flower and California blackberry ($r = -0.3313$, 58 d.f., $P = 0.0097$) and there was an inverse correlation between the number of Monterey pine seedlings and total percent cover of all shrubs (r = -0.4759, 58 d.f., $P<0.001$). There was also an inverse correlation between the number of Monterey pine seedlings and percent cover of poison oak (r = -0.3194, 58 d.f., $P = 0.0020$).

Changes on the Monterey Peninsula from 1965-1966 to 2005

The mean trees per hectare decreased and the percentage of Monterey pine with a DBH >31 cm decreased, while the percentage of Monterey pine with a DBH <21cm increased. Examining data collected in 1965-1966, 1994 and 2005, most of the change occurred between 1994 and 2005 (Figure 1.8). The number of coast live oak increased, but the proportion of oaks in the three size classes of 10-21cm, 22-31cm and >31cm has remained relatively unchanged from 1965-1966 to 2005 (Table 1.8). Comparison of 1,520 quadrats, in 38 stands in 1965-1966 with 600 quadrats, in 30 transects in 2005 revealed only two species, yerba buena and western bracken fern, that had not changed significantly in quadrat frequency. Of the four shrub species recorded, quadrat frequency decreased over the forty-year period, with exception for poison oak, which significantly increased (Table 1.9).

Discussion

When examining the number of Monterey pines per hectare, the two Monterey coastal stands were not different from each other and the two Monterey inland stands were not different from each other. Difference between the three population locations and between inland and coastal stands, suggests a high variation of Monterey pines per hectare between geographic locations. The mean tree abundance per hectare for all species was similar among all of the stands except for the Cambria stand, which had a larger coast live oak component. The two Monterey coastal stands had more Monterey pines per hectare than the two Monterey inland stands and a lower mean LCR. However, the two Monterey coastal stands combined and the two Monterey inland stands combined had similar basal area of all species, basal area of Monterey pines, crown closure percentages, mean heights and mean DBH. This is consistent with higher densities of trees of similar size having lower LCRs due to shading of lower branches by adjacent trees. The lower mean LCR of the two Monterey coastal stands may be due to age. The crowns of Monterey pines tend to flatten with age (Scott, 1960), and it is possible trees are older in coastal stands and that the low mean LCR and flat crowns of the Monterey coastal stands are the result of offshore winds which can deform the crown of Monterey pines regardless of age.

Monterey pines in the Año Nuevo stand were larger (mean DBH 43.9cm) than the Cambria stand. In addition, basal area of Monterey pines and all species together were greater, but the number of Monterey pines per hectare was lower than the Cambria stand. The structural differences of the Año Nuevo stand may be due to the unique history of the population. The native population of Año Nuevo is the northern most population and contains a redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl) and Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) component, which are mostly absent from the Monterey Peninsula and Cambria populations. The Spanish mission-builders of the 1800s, seeking timber for missions, forts, general building construction, and many other uses, would have chosen the straight durable redwoods or the strong timbers of Douglas-fir over the generally crooked, decaysusceptible, and only moderately strong Monterey pines (Libby, 1997). Similar high grading likely occurred at the Monterey Peninsula and Cambria populations, but with Monterey pine effectively the only available species, several cycles of logging promoted reproduction of residual individual trees with poor form at the expense of genetically superior form individuals. It is these historical differences that may be reflected in the unique stand structure of the present day Año Nuevo stand.

The Año Nuevo and Cambria stands are located on donated land, which is owned and managed by California universities. To further contrast the three populations would require increasing the number of stands sampled within the Cambria and Año Nuevo populations to include geographic (coastal/inland) and ownership (private/public) variations similar to those sampled on the Monterey Peninsula.

The Monterey inland 1 stand had the lowest percentage of canopy closure (78.3%), the greatest abundance of poison oak (84% quadrat occurrence) and the lowest number of seedlings (42.5 per hectare). We would expect more light on the forest floor and therefore more seedlings. However it appears that the shrub layer, which developed as a result of lower canopy closure, has reduced the light environment on the forest floor. This is consistent with a low canopy closure in the Monterey inland 1 stand, resulting in increased understory competition and shrub species out-competing seedling regeneration. The lower percentage of canopy cover may also effect regeneration by increasing temperature and decreasing moisture on the forest floor. It has been reported that Monterey pines have greater seedling regeneration in cooler, damper sites than most other pines (McDonald and Laacke, 1990). Similar trends are found at the Año Nuevo stand where there is a high frequency of poison oak and California blackberry (78.5% and 72.8% quadrat occurrence, respectively) and low seedling counts (87.5 seedlings per hectare). Similarly low regeneration was found at the Año Nuevo stand in 1999, when seventeen 0.04 ha sub-plots of continuous forest inventory plots were sampled and Monterey pine seedlings or saplings were found in only 4 of the 17 plots for a total count of 45 per hectare (Piirto and Valkonen, 2005).

The two Monterey coastal stands combined had a greater amount of regeneration than the two Monterey inland stands combined. The coastal stands were also found to have greater frequency percentages of common yarrow, blue-eyed grass, horkelia species, Douglas iris, California bedstraw and daisy species which may suggest that on the Monterey Peninsula these herbaceous species are indicators of beneficial conditions for regeneration. The two Monterey inland stands had lower shrub species richness and more poison oak and California coffeeberry suggesting that these two shrub species may be indicators and/or contributors of non-beneficial conditions to regeneration.

There has been very little research conducted on the exotic species of native Monterey pine forests. In 2002, an informal survey (via questionnaire) of exotic plant species in the three mainland populations was performed, creating a non-comprehensive list of 38 exotic species (Rogers, 2002). The three most common exotic species found in 2005 were rattlesnake grass, pampas grass and French broom. Each of these received an “invasive” rating in the 2002 survey, indicating that the species were not only present in each of the three native populations, but identified as spreading from the original site of introduction. None of these three exotic species were found in the sampling of the Año Nuevo stand in 2005.

The Cambria stand had a higher frequency of occurrence for rattlesnake grass than any other stand. This may be due to the land use history of the Cambria stand sampled at the Kenneth S. Norris Rancho Marino Reserve. Year round grazing occurred at the reserve from 1940 to 1997 (Don Canestro, Reserve Director, personal communication, October 2005). Research conducted at the nearby Hearst Ranch suggests that cattle do not graze within the Monterey pine forest and generally forage elsewhere (Mel George, U.C. Davis, personal communication, November 2005). At the Kenneth S. Norris Rancho Marino Reserve, the cattle would have grazed on the coastal prairie between the ocean bluffs and native stand. It is possible that the halt in grazing in 1997 released all of the grass species of the coastal prairie, allowing rattlesnake grass to out-compete the native grasses and spread into the nearby native stand.

The pitch canker severity rating and proportion of Monterey pines with pitch canker symptoms were higher at the two Monterey coastal stands combined than the two Monterey inland stands combined. This supports the results of Wikler et al.'s three year study conducted on the Monterey Peninsula, which found a higher pitch canker severity rating and increased rate of spread in coastal plots than inland plots (Wikler et al., 2003).

The proportion of trees with pitch moth attacks and the number of attacks per tree were similar among inland and coastal stands on the Monterey Peninsula. The proportion of trees with red turpentine beetle attacks and number of attacks per tree were higher at the coast. This may be related to the high incidence of pitch canker along the coast, as red turpentine beetles typically infest stressed or dying trees (Barr et al., 1978). In 2005, the coastal stands also had a greater number of snags per hectare than the inland stands. It is not clear if they were killed by pitch canker, and these snags may be reflective of historically high red turpentine beetle populations.

The proportion of Monterey pines with western dwarf mistletoe and incidence on the mainstem were variable among the six native stands. In lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests, high variability of dwarf mistletoe infection reflected high genetic diversity and differing climatic conditions (Wu and Ying, 1998; Muir et al., 2004) and similar explanations of variability of dwarf mistletoe infection may be applicable to native Monterey pine forests.

The proportion of Monterey pines infected with western gall rust was low in all six stands. The proportion of infected trees in the two coastal stands and two inland stands were not different, and the proportion of infected trees in the Cambria stand and Año Nuevo stand were not different. Western gall rust does not require an alternative host to complete its life cycle and infection occurs directly between trees. This can allow for rapid intensification of the disease when conditions optimal for infection occur (Peterson, 1960). The low proportion of infected trees may indicate the conditions of native Monterey pine are less susceptible to western gall rust than other pine species.

The methods for assessing regeneration in 2005 were designed to replicate the methodology used in 1999 to collect regeneration data. The same four stands were sampled both years, but the locations of transects within the stands were different.

Seedlings were present in each of the four Monterey Peninsula stands in 1999 and each stand had an increase in seedlings per hectare in 2005.

The Monterey coastal 2 stand had the greatest number of total recruits per hectare in 1999 and 2005 (1202 and 1620, respectively). In 2005, the Cambria stand which was approximately 1 km from the ocean, had 864 total recruits per hectare and was most comparable to the two Monterey coastal stands (1022 and 1620), while the Año Nuevo stand, which was approximately 5 km from the ocean, had a total of 150 total recruits per hectare and was most comparable to the two Monterey inland stands (218 and 190, respectively).

In 2005, the two Monterey coastal stands had more total recruits per hectare than the two Monterey inland stands. In both of the Monterey coastal stands the number of recruits in the each cohort increased, except for slight decreases in the >3.6m tree size class of both stands. In the two Monterey inland stands the number of seedlings per hectare has increased from 1999 to 2005, but at a much slower rate than the Monterey coastal stands.

The inverse correlation between the number of Monterey pine seedlings and total percent cover of all shrubs, and percent cover of poison oak, suggests that active management to remove understory shrubs and poison oak in both the Monterey inland stands and Año Nuevo stands would increase natural regeneration. The lower shrub species richness and research conducted on Monterey pine seedling growth in New Zealand, showed that regeneration was greater in plots without Scotch broom (*Cytisus scoparius* (L.) Link) competition, compared to plots with shrub competition (Watt et al., 2004). Although the research was conducted on a plantation, the removal of shrub competition in the native stands would likely have a similar effect of increased regeneration.

The data collected by White in the summers of 1965-1966, provides a unique opportunity to examine the development of the native Monterey Peninsula population over a 40-year period. The methodology used in 1965-1966 (Vogl et al. 1977) and repeated by White in 1994 (White 1999) was different than the methods used in 2005. White collected data from 38 stands approximately 1 hectare in size, omitting the Monterey coastal 1 stand (Huckleberry Hill). Ten quarter points were randomly located within each stand and a total of 40 trees (DBH >10cm) and 40 saplings (2.5cm-10cm DBH) per stand were sampled for frequency, species, basal area and density within each stand (Vogl et al. 1977). Understory vegetation and seedlings of each stand were tallied in forty 0.1m x 0.1m quadrats. In February of 1994, when the 38 stands located on the Monterey Peninsula were to be resampled, twelve of the stands were found to have been modified since 1965-1966 such that data collection was not possible. Another seven stands were not accurately relocated, reducing the sample size to 19 of the original 38 stands (White 1999).

Acknowledging these sampling differences, trends can still be observed over the past 40 years. Pitch canker may be the causal agent, which is shifting the Monterey Peninsula forests to a more open system, allowing for the release of younger cohorts of trees. The increased number of coast live oak may indicate that the introduction of pitch canker is affecting the abundance of coast live oak.

