FIRE ECOLOGY OF THE MOUNTAIN PINE, PINUS HARTWEGII

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1. INTRODUCTION

In Mexico an average of 8,903 registered fires occur each year, burning on average 324,865 ha (CONAFOR, 2003). Many of these fires occur in Mexico's extensive pinelands. One of these is forests dominated by *Pinus hartwegii* Lindl. which, even though it is a species adapted to fire, is being exposed to both excessive fire associated with cattle-raising burning, and to a lack of fire in places where there is effective fire prevention and suppression.

This work presents the results of on-going and completed research by the author and his team, as well as a review of the available literature. It adds to and updates the information presented in Rodríguez-Trejo (2001) and Rodríguez-Trejo & Fulé (2003). Matos (1995) and Farjon & Styles (1997) indicate that *P. hartwegii* and *P. rudis* are one and the same species, and that approach is followed in the present work, despite some of the references pertain to work done with *P. rudis*.

It is important to understand the differences in how the management of fire is approached in different viewed and countries, states and ecological regions. Rural communites in different regions have different objectives for using fire, and government administrations will have different approaches to preventina. suppressing, regulating the use of, and evaluating the impact of, fire in order to protect forest resources and restore and maintain ecological systems. How the government educates and informs the users

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2. THE ECOSYSTEM

Pinus hartwegii occurs in both Mexico and Guatemala. In Mexico, this species is reported in 17 states (Nuevo Leon, Tamaulipas, Hidalgo, Distrito Federal, Morelos. Colima. Michoacán, Jalisco. Oaxaca, Chiapas, Puebla, Veracruz, Tlaxcala. Estado de Mexico, Coahuila, Nayarit and Guerrero), at altitudes of 2,200 -4 000 mmsl (Rzedowski, 1978, 1981; Perry, 1991). *P. hartweqii* is found principally in places with semi-cold climate, with mean annual temperatures of 5 - 12° C, and with an annual rainfall of 967 - 1,200 mm, with less than 5 percent occurring in the winter months (Mendoza-Briseño, 1977; Benitez-Badillo, 1988; García, 1981). The soils are andosols, podzols or brown forest soils (Aguirre-Bravo and Rey-Contreras, 1980; Benitez-Badillo, 1988), but in some cases it is also found on malpaís (lavic material).

At the Zoguiapan Forest Experiment Station, Edo. de Méx., Zavala-Chávez (1984) describes the vegetation associated with the pines as primarily Alnus, mixed occasionally with other trees like Salix oxylepis, Arbutus glandulosa and Buddleia parviflora. The ground cover is composed of Gentianoides. Eupatorium, species of Penstemon glabratum and Baccharis conferta (forming a thin shrub like stratum), Muhlenbergia quadridentata. and М. Festuca tolucensis. F. macroura, hephaestophila, and Lupinus spp. in the herbaceous layer.

3. FIRE REGIME AND ITS ROLE IN FOREST SUCCESSION

To date, dendrochronological studies about *P. hartwegii* ecosystems have

not been completed, but one can infer that frequent, low-intensity surface fires maintain the pure, open stands of pine, if they are not influenced by human disturbance. The ignition sources are both natural (lightning) and human in origin. In places like Popocatépetl volcano, volcanic activity is an ignition source. The fire return interval probably does not exceed 10 years, and the mean is about 5 years. Today, fires of human origin are more frequent than those of natural origin. The fire season begins in January and continues through May and sometimes into June. In some years, fires have occurred as early as November. At higher elevations, near the tree line, an excess of fire can eliminate the tree stratum altogether. Miranda & Hernández-Xolocotzi (1985) have noted that very frequent fires at these elevations eliminate the pines and favor grassland of Muhlenbergia macroura and Festuca tolucensis. Within a portion of the pine zone, Ern (1973) considers the pine forests to be seral to a climax forest of Abies religiosa, which would develop in the absence of fire.

