THESIS

INFLUENCE OF CLIMATIC ZONES ON THE DISTRIBUTION AND ABUNDANCE OF DAMAGE AGENTS AND FOREST TYPES IN COLORADO, UNITED STATES AND JALISCO, MEXICO

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ABSTRACT

INFLUENCE OF CLIMATIC ZONES ON THE DISTRIBUTION AND ABUNDANCE OF DAMAGE AGENTS AND FOREST TYPES IN COLORADO, UNITED STATES AND JALISCO, MEXICO

This study investigated: the relationship between temperature, precipitation and insect abundance in the forests of Colorado, USA and Jalisco, Mexico to quantify the latitudinal effects on disease and insect population, and developed a simple climate change model to predict the influence of changes in temperature and precipitation on the abundance of forest pests in the states of Jalisco and Colorado. In Jalisco, the source of information available on the distribution and abundance of forest types and causal agents were from a set of permanent sample plots located throughout the state. In Colorado a vegetation map was available which provided detailed information of the distribution of forests types across climate zones. Aerial survey data was also available providing complete coverage of the state with respect to the area damaged by the various causal agents. Results of this study indicated that temperature and precipitation have a significant influence on the distribution and abundance of forest types and forest insects and diseases in both Jalisco and Colorado. The linear and spatial correlations observed between climate zone and the distribution and abundance of forest types and causal agents were weaker in Jalisco than those observed in Colorado. This may be due to the type of data used in the analysis.

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INTRODUCTION

Forests provide many goods and services such as lumber, paper, nutrients storage, climate regulation, habitat for countless plant and animals, and recreational opportunities. Forests cover some 4.03 billion hectares, or approximately 31% of the world's land surface. This area is down from the pre-industrial period of 5.9 billion hectares. The decline is linked primarily to land clearing for agriculture and pastures and harvesting for fuel and fiber. A changing climate is also having an impact on the health of the remaining forests (FAO, 2011). The world's climate is changing and may be linked to the decrease in forested lands worldwide (FAO, 2011). Increasing temperatures and levels of atmospheric carbon dioxide as well as changes in precipitation pattern, and increasing occurrences of extreme climatic events are just some of the changes that are occurring. These changes are having notable impacts on the world's forests and expansion of forest pests (Battisti, 2004). Insects and diseases may be the first indicators of climate change (Logan et al., 2003), and there are already numerous examples where insect and pathogen lifecycles or habitats have been altered by local, national or regional climatic changes (FAO, 2010). For example, the pine processionary moth *(Thaumetopoea pityocampa)* has expanded its geographical range in Europe, as a result of enhanced winter survival under a warmer climate (Buffo et al., 2007).

Forest pests and pathogens can also have a significant impact on forest conditions worldwide. The impact from forest pests are estimated to be 50 times higher than the impact from fire alone, and with an economic affect nearly five times as great (Logan et al., 2003)**.** In 2000, it was noted that 7,880 ha of forests and other wooded lands in Mexico were damaged by forest insects and 2,000 ha were damaged by forest diseases (FAO, 2005). It was also noted the most common and damaging pests in the forests of Mexico and the western U.S. were bark beetles of the genus *Dendroctonus* (Cibrián-Tovar et al., 1995; Carroll et al., 2003). Salinas et al. (2010) found in Mexico, bark beetles of the genus *Dendroctonus* are natural inhabitants of forest but under certain conditions the beetles may lead to large-scale tree mortality. Salinas et al. (2010) found that regions affected the most by bark beetle attack were small zones within some mountain systems. The area's most affected by this insect during the last hundred years were in the Transverse Volcanic Belt, followed by the Sierra Madre Occidental and Sierra Madre del Sur (Salinas et al., 2010). In addition, since the mid-1970s, winter temperature have increased in North America resulting in both increased larval and adult stages in population size and geographic extent of mountain pine beetles, allowing for a rapid, widespread infestation of millions of hectares of pine forests (Logan et al., 1999; Safranyik et al., 2010).

Hebertson and Jenkins (2008) investigated the impact of climate on spruce beetle outbreaks in Utah and Colorado, USA between 1905 and 1996 and found that historic outbreak years in the Intermountain region were related to generally warm fall and winter temperatures and drought conditions. Similarly, outbreaks in both Canada (Yukon Territory) and the US (Alaska) appear to be related to extremely high summer temperatures which influenced spruce beetle population size through a combination of increased overwinter survival, a halving of the maturation time from two years to one year, and regional drought-induced stress of mature host trees (Berg et al., 2006).

Climate change is anticipated to influence pest populations, distribution, and development (Hlásny et al., 2011). Many studies have found that warmer winter temperatures may increase overwinter survival while higher summer temperatures in most cases will accelerate the rate of development of insects and increase their reproductive capacity (Ayres and Lombardero, 2000; Logan et al., 2003). For example, a study carried out by Rouault et al. (2006)

in western Europe during and after the 2003 drought found that woodborers were positively influenced by the high temperatures which increased their development rates and the prolonged water stress that lowered host tree resistance, while defoliators benefited from the increased nitrogen content in plant tissues which has been linked to moderate or intermittent water stress. Also, Battisti et al. (2006) found during the summer of 2003, the warmest summer in Europe in the last 500 years, *Thaumetopoea pityocampa* exhibited an unprecedented expansion to high elevation pine stands in the Italian Alps, increasing its altitudinal range limit by one third of the total altitudinal expansion over the previous three decades.