Difference in sampling methods of understory vegetation may not enable accurate comparison of the understory plant community over time.

Conclusion

Pitch canker and red turpentine beetles are more prevalent in coastal stands than inland stands on the Monterey Peninsula. Regeneration rates and recruitment success is also greater in the coastal stands. Pitch canker may have opened the forest for natural regeneration in the coastal stands, while shrubs reduce the light reaching the forest floor in the inland stands and out-compete regeneration. The richness of shrub species is lower in the inland stands and the negative correlation of poison oak percent cover to seedling regeneration, indicate poison oak is dominating the understory and regeneration of the inland stands.

To increase regeneration and recruitment of the inland stands, active management may be required. The removal of shrub species by prescribed burning or mechanical treatment would reduce the percent of shrub cover and be expected enhance the regeneration of native Monterey pine.

This research is one of the few contemporary characterizations of the forest health, stand structure and understory plant community of the three native Monterey pine populations. Further research based upon these results would develop further understanding of the complex relationships among overstory, understory and forest health in the native Monterey pine populations. In particular, manipulative studies where altered overstory and understory conditions are created would help to understand the potential for future management to influence Monterey pine regeneration.

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Table 1.1: Frequency (%) of occurrence for the twelve most common herbaceous species of six native Monterey pine stands in coastal California in 2005. Each stand was >80 ha in size. Four stands were located on the Monterey Peninsula, and one stand each was located at Año Nuevo and Cambria. Data were square root transformed for all species, as a result asymmetric SE are reported.

	Stands												
	Monterey coastal 1		Monterey coastal 2		Monterey inland 1		Monterey inland 2		Año Nuevo		Cambria		significant
herbaceous species	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	contrasts [1]
Achillea millefolium L.	3.1	+1.2	3.0	+1.2	0.4	+0.9	0.8	+0.9	0.0	+0.0	3.6	+1.3	
common yarrow		-1.4		-1.4		-1.0		-1.1		-0.0		-1.4	b,c
Agastache urticifolia (Benth.) Kuntze	0.4	+1.6	1.6	+2.0	11.9	+4.1	13.2	+4.3	21.2	+5.4	13.7	+4.4	
horsemint		-2.3		-2.7		-4.8		-4.9		-6.0		-5.0	a,c
Calystegia occidentalis (Gray) Brum.	0.0	+0.0	1.3	+0.8	1.4	+0.8	0.7	+0.7	0.4	+0.7	2.7	+0.9	
western morning glory		-0.0		-0.9		-0.9		-0.8		-0.8		-1.0	none
Erigeron L.	9.9	+3.0	13.0	+3.4	0.0	+0.0	0.0	+0.0	12.0	+3.3	0.4	+1.3	
daisy species		-3.4		-3.8		-0.0		-0.0		-3.7		-1.8	b,c
Fragaria vesca L.	2.0	+1.5	8.3	+2.3	2.8	+1.6	1.5	+1.4	2.5	+1.5	9.3	+2.4	
wood strawberry		-1.7		-2.6		-1.9		-1.7		-1.8		-2.7	b,d
Galium californicum H.& A.	2.3	+1.6	7.5	+2.5	0.0	+0.0	0.0	+0.0	0.4	+1.2	0.0	+0.0	
California bedstraw		-1.9		-2.8		-0.0		-0.0		-1.6		-0.0	c
Galium murale (L.) All.	12.0	+5.0	20.9	+6.5	33.4	+8.2	27.5	+7.5	9.1	+4.5	28.9	+7.7	
tiny bedstraw		-6.1		-7.6		-9.3		-8.5		-5.5		-8.7	b
Horkelia Cham. & Schlecht.	1.9	+1.3	8.5	+2.1	0.0	+0.0	0.0	+0.0	0.0	+0.0	1.6	+1.2	
horkelia species		-1.5		-2.3		-0.0		-0.0		-0.0		-1.5	c,d
Iris douglasiana Herb.	3.0	+1.6	4.7	+1.8	0.0	+0.0	0.0	+0.0	2.3	+1.5	0.0	+0.0	
Douglas iris		-1.9		-2.1		-0.0		-0.0		-1.7		-0.0	c
Satureja douglasii (Benth.) Briq.	9.8	+3.9	13.7	+4.6	12.5	+4.4	4.5	+2.9	2.6	+2.4	14.9	+4.8	
yerba buena		-4.7		-5.4		-5.2		-3.7		-3.2		-5.6	b
Sisyrinchium bellum Wats.	0.0	+0.0	4.4	+1.1	0.0	+0.0	0.4	+0.7	0.7	+0.7	0.0	+0.0	
blue-eyed grass		-0.0		-1.2		-0.0		-0.8		-0.8		-0.0	c,d
Vicia americana Willd.	1.3	+1.7	2.2	+1.9	8.1	+3.1	3.0	+2.1	3.9	+2.3	11.7	+3.6	
American vetch		-2.3		-2.5		-3.6		-2.7		-2.9		-4.1	none

[1] a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined, b = the Año Nuevo stand v. the Cambria stand, c = the two Monterey coastal stands combined v. the two Monterey inland stands combined, d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand, e = the Monterey inland 1 stand v. the Monterey inland 2 stand. SE; standard error. $\alpha = 0.05$.

Table 1.2: Frequency (%) of occurrence for the nine most common shrub species of six native Monterey pine stands in coastal California in 2005. Each stand was >80 ha in size, four were located on the Monterey Peninsula and one each at Año Nuevo and Cambria Data were square root transformed for all species except poison oak, as a result asymmetric SE are reported.

	Stands												
	Monterey coastal 1		Monterey coastal 2		Monterey inland 1		Monterey inland 2		Año Nuevo		Cambria		
shrub species	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	significant contrasts[1]
Arctostaphylos hookeri G. Don	9.1	+2.9	7.9	+2.8	0.0	+0.0	0.7	+1.5	0.0	+0.0	0.0	+0.0	
Hooker's manzanita		-3.4		-3.3		-0.0		-1.9		-0.0		-0.0	a,c
Arctostaphylos tomentosa (Pursh) Lindl.	16.2	+3.6	2.8	+1.8	1.4	+1.6	10.3	+2.9	0.0	+0.0	0.0	+0.0	
shaggy-barked manzanita		-4.0		-2.2		-1.9		-3.3		-0.0		-0.0	a,d,e
Baccharis pilularis DC.	2.1	+1.4	1.9	+1.4	2.5	+1.5	0.0	+0.0	6.0	+1.9	1.5	+1.4	
coyote brush		-1.7		-1.7		-1.8		-0.0		-2.2		-1.6	none
Mimulus aurantiacus Curt.	7.6	+3.6	26.6	+6.3	23.7	+6.0	17.7	+5.2	0.4	+1.7	21.7	+5.8	
sticky monkey flower		-4.4		-7.1		-6.8		-5.9		-2.5		-6.5	a,b,d
Rhamnus californica Eschs.	2.5	+1.9	0.0	+0.0	12.7	+3.5	2.9	+2.0	0.8	+1.5	14.7	+3.8	
California coffeeberry		-2.4		-0.0		-3.9		-2.5		-2.0		-4.2	b,c,e
R*ubus ursinus* Cham. & Schlecht.	29.1	+5.5	4.6	+2.5	7.8	+3.1	5.8	+2.7	72.8	+8.7	17.7	+4.4	
California blackberry		-6.0		-3.0		-3.6		-3.2		-9.2		-4.9	a,b,d
S*ymphoricarpos mollis* Nutt.	5.1	+2.7	18.5	+4.7	10.4	+3.7	4.2	+2.5	3.6	+2.4	2.6	+2.2	
creeping snowberry		-3.3		-5.3		-4.2		-3.1		-3.0		-2.8	a,d
Toxicodendron diversilobum (T.&G.) Greene	20.0	+7.9	27.0	+7.9	84.0	+7.9	47.5	+7.9	78.5	+7.9	52.5	+7.9	
poison oak		-7.9		-7.9		-7.9		-7.9		-7.9		-7.9	a,b,c,e
Vaccinium ovatum Pursh	21.4	+3.6	0.0	+0.0	0.0	+0.0	0.0	+0.0	0.0	+0.0	0.0	+0.0	
evergreen huckleberry		-3.8		-0.0		-0.0		-0.0		-0.0		-0.0	a,c,e

[1] a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined, b = the Año Nuevo stand v. the Cambria stand, c = the two Monterey coastal stands combined v. the two Monterey inland stands combined, d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand, e = the Monterey inland 1 stand v. the Monterey inland 2 stand. SE; standard error. $\alpha = 0.05$.

Table 1.3: Frequency (%) of occurrence for grass and sedge species of six native Monterey pine stands in coastal California in 2005. Each stand was >80 ha in size, four were located on the Monterey Peninsula and one each at Año Nuevo and Cambria.

	Stands												
	Monterey coastal 1		Monterey coastal 2		Monterey inland 1		Monterey inland 2		Año Nuevo		Cambria		significant
	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	contrasts [1]
Cyperaceae	4.7	+1.7	2.9	+1.5	0.0	+0.0	0.4	+1.0	8.1	+2.1	0.0	+0.0	
sedge species		-1.9		-1.7		-0.0		-1.3		-2.3		-0.0	b,c
Poaceae	61.5	+6.8	86.5	+6.8	64.0	+6.8	64.5	+6.8	79.0	+6.8	83.0	+6.8	
grass species		-6.8		-6.8		-6.8		-6.8		-6.8		-6.8	a,d

[1] a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined, b = the Año Nuevo stand v. the Cambria stand, c = the two Monterey coastal stands combined v. the two Monterey inland stands combined, d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand, e = the Monterey inland 1 stand v. the Monterey inland 2 stand. SE; standard error. $\alpha = 0.05$.

Table 1.4: Frequency (%) of occurrence for the three most common exotic species of six native Monterey pine stands in coastal California in 2005. Each stand was >80 ha in size, four were located on the Monterey Peninsula and one each at Año Nuevo and Cambria.

	Stands												
	Monterey coastal 1		Monterey coastal 2		Monterey inland 1		Monterey inland 2		Año Nuevo		Cambria		significant
exotic species	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	contrasts[1]
Briza maxima L.	1.1	+1.3	0.8	+1.2	0.0	+0.0	0.0	+0.0	0.0	+0.0	47.6	+4.9	
rattlesnake grass		-1.5		-1.5		-0.0		-0.0		-0.0		-5.3	a,b
Cortaderia jubata (Lemoine) Stapf	2.0	+1.2	0.4	+0.9	3.6	+1.4	0.0	+0.0	0.0	+0.0	0.0	+0.0	
pampas grass		-1.4		-1.1		-1.6		-0.0		-0.0		-0.0	e
Genista monspessulana (L.) L. Johnson	1.6	+0.9	2.6	+1.0	0.0	+0.0	1.8	+0.9	0.0	+0.0	0.0	+0.0	
french broom		-1.0		-1.2		-0.0		-1.1		-0.0		-0.0	a,d

[1] a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined, b = the Año Nuevo stand v. the Cambria stand, c = the two Monterey coastal stands combined v. the two Monterey inland stands combined, d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand, e = the Monterey inland 1 stand v. the Monterey inland 2 stand. SE; standard error. $\alpha = 0.05$.