4. FIRE BEHAVIOR

4.1 Fuels

Fuel loads in *Pinus hartwegii* forests vary depending on forest developmental stage, altitude, and type and degree of disturbance. Rodríguez-Trejo (1988) and Rodríguez-Trejo & Sierra-Pineda (1995) report fuel loads ranging from 5.64 to 22.60 ton/ha (mean = 15.06 ton/ha). The pine saplings can make up anywhere from zero to 31% of the total load (mean = 8.8%); the shrubs from zero to 8.5% (mean = 1.3%); grasses 10.2 to 67.7% (mean = 38.3%); needle cast from near zero to 14% (mean = 4.7%); and dead woody debris (1-1,000 hour time lag fuels) can constitute 4.5 to 82% (mean = 46.9%) of the total fuel load.

4.2 Topography

Pinus hartwegii is found on plateaus adjacent to alpine grassland, on lands with very steep slopes and ravines, in some cases with slopes greater than 100%, and on malpaís.

4.3 Weather Conditions

At the elevation at which these pine forests are found, winds at the time of highest fire danger may reach 20 km/h. particularly during February and March. Wind direction is fairly predictable with daytime winds ascending the mountain slopes and after dusk they descend in the opposite direction. However, at times, descending winds can be common in the daytime. Due to the dissected topography turbulent winds are commonplace. Although temperatures are generally low at these high elevations, abundant fine fuels (grasses, leaf litter, twigs) are highly available during the dry season. For example, the relative humidity (RH) can be as low as 32% toward 8:30 am in April and by 11 am the RH may be as low as 18%. The corresponding light fuel moistures are 9% and 4 % respectively.

4.4 Fire Characteristics

The relatively low total fuel load, suggest a moderate fire behavior. This is not necessarily the case. Fire behavior would be moderate, with low-intensity and slow rate of spread if the area burning is relatively flat, the wind moderate, and/or the time of burn is in the evening or at night. Under these moderate conditions, the rate of spread would be about 5 m/min and the flame length would range from 3 m to less that 1 m. Under conditions of high winds on steep slopes, the rate of spread can exceed 60 m/min with flames lengths of 6-8 m. Under moderate, early-morning, prescribed burn conditions using backing fires burning down slope, the rate of spread can be held to 1 m/min with flame lengths not exceeding 0.5 m.

Although fires in *Pinus hartwegii* forests are generally superficial, in malpaís, the accumulation of fuel amongst the rocks makes subterranean fires possible. The low density of the pines and limited contact among tree crowns does not permit aerial burning, although in some dense clumps and individuals covered by extracted resin, the flames can burn into the crowns.

4. ADAPTATIONS TO FIRE IN Pinus hartwegii

Pinus hartwegii is one of the most fire-adapted of the Mexican pines. It is one of the six pines species that have been documented in Mexico to possess five or six different kinds of adaptations to fire (Rodríguez-Trejo & Fulé, 2003). The specific adaptations are explained in the following paragraphs.

5.1 Regeneration

Fire removes litter and grasses that serve as a barrier to seeds and permits the seed direct contact with mineral soil. Fire also eliminates temporary competition from ground cover vegetation. The soil is enriched by the ash and provides nutrients for the seedlings. During mast years, considerable regeneration can occur on Sarukhán-Kermes and burned areas. Franco-Bagueiro (1981), recognized that fire is an important element for the successful regeneration of Pinus hartwegii. That notwithstanding, seedlings are susceptible to fire. Velázguez (1984) and Velázguez et al. (1986), indicate a survival equal to 84.3% (56,667 plants/ha) right after low-intensity prescribed fire, but on steep slopes, it is reduced 8.1% (5,733 plants/ha). to Hernández (1990) recommends not using prescribed fire when seedlings are present and fuel loads are greater than 4 ton/ha. Otherwise, seedling mortality could be areater than 50%.