Temperature and precipitation influence insect phenology, feeding habits, frequency and timing of new generations, dispersal, emergence onset, winter survival, the behavior of parasitoids, predators and other bio-control agents, health and susceptibility of host trees, dynamics of symbionts and others characteristics (Ayres, 1993; Bale et al., 2002; Burnett, 1949; Dukes et al., 2009; Heliovaara and Peltonen, 1999; Logan et al., 2003). Changes in climatic conditions can alter an insect distribution, ecologic role and interaction, change in insect assemblages, northern migration, change timing of life history event, and increase or decrease in host defense chemicals (Danks, 1992). Both temperature and precipitation show geographic patterns, and both are capable of changing with time. As a result, these environmental factors are able to influence insect and disease distributions (Danks, 1992). The effect of temperature on forest pests will vary among species depending on their environment, life history, and ability to adapt. Flexible species that are polyphagous, occupy different habitat types across a range of latitudes and altitudes, and show high phenotypic and genotypic plasticity and are less likely to be adversely affected by climate change than specialist species occupying narrow niches in extreme environments (Bale et al., 2002). For example, Hill et al. (1999) described two species of British butterflies (one northern and one southern) colonizing new areas during range expansion that had longer wings and larger thoraxes than long established, resident populations. Also, changes in butterfly phenology have been reported from the United Kingdom where 26 of 35 species had altered their appearance in response to climate warming (Roy and Sparks, 2000). In addition, Parmesan and Yohe (2003) reported that more than 1,700 insect species in the Northern Hemisphere have exhibited significant range shifts averaging 6.1 km per decade towards the poles as a result of changing climate trends.

Climate plays a major role in defining the distributional range of a species. With changes in climate, these limits are shifting as species expand into higher latitudes and altitudes and disappear from areas that have become climatically unsuitable (Parmesan, 2006). Climate warming at temperate and more polar latitudes can ameliorate the thermal environment by altering the optimal timing of seasonal events and the length of the day available to the insects (Bradshaw et al., 2004; Gomi et al., 2007). The genetic response of insects to recent rapid climate change can occur over short periods of time such as five years or may take longer at higher latitudes where the climate is changing faster; selection is more intense than at lower latitudes (Bradshaw and Holzapfel, 2001). Indeed, over the next century temperate and more northern insects are expected to achieve increasing fitness due to the warmer temperatures alone and this effect increases with latitude (Deutsch et al., 2008). Thus, the spread of insect infestation and their response to climate change is expected to be more sever in Alaska compared to Colorado or Mexico. Higher latitude insect infestations are expected to increase as a result of climate change.

Increasing temperatures in temperate regions are anticipated to decline winter survival, while higher temperatures in more northern regions will extend the summer season thereby increasing growth and reproduction (Bale et al., 2002). Due to the more severe environmental control, and predicted increases in temperature in boreal and polar regions, the effect of temperature are expected to be significant on species from those regions than on species in temperate or tropical zones (Bale et al., 2002). However, Deutsch et al. (2008) suggest that in the absence of ameliorating factors such as migration and adaptation, the greatest annihilation dangers from climate change may be in the tropics. Increasing temperature in the tropics, although estimated to be smaller in magnitude, could have the most harmful effects because tropical insects have very narrow ranges of climatic appropriateness compared to higher latitude species, and are already living very close to their ideal temperature (Deutsch et al., 2008).

The objective of this study was to examine the relationship between temperature, precipitation and insect damage in the forests of Colorado, USA and Jalisco, Mexico to quantify the latitudinal effects on disease and insect population. A second objective was to develop a simple climate change model to predict the influence of changes in temperature and precipitation on the occurrence damage from forest pests in the states of Jalisco and Colorado.

METHODS

Study Areas

The state of Jalisco is located in western Mexico between 22°45’ and 18°55’ N latitude and 101°28’ and 105°42’ W longitude and contains an area of approximately eight million hectares (Fig. 1). Climatic variation in the region is influenced by an interaction between westerly winds of maritime air masses and the effects of mountain ranges.

Temperature and precipitation-evaporation zones for the region are shown in Figure 1 (Reich et al., 2008b). These zones coincide in general with those used to describe vegetation in

Mexico (Rzedowski, 1978). Furthermore, these zones define three broad ecological regions: 1) the *sub-humid tropical zone* is located along the Pacific coast and is characterized by high temperatures, monsoon rains during summer months (730-1200mm) and an annual dry period that ranges from 5 to 9 months. Tropical dry forests dominate this region and occur on terrain with elevations from sea level to 4000 m near the Colima volcano. 2.) At higher elevations the *sub-humid temperate zone* covers the greatest portion of the state. Pine (*Pinus* spp.), oak (*Quercus* spp.) and mixed deciduous hardwood forests dominate this zone (1000-2600 m) that has an average annual rainfall of 900-1500 mm (Perry, 1991). This zone gradually changes into 3), an *arid and semi-arid zone* that has an annual precipitation of 400mm or less for 8 to 12 months. Dominant vegetation includes mesquite-acacia (*Prosopis-Acacia*) and xerophytic shrub.