Table 1.5: Pest and disease incidence (%) of six native Monterey pine stands in coastal California in 2005. Each stand was >80 ha in size, four were located on the Monterey Peninsula and one each at Año Nuevo and Cambria.

	Stands												
	Monterey coastal 1		Monterey coastal 2		Monterey inland 1		Monterey inland 2		Año Nuevo		Cambria		significant
Pests and Diseases	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	contrasts[1]
pitch canker	21.9	2.1	36.3	2.6	22.9	2.7	14.6	2.1	35.3	3.5	8.0	1.4	a,b,c,d,e
sequoia pitch moth	16.4	1.9	45.3	2.7	29.8	2.9	32.2	2.7	0.0	0.0	12.2	1.7	a,b,d
red turpentine beetle	22.6	2.1	36.6	2.7	20.8	2.6	22.4	2.4	35.3	3.5	13.0	1.8	a,b,c,d
dwarf mistletoe	10.0	1.5	38.4	2.7	26.1	2.8	10.2	1.8	0.0	0.0	3.3	0.9	a,b,c,d,e
dwarf mistletoe on mainstem	8.7	1.4	35.6	2.6	22.0	2.7	8.5	1.6	0.0	0.0	3.3	0.9	a,b,c,d,e
western gall rust	1.2	0.6	6.3	1.3	9.8	1.9	1.0	0.6	1.6	0.9	2.2	0.8	a,d,e

[1] a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined, b = the Año Nuevo stand v. the Cambria stand, c = the two Monterey coastal stands combined v. the two Monterey inland stands combined, d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand, e = the Monterey inland 1 stand v. the Monterey inland 2 stand. SE; standard error. $\alpha = 0.05$.

Table 1.6: Forest health severity measures of six native Monterey pine stands in coastal California in 2005. Each stand was >80 ha in size, four were located on the Monterey Peninsula and one each at Año Nuevo and Cambria.

	Stands												
	Monterey coastal 1		Monterey coastal 2		Monterey inland 1		Monterey inland 2		Año Nuevo		Cambria		
Pests and Diseases	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	significant contrasts[1]
Hawksworth mistletoe rating	0.6	+0.1 -0.1	11.4	+0.1 -0.1	0.5	+0.1 -0.1	0.5	+0.1 -0.1	0.0	+0.0 -0.0	0.2	+0.1 -0.1	a,c,d
pitch canker plot severity rating	3.8	+1.1 -1.0	10.6	+1.3 -1.2	5.5	+1.3 -1.2	2.2	+0.8 -0.7	7.5	+ 1.5 -1.3	1.3	+0.7 -0.5	b,c,d,e
sequoia pitch moth incidence	0.9	+0.4 -0.3	3.9	+0.6 -0.6	1.7	+0.4 -0.4	3.0	+0.6 -0.5	0.0	+0.0 -0.0	1.5	+0.4 -0.4	b,d
red turpentine beetle incidence	2.6	+0.5 -0.4	4.1	+0.6 -0.5	1.8	+0.4 -0.4	2.3	+0.4 -0.4	1.8	+0.4 -0.4	2.5	+0.5 -0.4	c,d

[1] a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined, b = the Año Nuevo stand v. the Cambria stand, c = the two Monterey coastal stands combined v. the two Monterey inland stands combined, d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand, e = the Monterey inland 1 stand v. the Monterey inland 2 stand. SE; standard error. $\alpha = 0.05$.

Table 1.7: Regeneration of six native Monterey pine stands in coastal California in 1999 and 2005. Each stand was >80 ha in size. Four stands were located on the Monterey Peninsula and one each at Año Nuevo and Cambria. 1999 does not include the Ano Nuevo and Cambria stands.

		Stands												
		Monterey coastal 1		Monterey coastal 2		Monterey inland 1		Monterey inland 2		Año Nuevo		Cambria		
regeneration cohorts	year	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	significant contrasts[1]
seedlings	1999	463.5	+130.9 -74.1	681.3	+337.0 -202.4	37.5	+14.3 -8.3	3.1	+1.2 -0.7	n/a		n/a		c,e
	2005	477.5	+157.9 -84.5	1130.0	+655.9 -350.7	42.5	+6.6 -3.5	82.5	+35.4 -18.9	87.5	+31.6 -16.9	100.0	+13.2 -7.1	a,c
0.15m-.60m	1999	352.5	+39.9 -19.1	780.0	+341.5 -177.1	202.5	+175.9 -88.1	36.7	+0.9 -0.3	n/a		n/a		d,e
	2005	866.0	+61.3 -29.0	1100.0	+276.9 -131.1	18.0	+2.6 -1.3	30.0	+4.4 -2.1	2.0	+1.5 -0.7	210.0	+9.5 -4.5	a,c
0.6m-3.6m	1999	50.0	+9.8 -4.3	285.0	+63.2 -30.5	202.5	+104.2 -48.3	158.1	+86.7 -38.4	n/a		n/a		none
	2005	156.0	+72.4 -53.8	520.0	+139.8 -121.2	200.0	+79.6 -61.0	160.0	+81.4 -62.8	148.0	+77.0 -58.3	654.0	+128.0 -109.4	d
>3.6m	1999	596.7	+92.8 -85.9	540.0	+78.6 -73.0	385.0	+69.8 -63.6	242.9	+56.3 -49.4	n/a		n/a		c
	2005	554.0	+51.8 -51.8	458.0	+51.8 -51.8	412.0	+51.8 -51.8	416.0	+51.8 -51.8	374.0	+51.8 -51.8	526.0	+51.8 -51.8	b

[1] a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined, b = the Año Nuevo stand v. the Cambria stand, c = the two Monterey coastal stands combined v. the two Monterey inland stands combined, d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand, e = the Monterey inland 1 stand v. the Monterey inland 2 stand. SE; standard error. $\alpha = 0.05$.

Table 1.8: Stand structure comparisons from 1965-1966, 1994 and 2005 of the native Monterey pine population on the Monterey Peninsula, California

	Year		
	1965-1966	1994	2005 [1]
No. Monterey pine sampled	640	626	880
No. coast live oak sampled	120	134	255
mean trees/ha	636	460	302
mean stand dbh (cm)	34	40.2	27.8
mean Monterey pine dbh (cm)	37.2	44.3	32.8
mean coast live oak dbh (cm)	21.1	18.7	17.7
% Monterey pine 10-21 dbh (cm)	30	22	42
% Monterey pine 22-31dbh (cm)	26	16	26
% Monterey pine >31dbh (cm)	44	62	32
No. Monterey pine >100 dbh (cm)	1	4	9
% coast live oak 10-21 dbh (cm)	72	72	77
% coast live oak 22-31 dbh (cm)	16	18	16
% coast live oak >31 dbh (cm)	12	10	7
No. coast live oak >50 dbh (cm)	7	3	3

[1] Monterey coastal 1 stand (Huckleberry Hill) was purposely avoided by White in 1965-1966 and 1994, for accurate comparison the Monterey coastal 1 stand is excluded from the 2005 data.

Table 1.9: Frequency (%) of occurrence for understory species in 1965-1966 and 2005 of the native Monterey pine population located on the Monterey Peninsula, California.

	1965-1966		2005 [1]		Comparison of quadrat frequency	
understory species	stand frequency (%)	quadrat presence (%)	transect frequency (%)	quadrat presence (%)	*G*	*P*
Galium murale (L.) All. tiny bedstraw	95.8	47.6	83.3	32.2	42.13	<0.0001
Toxicodendron diversilobum (T.&G.) Greene poison oak	93.7	29.3	86.7	52.8	100.66	<0.0001
Vicia americana Willd. American vetch	54.1	35.7	36.7	6.7	216.71	<0.0001
Symphoricarpos mollis Nutt. creeping snowberry	43.7	34.0	60.0	13.8	94.50	<0.0001
R*ubus ursinus* Cham. & Schlecht. California blackberry	60.4	20.6	46.7	8.8	52.69	<0.0001
Satureja douglasii (Benth.) Briq. yerba buena	52.0	14.6	56.7	14.3	0.02	0.8875
Mimulus aurantiacus Curt. sticky monkey flower	89.5	6.0	80.0	2.8	10.14	0.0015
Fragaria vesca L. wood strawberry	33.3	9.5	40.0	5.7	8.51	0.0035
Galium californicum H.& A. California bedstraw	27.0	8.6	10.0	4.6	10.63	0.0011
Iris douglasiana Herb. Douglas iris	33.3	5.0	13.3	2.7	5.95	0.0147
Achillea millefolium L. common yarrow	31.2	5.3	23.3	1.8	14.68	0.0001
Pteridium aquilinum (L.) Kuhn western bracken fern	25.0	6.5	33.3	6.2	0.08	0.7773

[1] Monterey coastal 1 stand (Huckleberry Hill) was purposely avoided by White in 1965-1966 and 1994, for accurate comparison the Monterey coastal 1 stand is excluded from the 2005 data.

Figure 1.1: Map showing the approximate locations of three native Monterey pine (*Pinus radiata*) populations along the central coast of California. In 2005, six stands >80ha in size were selected for sampling; four on the Monterey Peninsula and one each at Año Nuevo and Cambria.

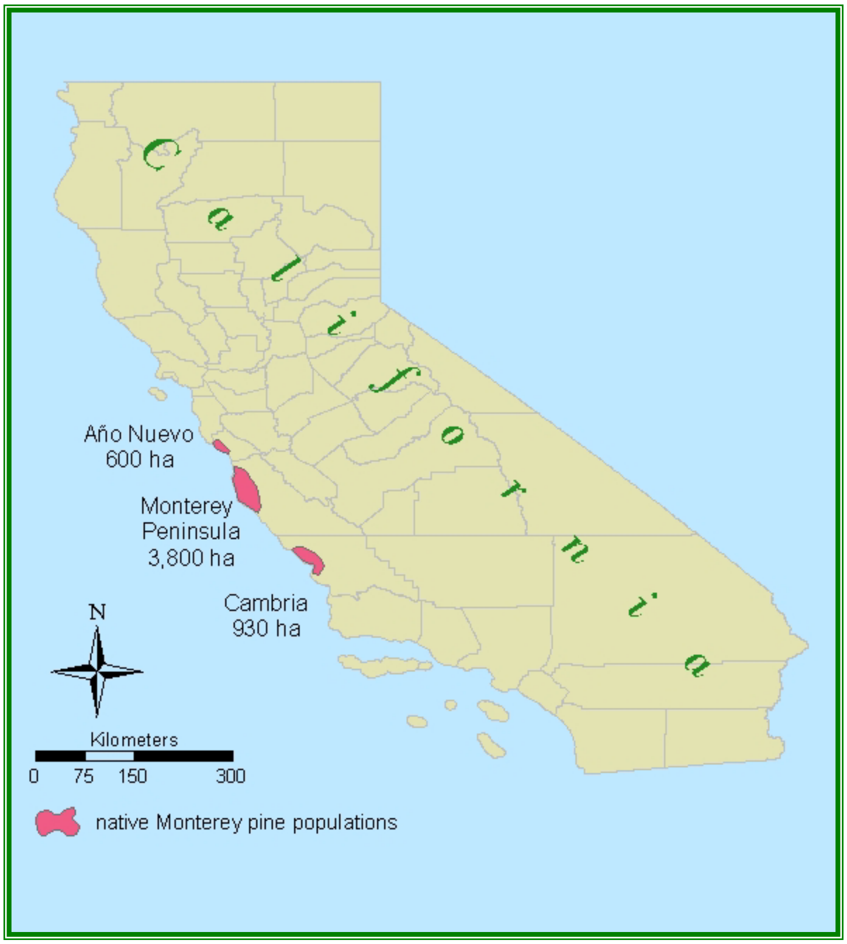


Figure 1.2: Map of sampling transect, plots and quadrats within six native Monterey pine stands in coastal California. Each stand was >80ha in size. Four stands were located on the Monterey Peninsula, and one stand each was located at Año Nuevo and Cambria. In 2005, 10 sampling installations consisting of one 100m x 5m belt transect with a 1m x 1m quadrat placed every 5m along the transect, and one 0.04 hectare plot placed at the beginning, middle and end of the transect, were installed in each stand.