5.2 Grass Stage

In some populations of Pinus hartwegii, a grass stage is notable (Fig. 1). In general, a grass stage in pines is characterized by little or no height growth for several to up to 12 years. Pinus palustris in the southeastern United States is the classic example of a pine species with a grass stage. Although there is no vertical growth. there is profuse growth of both aciculae and roots. After a period in this stage, species like P. palustris and P. montezumae will have reached 2.5 cm in diameters at the base and will then begin a rapid period of height growth (Mitchell, 1998, pers. comm.; Becerra Luna, 1995). Pinus hartwegii probably behaves the same way. Dense



Figure 1. Grass stage in *P. hartwegii*.



Figure 2. Re-sprouts in P. hartwegii.

aciculae and scales protect and surround the terminal bud. This dense cluster of needles provides the bud some protection from the heat of a passing fire.

5.3 Re-sprouting

Pinus hartwegii seedlings have the capability to re-sprout at the root collar if the main stem is killed by fire (Fig. 2). Although this characteristic is common, it is not observed in all populations. There appears to be considerable variation in both time and space regarding the capacity to re-spout. For example, there are populations at the Zoquipan Experiment Station in the State of Mexico that re-sprout profusely, while in

Ajusco there are populations with only limited re-sprouting ability after fire. Rodríguez-Trejo (1996) suggests that the ability to re-sprout decreases with tree age. For example, in stands 1 to 8 years old (1.3 to 4 m tall) 27.7% of the trees re-sprouted after fire, while 96.7% of trees less that 1.3 m tall re-sprouted. In similar manner, González-Rosales (2001) and González-Rosales & Rodríguez-Trejo (submitted), refer to an inverse relation among crown scorch (burn or dehydration of the foliage due to heat of flames) and the number of resprouts, with 0.68 re-sprouts/tree when scorch affected more that 66% of the crown. 1.09 re-sprouts/tree when scorch affected 33 to 66% of the crown, and 1.34 resprouts/tree when scorch affected less than 33% of the crown. Bonilla-Beas (1992, pers. comm.) observed re-sprouts in P. hartwegii with less than 10 cm of basal diameter at areas burned near Perote, Ver.

5.4 Bark Thickness

Bark provides crucial protection to the vascular cambium against fires. The application of temperatures of 60° C during two to 60 minutes proves to be lethal for plant tissue depending on moisture content (Wright, 1970). In Pinus palustris, a bark thickness of 1 to 1.3 cm has an isolation capability of 1:10 (Fahnestock & Hare, 1964), that is, the temperatures that the cambium is subjected to during a fire, is 1/10 of the temperature of the fire. In the case of Pinus hartwegii, in trees with a diameter of 15 cm and 0.38 cm of bark thickness, González-Rosales (2001) reports a 100% survival of trees after fires of moderate intensity, even though Rodríguez-Trejo (1996) mentions that trees of smaller diameter (and as a consequence less bark thickness), also survive low-intensity fires.

5.5 Crown Scorch

Fire is a factor in natural pruning. When the crown is subjected to scorch, either the trees are killed, or the branches are pruned. When limited, such pruning yields an important effect on diameter growth. Rodríguez-Trejo (1996) observed

that trees of P. hartwegii that were 100% scorched recovered 40% of their crown 16 months after a fire occurred in an understory thicket of Quercus frutex. This particular fire occurred at the beginning of the fire season. Noted also was that crown scorch of more than 50% resulted in a 32% reduction in radial growth the following year in trees that were 35 years old. Conversely, González-Rosales (2001) and González-Rosales & Rodríguez-Trejo (submitted), indicate that less than 33% of crown scorch increases the width of annual ring growth that is formed the year following fire, but that severe crown scorch (>66%), results in a reduction of the aforementioned growth. They found that scorch of younger crowns of less than 33% (low) produced annual rings with a mean width of 3.09 mm, while control trees produced 2.33 mm of growth. Trees with 33 to 66% scorch produced annual rings of 2.41 mm, which was not statistically different from control trees. Scorch greater that 66% produced rings of 2.03 mm (See Figure 3).

Height growth is also affected by scorch. It was noted that height growth one year after fire is 38% greater in trees with 33% or less crown scorch compared to controls.

5.6 Foliage Recovery

Pinus hartwegii can tolerate loss of all of its foliage, at least after fires during the winter months, as long as the terminal bud is not killed, or if it is, that there are dormant buds that can take its place. It seems that the greater the amount of scorch, the higher the priority the tree places on recuperating its photosynthetic area. According to González-Rosales (2001) and González-Rosales & Rodríguez-Trejo (submitted), trees that loose more than 66% of their crown foliage recover 69.9% after one year, those that loose 33 to 66% of their crown foliage recover 39.3%, while those that loose less that 33% of their crown foliage recover only 11.8%.

During its initial period of growth after the grass stage, *P. hartwegii* tolerates fire of low-intensity. Cedeño (1989) showed



Figure 3. Width of annual ring growth (mm) of *Pinus hartwegii* one year pre-burn (white bars) and one year post-burn (black bars). The treatments correspond to levels of crown scorch. The error bars represent standard error (adapted from González-Rosales, 2001 and González-Rosales & Rodríguez-Trejo, submitted).

that with trees of 0.5 to 1.2 m in height, a prescribed burn in grass fuels 0.6 m in height in February, at 6:45 A.M, at - 3° C, resulted in a mortality of only 2.5% 15 days post-burn.

6. LIFE HISTORY OF *Pinus hartwegii* IN A FIRE ENVIRONMENT

The adaptations to fire described above correspond to several life history stages of the tree. Pinus hartwegii releases its seed in winter. If the seed falls on an unburned site, it germinates, but will likely be killed by fire within a year. If the site happens to remain unburned for more than a year, the tree is likely to become well established. If the site had recently burned prior to seed fall, seedlings are likely to survive because the site is relatively fire proof until fuels accumulate. In either of the last two cases, the seedlings are given time to reach the grass stage. In the grass stage, trees will have a stem diameter of approximately one centimeter and will have produced a dense clump of foliage around the bud. From about age two, the plant can suffer the loss of this foliage, but still survive. When the diameter reaches around 1 cm. dormant buds are available allowing the tree to re-sprout after fire damage. This process of destruction of the terminal bud by fire (or by some other factor) that stimulates new

growth from dormant buds can last for several years. Trees less than 1 m in height typically have multiple stems, indicating several re-sprouting events. This is evidence of the resilience of this species in the face of repeated fire. Eventually, one to several of the re-sprouts are able to produce enough bark to protect the cambium. Then one or two of the stems will reach a height of 4 m or more. At this height, the terminal buds are likely to survive a low-intensity fire. Competition among the stems will eventually lead to a single trunk or sometimes two trunks. Frequently the lowermost trunk is the one that is lost, because of competition for light, and because it is more likely to suffer loss of its foliage and bud during intense fires. Each time there is a fire the level of crown scorch will influence growth and vigor of the trees (modified of Rodríguez-Trejo, 1996).

7. RESPONSE OF ASSOCIATED SPECIES TO FIRE

Grasslands, dominated by *Muhlenbergia macroura* and *Festuca tolucensis that* are frequently associated with *Pinus hartwegii* also respond favorably to fire because these grass species re-grow from rhizomes. Also, there is a seasonal flowering response to fire by these species. In areas that suffer from fires during winter, Benitez-Badillo (1988) found that 14 months afterwards the grasses covered 87.5% of the ground surface; while on control areas the cover was 67.2%. Twenty percent of the individuals of *F. tolucensis*, bloomed between July and December in control areas, while in areas that burned, 80% of the individuals bloomed. Flowering in these individuals started as early as April. With *Muhlenbergia macroura*, flowering did not surpass 20% in unburned areas and occurred between July and January, while there was 80% flowering in the burned area. In this case the period of flowering was the same as those in the unburned area.