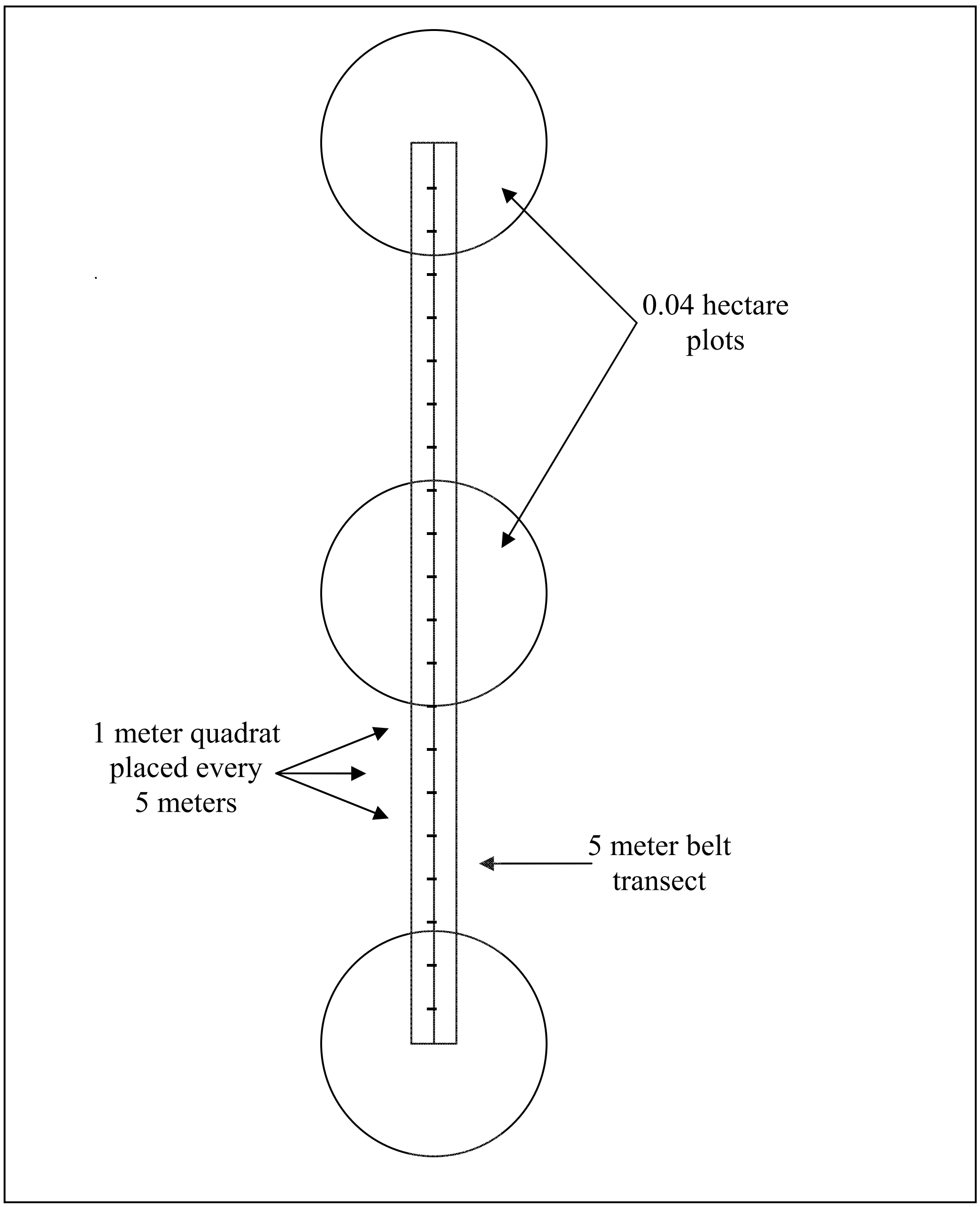
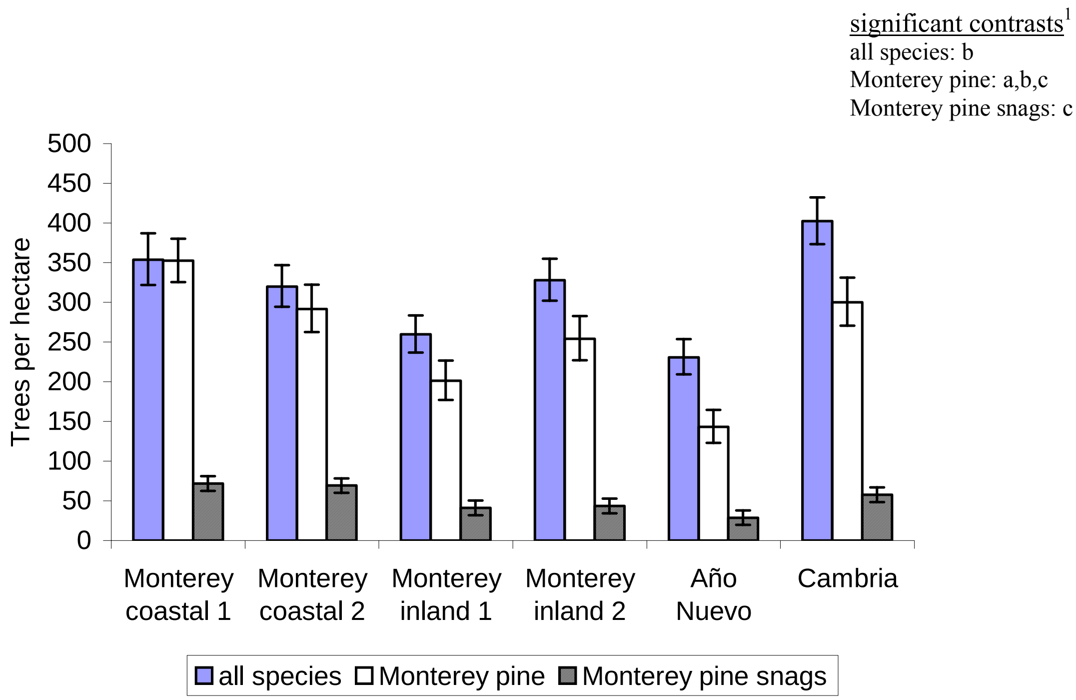
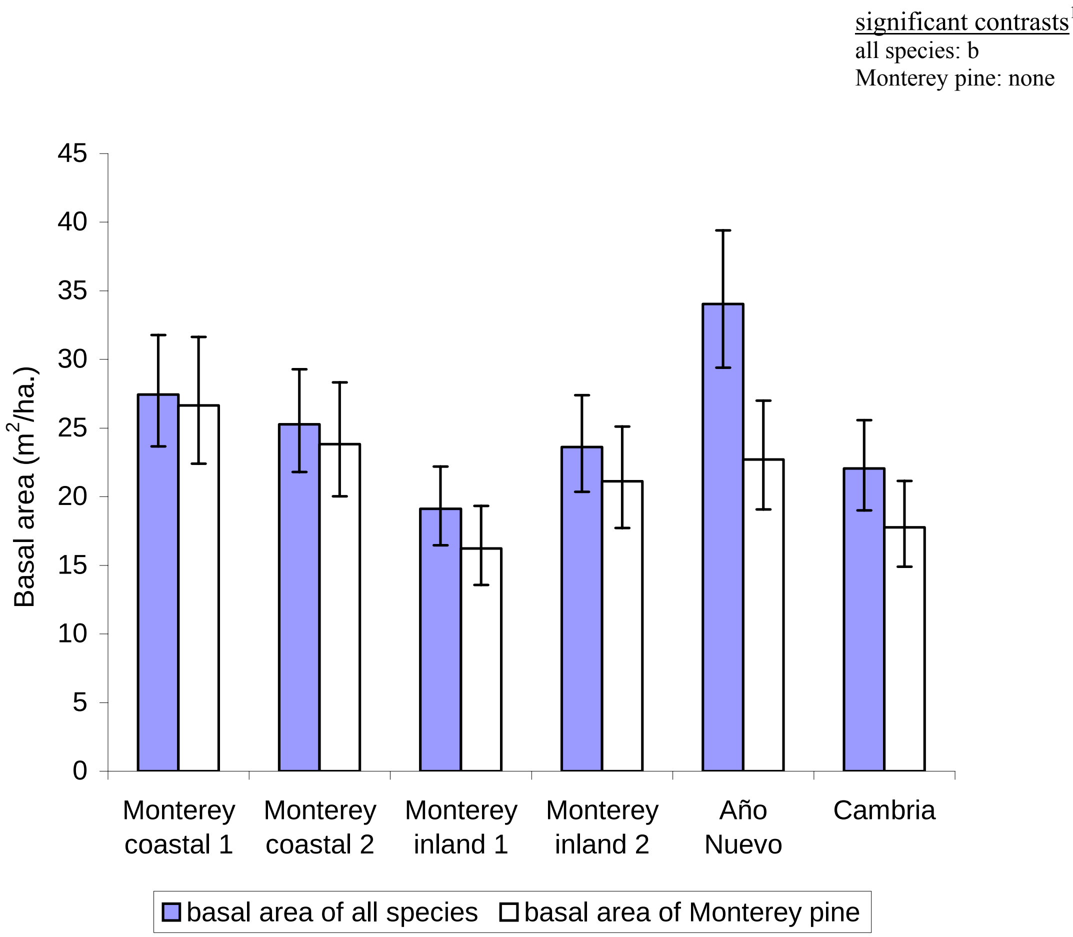


Figure 1.3: Mean number of overstory trees per hectare of six native Monterey pine stands in coastal California in 2005. Each stand was >80ha in size. Four stands were located on the Monterey Peninsula, and one stand each was located at Año Nuevo and Cambria.