Some plant species appear immediately after fire, and their presence is indicative of recent fire. Examples include the legume Lupinus montanus and The lupine Penstemon gentianoides. happens to be a nitrogen fixer. Also, its seed needs scarification, which may be caused by the fire. Rodríguez-Trejo & Rojo-Zenil (1997) refer to physical dormancy of At the Zoguiapan Forest this species. Experiment Station in the State of Mexico they documented zero germination of seed in controlled environment chambers, and 53.3% germination of seed treated with concentrated sulphuric acid for 15 minutes. In a similar manner, Acosta-Percástegui Acosta-Percástegui (2003)and & Rodríguez-Trejo (submitted), indicate the existence of an interaction among factors, e.g. light, temperature, and chemical scarification. Germination was 100% with the following treatment: 35 min of soaking in sulphuric acid, in the presence of light and 20° C in the daytime, 15° C by night. Germination was only 1% without pregerminative treatment, with light, and 25° and 20° C, in the davtime and night, respectively.

Martínez-José (in review), and Martínez-José & Rodríguez-Trejo (submitted) note that *Lupinus bilineatus* from central Mexico, associated with *P. hartwegii*, exhibits germination greater than 30% with fire. Without this treatment, the seeds practically do not germinate.

Right after the extensive and intense fires of 1998 (the severest season that Mexico has experienced), at several locations such as the Zoquiapan Forest Experiment Station, the tall shrub, *Senecio cinerarioides*, became dominant in pine stands and its presence continued for several years.

Alpha diversity in areas not burned for several years at Ajusco, Distrito Federal, differed from burned areas. In unburned areas there were 12 plant species, while in areas that burned in March, in either wildfires or low-intensity prescribed burns, there were 21 species a year later. Senecio cinerarioides, Penstemon gentianoides and Arenaria sp. are more abundant in burned areas. Alchemilla procumbens was found in both: burned and unburned sites. Senecio reticulatus tends to be more common in unburned areas. Senecio tolucanus is more abundant in sites prescribed burned with low-intensity in March (Martínez-Hernández, in review, and Martínez-Hernández & Rodríguez-Trejo, in review) (Figs. 4 and 5).



Figure 4. Penstemon gentianoides.

Regarding fauna, as is common in many ecosystems; reptiles and amphibians are very susceptible to direct mortality, given their slow mobility. Nonetheless, fires attract birds in search of insects that escape the flames. Most mammal species, can either flee the flames, or like rabbits, take refuge in their burrows and warrens. Vegetative recovery after a fire, coupled with lower levels of parasites, and increased nutrients and palatability actually improve the habitat and survival of some animal species, such as the endemic zacatuche (*Romerolagus diazii*), the rabbit of the volcanoes.



Figure 5. Senecio tolucanus.

8. **EFFECTS ON SOILS AND** HYDROLOGIC REGIME

There are a number of references on the effect of prescribed low-intensity fire on the chemical properties of soils, erosion, and run-off in Pinus hartwegii forests. Aguirre-Bravo (1978) and Aguirre-Bravo & Rev-Contreras (1980) describe the soils as fertile molic andosols, with a sandy texture, rich in organic matter, acidic (pH=5.5) to neutrals (pH=7), rich in nitrogen. They note that fire of low intensity did not cause significant changes in pH, but they registered a little nitrogen loss due to volatilization. Phosphorous increased in interval traces from 5.04 ppm, to 1.57 to

7.42 ppm. Calcium increased from 1,755 to 3,406, to 2,145 to 3,900 ppm. They also noted increases in K and Mg, along with a slight increase in Na.

Regarding erosion and run-off, Aguirre-Bravo (1978) and Aguirre-Bravo & Rey-Contreras (1980) indicate moderate and temporary loss of soil at 564.7 kg/ha per year from burned sites compared to 140 kg/ha per year from control areas. Run-off was 204 m³/ha/yr in burned-out areas and of 68.5 m³/ha/yr in places not affected by the fire.

9. EFFECTS ON THE AIR QUALITY

There are hundreds of byproducts contained in smoke that are toxic and/or corrosive, including CO, NO_x and SO₂. Also, we must be reminded that suspended particles are very harmful for health, and that CO₂, along with the water vapor, form the major mass of smoke, and contribute to the greenhouse effect. Contreras-Moctezuma (2002) and Contreras-Moctezuma et al. (2003), refer to emissions of NO, NO₂ NO_x, CO and SO₂ per unit weight of fuels (Chart 1) for the principal types of fuels. Note that S. cinerarioides, an abundant colonizer of severely burned areas is an important emitter of such products. If these areas burn again, even more contaminants will be released.