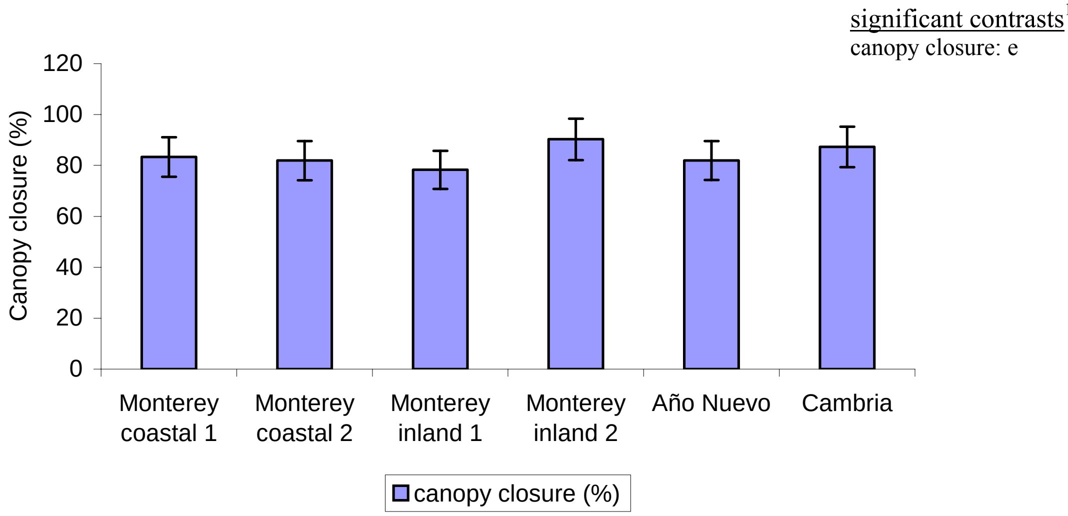
[1]Five user defined contrasts were performed following one way ANOVA;
a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined,
b = the Año Nuevo stand v. the Cambria stand,
c = the two Monterey coastal stands combined v. the two Monterey inland stands combined,
d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand,
e = the Monterey inland 1 stand v. the Monterey inland 2 stand.

Figure 1.4: Mean basal area (m^2/ha) of six native Monterey pine stands in coastal California in 2005. Each stand was >80ha in size. Four stands were located on the Monterey Peninsula, and one stand each was located at Año Nuevo and Cambria.



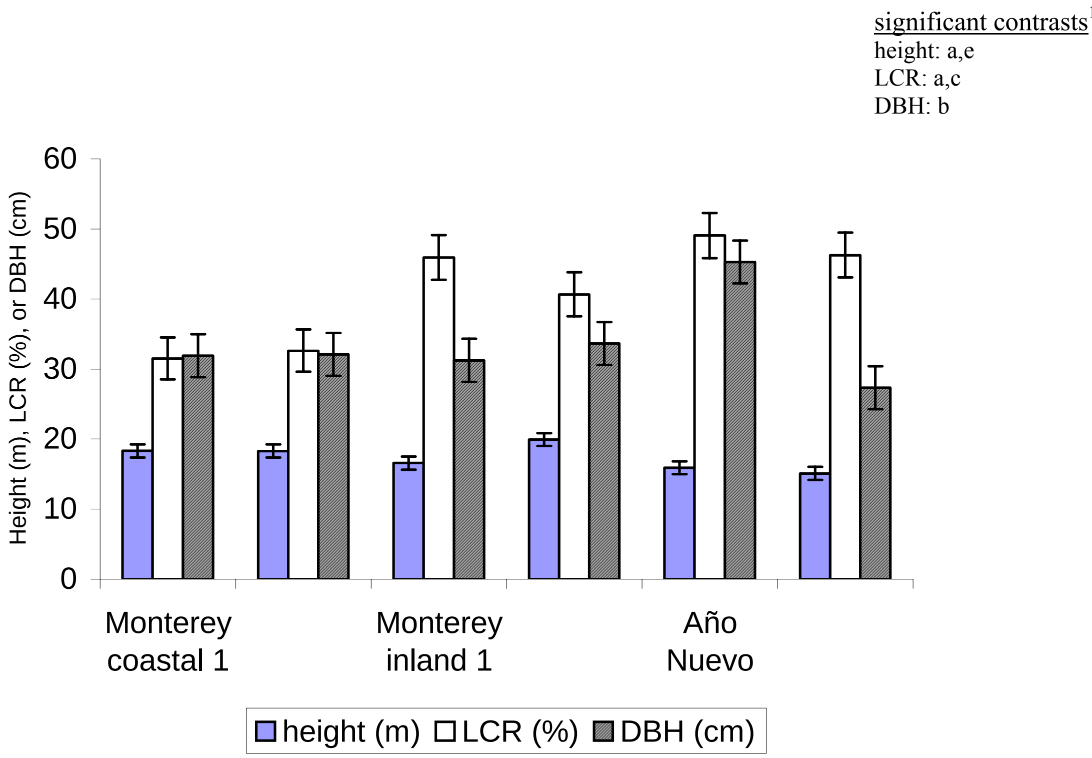
[1]Five user defined contrasts were performed following one way ANOVA;
a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined,
b = the Año Nuevo stand v. the Cambria stand,
c = the two Monterey coastal stands combined v. the two Monterey inland stands combined,
d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand,
e = the Monterey inland 1 stand v. the Monterey inland 2 stand.

Figure 1.5: Mean percent canopy closure of six native Monterey pine stands in coastal California in 2005. Each stand was >80ha in size. Four stands were located on the Monterey Peninsula, and one stand each was located at Año Nuevo and Cambria.



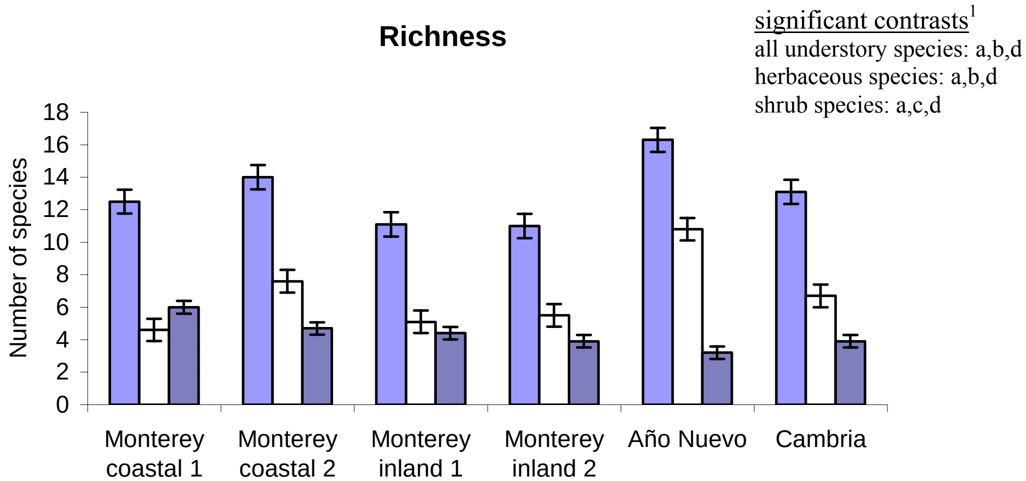
[1]Five user defined contrasts were performed following one way ANOVA;
a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined,
b = the Año Nuevo stand v. the Cambria stand,
c = the two Monterey coastal stands combined v. the two Monterey inland stands combined,
d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand,
e = the Monterey inland 1 stand v. the Monterey inland 2 stand.

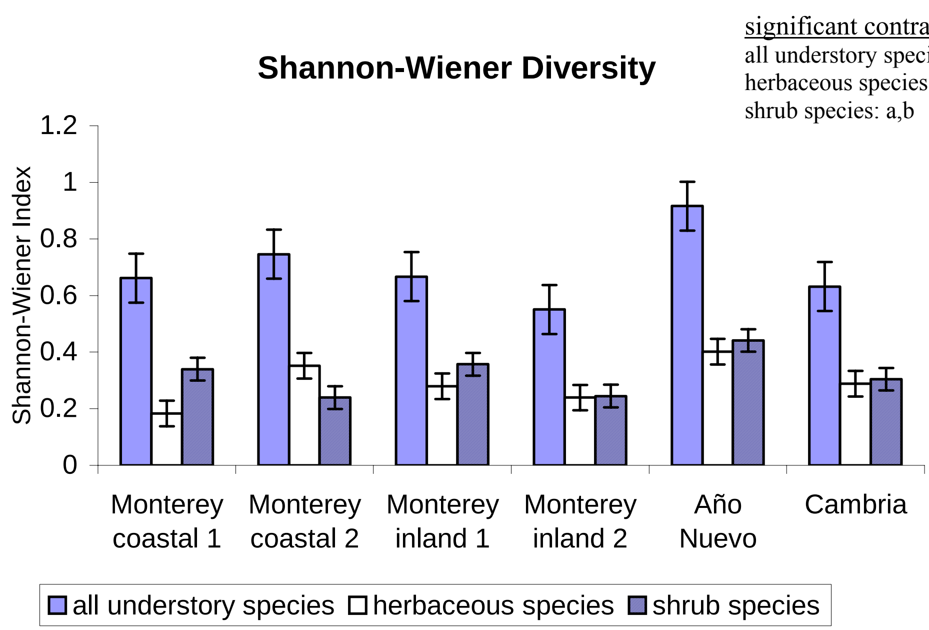
Figure 1.6: Height, live crown ratio (LCR) and diameter at breast height (DBH) of Monterey pines from six native Monterey pine stands in coastal California in 2005. Each stand was >80ha in size. Four stands were located on the Monterey Peninsula, and one stand each was located at Año Nuevo and Cambria.



[1]Five user defined contrasts were performed following one way ANOVA;
a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined,
b = the Año Nuevo stand v. the Cambria stand,
c = the two Monterey coastal stands combined v. the two Monterey inland stands combined,
d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand,
e = the Monterey inland 1 stand v. the Monterey inland 2 stand.

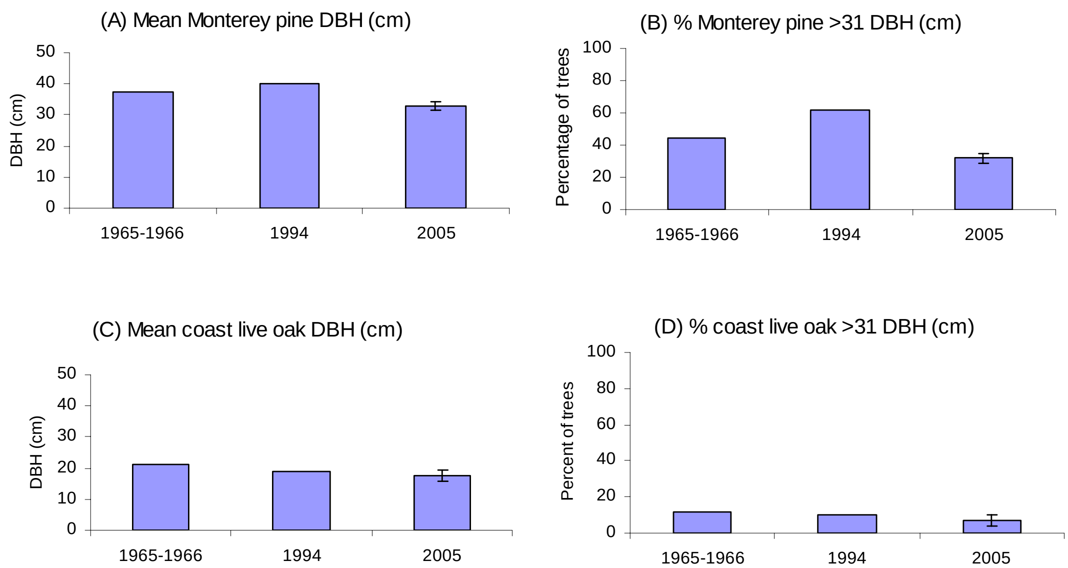
Figure 1.7: Richness and Shannon-Wiener Diversity indices of understory vegetation of six native Monterey pine stands in coastal California in 2005. Four stands were located on the Monterey Peninsula, and one stand each was located at Año Nuevo and Cambria.





[1]Five user defined contrasts were performed following one way ANOVA;
a = the four Monterey Peninsula stands combined v. the Año Nuevo and Cambria stands combined,
b = the Año Nuevo stand v. the Cambria stand,
c = the two Monterey coastal stands combined v. the two Monterey inland stands combined,
d = the Monterey coastal 1 stand v. the Monterey coastal 2 stand,
e = the Monterey inland 1 stand v. the Monterey inland 2 stand

Figure 1.8: The stand structure of the native Monterey Peninsula population over a 40-year time period for Monterey pine (A) and (B), and coast live oak (C) and (D). Data collection in 1965-66 is from 38 stands each approximately 1ha in size. Data collected in 1994 is of 19 stands 1ha in size. Data collected in 2005 is of three natural stands greater than 80 ha in size. Standard error values were not published for White's data collected in 1965-66 or 1994.



Chapter 2

TREE HEALTH AS A PREDICTOR OF MONTEREY PINE (*PINUS RADIATA*) STREET TREE REMOVAL FROM AN URBAN FOREST

(Prepared for “Hortscience”)

Abstract. The urban forest of Carmel-by-the-Sea, California, provides an array of benefits for residents and tourists including improving local air quality and promoting human health. Of publicly owned trees, 34% are Monterey pine (*Pinus radiata* D. Don). Data collected in 2005 from 285 Monterey pine street trees was integrated with a database dating back to 1988 to evaluate which biological and environmental factors were predictive of tree removal. Since 1994, this forest has been increasingly impacted by pitch canker, a disease caused by an exotic pathogen. The height and diameter in 1988 of trees that had been removed by 2005 were significantly greater than trees not removed and the presence of red turpentine beetles (Coleoptera: Scolytidae) in 1992 was a significant indicator of tree removal. Trees that developed pitch canker by 2005 were shorter in 1988, were more likely to have pitch moth and had a greater number of pitch moth attacks in 1988 than were trees which did not develop pitch canker by 2005. Measurements of tree heights and diameters, as well as attacks by the red turpentine beetle are useful predictors of future tree removal.

INTRODUCTION

Urban forests provide various benefits to people who visit, live and work in the city. An urban forest can conserve energy, reduce storm water runoff, improve local air quality, enhance community attractiveness and investment, increase property value, and even promote human health and well being (McPherson, 2003). One of the major beneficial effects is the improvement of local air quality by the removal of particulate pollution (Beckett et al., 2000). Adverse health effects have been linked to high concentrations of particulate matter (Zhu et al, 2002; Becker et al., 2003), especially finer particles that can penetrate deeper into the lung (Quarg, 1996). Conifers are more efficient at improving urban air quality than broadleaf species (Fergusson et al., 1980) due to their evergreen habit, speed of establishment and very high surface area (Godzik et al, 1979; Beckett et al., 1998).

Urban forests also reflect the values, lifestyle preferences, and aspirations of current and past residents (McPherson, 1998). The City of Carmel-by-the-Sea occupies 282 ha and is located in Monterey County, California, situated at the edge of the largest of three mainland native Monterey pine (*Pinus radiata* D. Don) populations (Huffman, 1994). Carmel-by-the-Sea is a residential community with a resident population of 4,081 and a central commercial district which sustains a large tourist population (U.S. Census Bureau, 2000). The urban forest creates the ambiance of a quaint, European style village, in which residents and visitors peacefully stroll amongst secluded courtyards and art galleries. The city recognizes that much of its charm and appeal is due to the urban forest, providing forested neighborhoods in which to live and a business community whose prosperity is linked to the attractiveness of the city. It is for these reasons that Carmel-by-the-Sea is protective of the urban forest, with an entire section of the municipal code devoted to its protection (Anonymous, 1998).

The most recent inventory of Carmel-by-the-Sea's urban forest (2001-2004) indicated Monterey pines comprised 34% of the city's 10,000 trees and 14% of the 19,000 privately owned trees (Mike Branson, City Forester, personal communication, November 2005). The Monterey pine street trees are publicly owned and include planted trees obtained from local nurseries as well as remnants of the native stand (Nowak and McBride, 1992). The Monterey pine street trees that were removed by 2005 had potential for property damage to adjacent structures due to size and/or dead limbs and top (Mike Branson, City Forester, personal communication, November 2005).

The Monterey pine street trees of Carmel-by-the-Sea are under stress from environmental and biological factors. Environmental stresses include paving of the ground around trees, soil compaction and root disruption. Among the native Monterey pine pests, four are most prevalent: sequoia pitch moth, *Synanthedon sequoiae* (Hy. Edwards) (Lepidoptera: Sesiidae), red turpentine beetle, *Dendroctonus valens* LeConte (Coleoptera: Scolytidae), dwarf mistletoe (*Arceuthobium* spp.) and western gall rust (*Peridermium harknessii*). In addition to native pest forest health issues, the recent threat of pitch canker, caused by the exotic pathogen *Fusarium circinatum* Nirenberg & O'Donnell [=*F. subglutinans* (Wollenw and Reinking) Nelson et al. f.sp. *pini* (Correll et al.)], is prevalent along the central coast of

California. Pitch canker was first identified in the adjacent natural Monterey pine stand and in the urban forest of Carmel-by-the-Sea in 1992 (Storer et al., 1994).

In 1988, the health of Monterey pine street trees in Carmel-by-the-Sea was compared to the health of Monterey pine trees in the adjacent natural stand. Pitch moth attacks were more common in the urban forest than the natural forest and were positively correlated with the amount of pruning and wounding, and negatively correlated with the amount of crown closure and stress. Red turpentine beetle attacks were also more common in the urban forest and were positively correlated with stress and diameter (Nowak and McBride, 1991).

Biological and environmental data was collected from Monterey pine street trees in 1988, 1991, 1992, 1994 and 2005. The health of individual trees was monitored over seventeen years to evaluate which factors were correlated with the removal of individual trees. There were three objectives of this research: 1) to determine which biological and environmental factors are predictive of the removal of Monterey pine street trees in Carmel-by-the-Sea, (2) to determine which biological and environmental factors are predictive of pitch canker in Monterey pine street trees, and 3) to provide recommendations regarding urban forest monitoring with a view to predicting future tree removal and replacement needs.

METHODS

Carmel-by-the-Sea (36º55’ N, 121º92’ W) was selected as the study site in 1988 because of the dominance of Monterey pine in the street tree population. Nowak and McBride (1991) sampled Monterey pine street trees greater than 10cm in diameter, using a systematic sampling design of five trees per city block. Monterey pines were measured on alternating city blocks through thirteen strata of urban and suburban areas of Carmel-by-the-Sea (179 blocks, 783 trees) (Nowak and McBride, 1991). The data collected in 1988 was accessed as part of the current study such that the history and conditions of the trees were known. Collection and analysis of the 1988 data and calculation of both stress indices used below were done entirely by Nowak and McBride (Nowak and McBride, 1991; Nowak and McBride, 1992).

1988 data collection

Tree attribute data collected in 1988 and utilized in the current analyses included height, diameter at breast height (DBH), distance of tree from road, trunk wounds (percent of trunk circumference girdled by wounds) and crown closure (number of crown sides touching adjacent tree crowns). Crown variables were measured to derive two different stress indices. The crown variables included, average needle retention (number of years), primary and secondary foliage color [numerically indexed blue green foliage = 1, yellow green foliage = 2, yellow foliage = 3, red foliage = 4, and brown foliage =5], percent of foliage exhibiting secondary color, crown ratio (percent of height above lowest branch), crown shape (1-9 scale, full crown to dead tree), foliage, trunk and general condition (1-9 scale, excellent health to dead tree) (Lillesand et al., 1978), percent large and small dead limbs, percent natural crown pruning and percent maintenance crown pruning. Limb and pruning percentages were based on the potential crown volume above the lowest branch. Percent of stem below the lowest branch that was maintenance pruned was also noted (Nowak and McBride, 1991).

Tree health data were collected for each Monterey pine. Sequoia pitch moth attacks, characterized by reddish brown frass pellets incorporated in a pitchy mass on the trunk and branches were counted. Red turpentine beetle attacks, characterized by pitch masses 2-5cm wide on the lower 3m of the trunk with small gray granules of crystallized resin and frass on the soil were counted. Dwarf mistletoe infection was characterized by small, leafless, yellow-green shoots, 2.5-25cm long, in tufts or scattered along the branches or trunk and assessed using the Hawksworth Mistletoe Rating Scale, which divides the live crown into horizontal thirds and each third is given an infection rating of 0-2 for a maximum severity rating of 6 per tree (Hawksworth, 1977). Western gall rust was based on percent of crown and stem infection and rated on a six-point rating system.

The first stress index (STRESS) was derived from 1988 data prior to data collection and was based on the amount of foliage retained relative to tree size and foliage color. The STRESS index was calculated by:

$$\text{STRESS} = 1-[(\text{percent of theoretical crown volume occupied by foliage}/100) \times (\text{foliage color weighting value}/100)]$$

where the foliage color weighting value = [(percent primary color/ primary color index) + (percent secondary color/ secondary color index)] and the color index was as described above.

A STRESS index value of 0 represents the “ideal” non-stressed tree with a crown composed of green, healthy needles and a value of 1 represents a dead tree with no needles (Nowak and McBride, 1991).

The second stress index (PCSTRS), here after referred to as the Nowak index, was derived through the use of ten crown variables (needle loss, foliage color, percent large dead limbs, percent small dead limbs, percent natural crown pruning, dead crown ratio, crown shape, foliage condition, trunk condition and general condition) were input such that larger values indicate increased stress. By principal component analysis, three components were found to adequately express all of the original values. These three components represented; (1) a general condition component composed of general, foliage and trunk condition, foliage color, needle loss and percent large dead limbs, (2) a limb loss component formed by percent natural pruning, crown shape and dead crown ratio, and (3) a small dead limb component composed of percent small dead limbs. The Nowak index was calculated from these variables to yield a singular Nowak index, with the same 0-1 range as the STRESS index (Nowak and McBride, 1991).

Subsequent data collection

In 1991 and 1992, the number of red turpentine beetle attacks was recorded for 285 street trees, representing approximately 35% of the original sample. In 1994 the same trees were visited, and red turpentine beetle attacks and Sequoia pitch moth attacks were counted. In addition, the presence or absence of pitch canker was recorded for each tree in 1994.

In 2005 the same tress were re-visited and DBH, height, number of red turpentine beetle attacks, pitch moth presence, dwarf mistletoe presence, number of pitch canker symptomatic tips (0, 1-10, >10) and bole cankers (0,1-3, >3) were recorded for 204 of the original 285 trees. Absence was recorded if the tree had been removed.