These sources refer to estimates of emissions for each contaminant per unit of burned surface: 4.069 kg/ha of NO. 3.652 kg/ha of NO₂, 9.372 kg/ha of NO_X, 2.838 kg/ha of SO₂, and 198.685 kg/ha of CO.

Fuel		Emission (kg of contaminant/ton of fuel)			
	NO	NO ₂	NOx	SO ₂	CO
Muhlenbergia macroura	0.34a	0.25a	0.80d	0.46b	14.66b
P. hartwegii needles	1.55a	0.55a	2.83bc	0.58b	51.39a
P. hartwegii wood	0.73a	1.00a	1.73c	0.14b	46.62ab
Senecio cinerarioides	1.37a	0.62a	7.06a	1.98a	76.71a
Lupinus montanus	1.75a	0.59a	3.62b	0.49b	74.07a

Emissions of contaminants per unit weight of fuels in a forest of Pinus hartwegii (adapted of Contreras-Chart 1

9. DETRIMENTAL EFFECTS OF EXCESS FIRE

Detrimental fire effects can manifest themselves because of fire intensity, particularly after a prolonged period of fire exclusion, or due to very frequent fires from human origins. In both cases, the effects present themselves as degradation in ecosystem health, increased likelihood of and disease insect outbreaks. and excessive erosion of soils. For example, in the very intense fires of 1998 on the volcano Ajusco, in the Distrito Federal, the grassland cover was killed and recolonization is taking a long time.

Too much fire, e.g. very frequent fire, limits the natural regeneration of the pines (Verduzco, 1966). On-going research documented survival of trees between 2 to 6 m in height in unburned areas at 95%, while after a low-intensity prescribed fire in March it was 90%, and after a wildfire in May it was 30%. There was no significant difference between the first two (Figures 6 to 8).

Another detrimental by-product of fire is smoke. This is particularly important because various forests are located in the central part of the country, relatively close to urban zones like the Mexico City, where air quality is a chronic concern.



Figure 6. Unburned area.

11. DISCUSSION

Too frequent fires are in all respect harmful to the ecosystem; however, the exclusion of fire leads to eventual accumulation of fuel that will result in very destructive, high-intensity fires, that would kill large stands of trees which would not



Figure 7. Low intensity prescribed burned (March) site.



Figure 8. Site affected by a fire in May.

have the capacity to re-sprout. It would also, reduce the vigor of those that survive, and make the forest more susceptible to plagues, increase erosion, and cause increased mortality of both flora and fauna by direct and indirect effects.

The management, conservation and restoration of these ecosystems should include the reduction in the number of fires in some places, while re-introducing

appropriate fire in other areas. То accomplish both of these, it will be necessary to maintain and increase the efficiency of prevention and suppression of fires of human origin, and to incorporate the use of low-intensity prescribed fire, with ecologically based objectives. The importance of fire in maintaining desired species composition (e.g. preventing succession from lower altitudinal sites), structure (open; relatively low-density), and function (recycling of organic matter and nutrients; regeneration from seed and resprouts; productivity; phenology) has been well-documented and needs to be better understood and incorporated into management plans and actions.

Also, it should be emphasized to farmers the importance of using fire appropriately and carefully. It is a combination of poverty and the lack of a forestry culture that is the root cause of the majority of undesirable fires in these forests. Forest managers need to consider the needs of local farmers, and provide them with the tools and information to better manage their use of fire and to better appreciate the benefits derived from the forests adjacent to their agricultural plots or rangelands. The technology of prescribed fire to manage these forest ecosystems needs to be developed, along with a better understanding of fire effects under different types of burns. We particularly need dendrochronological studies to help us identify the appropriate fire regime for given

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