Statistical analysis

Comparisons of the historical presence or absence of different tree and forest health attributes (non-parametric variables) between the trees with pitch canker symptoms in 2005 and trees without pitch canker symptoms in 2005, were made using *G*-tests of independence. Similar tests were used to compare historical presence or absence of different tree and forest health attributes between the trees that had been removed by 2005 and trees that were still standing in 2005.

Differences in means of continuous variables between trees that had pitch canker and trees without pitch canker in 2005, and between trees that had been removed and trees that had not been removed in 2005 were tested using one-way ANOVA. Data were transformed when necessary to ensure homogeneity of the variances. All statistical analyses were completed using Statistix 8.0 (Analytical Software, 2003) and Microsoft Excel.

RESULTS

Data from a total of 285 trees in 1988 were used; 281 of these trees were revisited in 1991, 280 trees in 1992, 123 trees in 1994 and 204 trees in 2005. The percent of trees removed steadily increased from 6.3% in 1991 to 30.8% in 2005. The percent of trees with pitch canker increased from 7.9% in 1994 to 79.4% in 2005. (Figure 2.1)

In 1994, 92.1% of the trees had no symptomatic branch tips and no stem cankers were found. In 2005, 20.6% of trees had no symptomatic tips, 38.2% had 1-10 symptomatic tips and 41.2% had >10 symptomatic tips. From 1994 to 2005, the percent of trees with 1-3 stem cankers increased to 8.8% and the number of tress with >3 stem cankers increased to 4.4% (Figure 2.2).

The development of pitch canker was not independent of pitch moth in 1988, crown closure rating in 1988, tree height in 1988 and STRESS index in 1988 (Table 2.1). Trees with pitch moth in 1988 and a crown closure rating greater than 2 in 1988 were more likely to develop pitch canker by 2005 than were trees without these tree health and tree attributes. Trees above 10m in height in 1988 and with a STRESS index above 0.5 in 1988 were less likely to develop pitch canker by 2005 than were trees without these tree health and tree attributes (Table 2.1).

Of trees with pitch canker in 2005, the mean number of pitch moth attacks in 1988 was greater than trees without pitch canker in 2005. Of trees with pitch canker in 2005, the mean height, mean Nowak index and mean STRESS index was lower than trees without pitch canker in 2005 (Table 2.2).

Tree removal was not independent of red turpentine beetle symptoms in 1992, tree height in 1988 and DBH in 1988 (Table 2.3). Trees with red turpentine beetle symptoms in 1992, a height greater than 10m in 1988 and DBH greater than 50cm in

1988 were more likely to have been removed by 2005 than were trees without these tree health and tree attributes (Table 2.3).

Of trees removed by 2005, the mean number of red turpentine beetle attacks in 1992 and 1994, mean DBH in 1988, mean height in 1988, and mean Nowak index in 1988 was greater than the trees that were not removed by 2005 (Table 2.4).

DISCUSSION

Tree removal in Carmel-by-the-Sea has continued to occur throughout the years of the studies reported here, and pitch canker is becoming prevalent among the remaining street Monterey pines. In the areas sampled, over 30% of all Monterey pine trees have been removed in the past 17 years and almost 80% of the remaining trees have at least one pitch canker symptom. The progression of the disease appears consistent with previous studies where stem cankers were found to be a later stage of disease development after large numbers of branch tips were affected (Storer et al, 2002). Disease progression in these stands will perhaps be more rapid since these trees are in close proximity to the ocean, and previous work has indicated that disease development in coastal stands is more rapid than disease development in inland areas (Wikler et al., 2003). It remains to be documented whether urban trees in Carmel-by-the-Sea go into disease remission as has been observed for a subset of pitch canker infected trees in other parts of California (Gordon et al., 2001). It is reasonable to expect that such remission will be evident in Carmel-by-the-Sea in the future. For this reason, pitch canker alone, unless causing a tree to be hazardous, should not be a reason for tree removal.

The mean STRESS and Nowak indices in 1988 were lower for trees that developed pitch canker by 2005. This suggests that pitch canker has spread among the least stressed trees as measured by these indices. Pitch canker is vectored by a number of insect species, including twig beetles (*Pityophthorus* spp (Coleoptera: Scolytidae) and the Monterey pine cone beetle, *Conophthorus radiatae* (Coleoptera: Scolytidae) (Hoover et al., 1996; Storer et al., 2003). It has been suggested that the pitch canker pathogen may be vectored during exploratory feeding by twig beetles, *Pityophthorus* spp., without the branch becoming infested (Gordon et al., 2001). Such feeding may be as likely to occur on stressed as unstressed trees. Using a stress index that includes canopy condition may categorize healthy trees with a large crown as unstressed, while from a pitch canker vectoring point of view these trees may have more branches where twig beetles would initiate feeding than would be present in a stressed tree with a small canopy. Since healthy Monterey pines produce cones at an early age, a similar situation may be present for cone beetle vectors, where trees with large vigorous crowns have greater cone production, and therefore are more likely to be infested by cone beetles.

Trees that had pitch moth in 1988 were more likely to develop pitch canker by 2005. In addition, trees with pitch canker in 2005 had more pitch moth attacks on them in 1988. It would be expected that trees with pitch canker would have more pitch moth attacks due to attraction of this insect to tree resin produced in response to pitch canker. Pitch canker was not known to occur in Carmel-by-the-Sea in 1988 but trees that had a higher number of pitch moth attacks at that time were more likely to develop pitch canker in the future. Since there is no evidence for attraction of pitch canker vectoring insects to resin, it is unlikely that attraction of increased numbers of vectors to trees with pitch moth would explain this effect. It is more likely that some trees are inherently more susceptible to insect and pathogen attack than others, and that the stress indices used do not reflect this type of physiological stress.

The presence and mean number of red turpentine beetle attacks in 1992 and the mean number of red turpentine beetle attacks in 1994 were predictive of tree removal by 2005, but the presence and absence data from 1988 was not predictive of tree removal. This suggests that beyond about thirteen years, other factors such as tree size become more predictive of tree removal than the presence or absence of red turpentine beetle attacks. However, the predictive value of the mean number of red turpentine beetle attacks in 1988 approached significance (P=0.084) suggesting that the numbers of symptoms of attack by this insect are still an important component of tree removals. Observations of trees in other parts of the city for which 1988 data are available could be visited to increase the size of the database and further examine the predictive value of 1988 red turpentine beetle attacks.

The STRESS and Nowak indices were highly correlated in 1988 (Nowak and Mcbride, 1991). Trees removed by 2005 had a significantly higher Nowak index in 1988, and the higher STRESS index in 1988 of trees that were cut by 2005 approached significance (P=0.077). This suggests that trees which were more stressed in 1998, as measured by these indices, were more likely to be removed by 2005. Mean DBH and height were also predictive of tree removal during this time frame. As would be expected, larger trees are more likely to have been removed over the 17 years of data available here. Monterey pine is a short lived tree that grows to its full size in 80-100 years (McDonald and Laacke, 1990) and therefore it is to be expected that significant tree removal would occur over 17 years in a mixed age urban forest of this type.

In order to develop predictions regarding the removal of Monterey pine trees into the future in this urban stand, data relating to tree size and red turpentine beetle attacks should be maintained. Developing indices of tree stress may also be useful, though these require that more attributes of each tree are assessed during data collection. It remains to be seen how the continued development of pitch canker in this area will affect tree removals, but it is likely that trees which do not go into remission from the disease will need to be removed over the coming decade.

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Table 2.1: Percent of trees with pitch canker in 2005 on which various forest health parameters were present or absent or above or below a particular threshold value as specified in the table in various years prior to 2005 in Carmel-by-the-Sea, California. Significant *P* values in **bold**, α = 0.05.

Tree health parameter		Number of trees	% with pitch canker in 2005	*G* statistic	*P* value
Red turpentine beetle in 1988	Yes	21	85.7%		
	No	183	78.6%	0.590	0.442
Red turpentine beetle in 1991	Yes	5	60.0%		
	No	194	80.4%	0.907	0.341
Red turpentine beetle in 1992	Yes	5	60.0%		
	No	118	83.9%	1.284	0.257
Red turpentine beetle in 1994	Yes	21	95.2%		
	No	102	80.4%	3.266	0.071
Red turpentine beetle in 2005	Yes	69	84.0%		
	No	128	76.6%	1.556	0.212
Pitch moth in 1988	Yes	152	82.2%		
	No	52	67.3%	4.716	**0.030**
Pitch moth in 1994	Yes	106	84.0%		
	No	17	76.5%	0.509	0.476
Gall rust in 1988	Yes	5	60.0%		
	No	199	79.8%	0.857	0.355
Dwarf mistletoe in 1988	Yes	18	72.2%		
	No	186	80.1%	0.556	0.456
Wounds in 1988	Yes	75	77.3%		
	No	129	80.6%	0.306	0.580
Pitch canker in 1994	Yes	11	63.6%		
	No	112	84.8%	2.411	0.120
Crown closure >2 1988	Yes	24	95.8%		
	No	180	77.2%	5.758	**0.016**
STRESS index[1] >0.5 1988	Yes	174	76.4%		
	No	30	96.6%	8.427	**0.004**
DBH >50cm 1988	Yes	76	77.6%		
	No	128	80.4%	0.229	0.632
Height >10m 1988	Yes	68	67.6%		
	No	136	85.2%	8.136	**0.004**
Distance to road <1m 1988	Yes	101	80.1%		
	No	103	78.6%	0.074	0.786

[1] STRESS index was based on the amount of foliage retained relative to tree size and foliage color.

Table 2.2: The means of biological and environmental factors for Monterey pine street trees with pitch canker in 2005, in Carmel-by-the-Sea, California. Red turpentine beetle, wound, gall rust and mistletoe data was square root transformed, resulting in asymmetrical SE. Significant *P* values in **bold**, $\alpha = 0.05$

	trees with pitch canker in 2005	trees without pitch canker in 2005		
	mean (+SE, -SE)	mean (+SE, -SE)	F	*P*
# red turpentine beetle 1988	0.17 (0.05, 0.05)	0.12 (0.10, 0.09)	0.27	0.604
# red turpentine beetle 1991	0.03 (0.02, 0.02)	0.05 (0.04, 0.04)	0.23	0.629
# red turpentine beetle 1992	0.07 (0.06, 0.05)	0.19 (0.14, 0.13)	0.75	0.390
# red turpentine beetle 1994	0.24 (0.06, 0.06)	0.06 (0.11, 0.10)	1.86	0.176
# pitch moth 1988	4.24 (0.36, 0.36)	1.90 (0.71, 0.71)	8.5	**0.004**
gall rust rating 1988	0.02 (0.01, 0.01)	0.05 (0.03, 0.03)	0.91	0.342
dwarf mistletoe rating 1988	0.08 (0.02, 0.02)	0.03 (0.04, 0.04)	0.08	0.774
% wound 1988	0.45 (0.06, 0.06)	0.40 (0.12, 0.11)	0.13	0.721
crown closure 1988	2.46 (0.38, 0.38)	1.12 (0.76, 0.76)	2.51	0.115
Nowak index[1] 1988	0.17 (0.01, 0.01)	0.21 (0.01, 0.01)	12.92	**<0.001**
STRESS[2] index 1988	0.69 (0.01, 0.01)	0.82 (0.03, 0.03)	18.61	**<0.001**
DBH (cm) 1988	45.94 (1.62, 1.62)	50.59 (3.2, 3.2)	1.69	0.195
height (m) 1988	8.62 (0.30, 0.30)	10.52 (0.60, 0.60)	8.14	**0.005**
distance to road (m) 1988	1.29 (0.08, 0.08)	1.49 (0.16, 0.16)	1.18	0.279

[1] Nowak index was derived through principal component analysis of ten crown variables.
[2] STRESS index was based on the amount of foliage retained relative to tree size and foliage color.

Table 2.3: Percent of trees removed by 2005 on which various forest health parameters were present or absent or above or below a particular threshold value as specified in the table in various years prior to 2005, in Carmel-by-the-Sea, California. Significant *P* values in **bold**, α = 0.05.

Tree health parameter		Number of trees	% of trees removed by 2005	*G* statistic	*P* value
Red turpentine beetle in 1988	Yes	31	32.2%		
	No	255	28.2%	0.210	0.647
Red turpentine beetle in 1991	Yes	9	44.4%		
	No	259	25.1%	1.413	0.235
Red turpentine beetle in 1992	Yes	13	61.5%		
	No	159	25.8%	6.380	**0.012**
Red turpentine beetle in 1994	Yes	34	38.2%		
	No	130	21.5%	3.669	0.055
Pitch moth in 1988	Yes	220	30.9%		
	No	66	21.2%	2.412	0.120
Pitch moth in 1994	Yes	143	25.9%		
	No	21	19.0%	0.463	0.496
Gall rust in 1988	Yes	5	0.0%		
	No	281	29.2%	6.706	**0.010**
Dwarf mistletoe in 1988	Yes	25	28.0%		
	No	261	28.7%	0.006	0.938
Wounds in 1988	Yes	105	28.6%		
	No	181	28.7%	0.001	0.975
Pitch canker in 1994	Yes	13	15.4%		
	No	151	25.8%	0.726	0.394
Crown closure >2 1988	Yes	27	29.6%		
	No	259	28.6%	0.013	0.909
STRESS index[1] >0.5 1988	Yes	250	30.4%		
	No	36	16.7%	3.127	0.077
DBH >50cm 1988	Yes	120	36.7%		
	No	166	22.9%	6.367	**0.012**
Height >10m 1988	Yes	106	35.8%		
	No	180	24.4%	4.148	**0.042**
Distance to road <1m 1988	Yes	138	26.8%		
	No	148	31.2%	0.629	0.428

[1] STRESS index was based on the amount of foliage retained relative to tree size and foliage color.

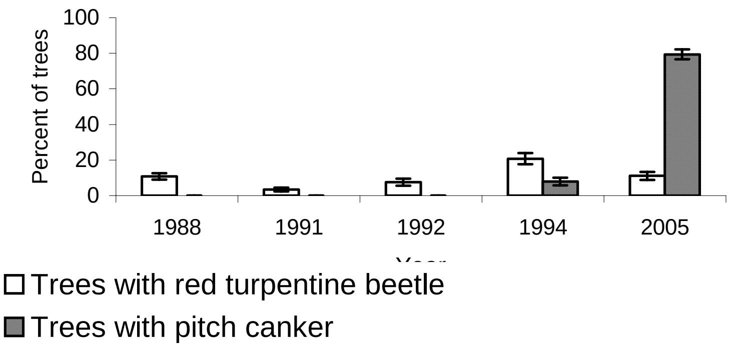
Table 2.4: The means of biological and environmental factors for Monterey pine street trees removed by 2005, in Carmel-by-the-Sea, California. Red turpentine beetle, wound, gall rust and mistletoe data was square root transformed, resulting in asymmetrical SE. Significant *P* values in **bold**, α = 0.05

	trees cut by 2005	trees uncut in 2005		
	mean (+SE, -SE)	mean (+SE, -SE)	F	*P*
# red turpentine beetle 1988	0.36 (0.11, 0.09)	0.16 (0.06, 0.05)	3.01	0.084
# red turpentine beetle 1991	0.10 (0.04, 0.04)	0.03 (0.02, 0.02)	1.94	0.165
# red turpentine beetle 1992	0.37 (0.12, 0.11)	0.09 (0.06, 0.06)	5.26	**0.023**
# red turpentine beetle 1994	0.74 (0.19, 0.18)	0.20 (0.08, 0.08)	8.19	**0.005**
# pitch moth 1988	4.12 (0.51, 0.51)	3.76 (0.32, 0.32)	0.36	0.549
gall rust rating 1988	0.01 (0.01, 0.01)	0.02 (0.01, 0.01)	1.80	0.181
dwarf mistletoe rating 1988	0.09 (0.03, 0.03)	0.07 (0.02, 0.02)	0.01	0.935
% wound 1988	0.44 (0.09, 0.08)	0.44 (0.06, 0.05)	0.00	0.979
crown closure 1988	2.94 (0.62, 0.62)	2.18 (0.39, 0.39)	1.05	0.306
Nowak index[1] 1988	0.20 (0.01, 0.01)	0.18 (0.01, 0.01)	4.62	**0.032**
STRESS[2] index 1988	0.76 (0.02, 0.02)	0.72 (0.01, 0.01)	3.15	0.077
DBH (cm) 1988	55.25 (2.38, 2.38)	46.90 (1.51, 1.51)	8.82	**0.003**
height (m) 1988	10.33 (0.43, 0.43)	9.01 (0.28, 0.28)	6.64	**0.011**
distance to road (m) 1988	1.55 (0.11, 0.11)	1.33 (0.07, 0.07)	2.47	0.117

[1] Nowak index was derived through principal component analysis of ten crown variables.
[2] STRESS index was based on the amount of foliage retained relative to tree size and foliage color.

Figure 2.1: The percent of (A) residual Monterey pine street trees with red turpentine beetle presence and pitch canker and (B) percent of cumulative tree removal in 1988, 1991, 1992, 1994 and 2005 in Carmel-by-the-Sea, California.

(A) Residual trees with red turpentine beetle and pitch canker



(B)Cumulative tree removal

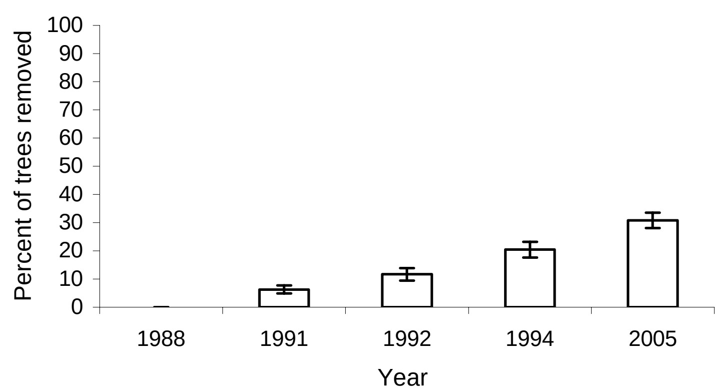
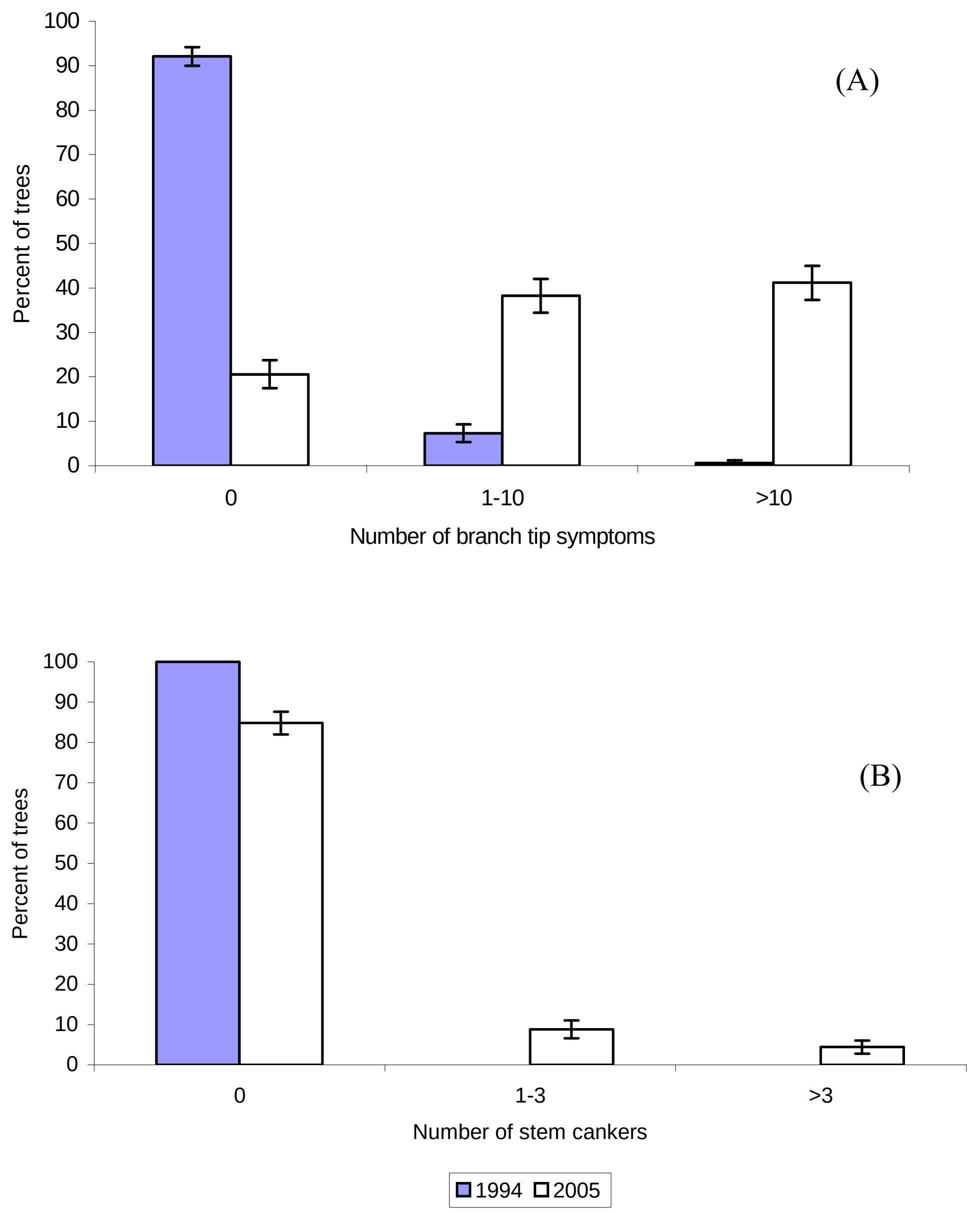


Figure 2.2: The percent of Monterey pine street trees with 0, 1-10, and >10 pitch canker tip symptoms (A) and the percent of Monterey pine street trees with 0, 1-3and >3 stem cankers in 1994 and 2005, in Carmel-by-the-Sea, California.



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