The state of Colorado is located in middle of United States between 37° N and 41° N latitude and 102° and 109° W longitudes and contains an area of approximately 26 million ha of which only 38% is forested (http://www.netstate.com/states/ geography /co_geography.htm).

Colorado's primary forest species have been grouped into nine forest types, based on the dominant overstory vegetation: aspen (*Populus tremuloides)*, piñon-juniper, spruce-fir *(Picea engelmannii*, *Abies lasiocarpa)*, mixed-conifer, oak shrubland *(Quercus gambelii*), ponderosa pine (*Pinus ponderosa)*, lodgepole pine *(Pinus contorta)*, montane riparian and plains riparian (Helms, 1998). The aspen is Colorado’s only widespread, native, deciduous tree and can be found from 6,900 to 10,500 feet in elevation and occur primarily on the West Slope. Piñon-juniper woodlands are widespread in the lower elevations ranging from 4,900 to 8,000 feet on Colorado's West Slope and exist in limited distribution in south-central Colorado and on the Eastern Plains (Colorado Natural Areas program, 1998). The spruce-fir combination often results in a climax-type forest at high elevations. The mixed-conifer forest type occurs at approximately

6,900 to 10,500 feet in elevation, nestled between lower-elevation forests such as ponderosa pine and higher-elevation subalpine fir forests such as spruce-fir. Colorado has 1.8 million acres of mixed-conifer forest. Oak shrublands cover approximately 2 million acres and occur between elevations of approximately 6,000 and 9,000 feet. These shrublands account for 10 percent of the forested lands in Colorado and are found throughout most of western Colorado and along the southern Front Range and in the central part of the state. Ponderosa pine is most common forest types and occurs between 6,000 and 9,000 feet. Ponderosa pine can occur on the landscape as low as 5,000 feet where prairies and shrublands transition into open ponderosa pine forests. Ponderosa pine is generally the dominant lower timberline species in Colorado's montane zone. Lodgepole pine (*Pinus contorta*) is a familiar species in the montane and subalpine fir forests of Colorado's northern Rocky Mountains between 8,000 and 10,000 feet in elevation. Montane riparian forests occur along rivers and streams in Colorado's foothill and mountain regions, beginning around 6,000 to 7,500 feet in elevation. Low-elevation plains riparian systems are found along rivers and streams throughout the western Great Plains (Colorado Natural Areas program, 1998).

Field data from Jalisco

The data used to characterize the distribution of forest types and pests in Jalisco, Mexico were obtained from an inventory and monitoring program designed to provide regional and local estimator of the natural resources in state (Reich et al., 2008b). In 2006, 1442 permanent plots were located throughout the state, of which 803 plots were classified as being forested. Only forested plots were considered in this study. The primary sampling unit was a 30 m x 30 m square plot corresponding to the spatial resolution of a Landsat 7 ETM+ image. Each plot was sub-divided into nine 10 m x10 m secondary sampling units, of which five were systematically selected for detailed measurement (Reich et al., 2008b). Information on forest type and information on the presence of any tree damage were extracted from the data base. Eight major of forest types occurred in state which included: tropical deciduous, sub-tropical deciduous, *mezquite*, pine, oak, cloud forest, palm, and xerophytic. Causal agents considered in the study included: wind, wood decay, insects, fungi, fire, dwarf mistletoe, defoliators, wood borers, and bark beetles.

GIS Layers

Climate zones

Climate data in the form of GIS layers were available as average monthly temperature (C), precipitation (mm) and evaporation (mm) for both Colorado, and Jalisco (Reich et al., 2008a; Aguirre-Bravo and Reich, 2006). These models were used to define temperature zones and precipitation zones that in combination defined 12 unique climate zones in Jalisco (Fig.1), and 20 unique climate zones in Colorado (Fig.2). The climate zones were based on a histogram equalization approach that produced a uniform distribution of temperatures and precipitations across the two states (Acharya and Ray, 2005). Zonal statistics were used to summarize the variability in temperature and precipitation in each climate zones for both states (Table 1 and 2).

Vegetation maps

A 30 m raster layer of the major vegetation types in Colorado was obtained from the Colorado Division of Wildlife. Major forest types included aspen, bristlecone pine, fir, gambel oak, lodgepole pine, piñon-juniper, ponderosa pine, spruce, mixed shrub, and willow. No reliable vegetation map was available for Jalisco, Mexico so information on the distribution and abundance of forest types were obtained from the field data.

Aerial survey data

Each year during the summer and early fall, the USDA Forest Service (FS) and Forest Health Protection (FHP) and its partners conduct aerial surveys to map forest insect and disease activity in Colorado. Aerial surveys provide an annual snapshot of forest health conditions over large areas more efficiently and economically than other survey methods. To conduct the survey, observers in small aircraft record areas of activity using a digital aerial sketch mapping system that incorporates a tablet PC, geographic information systems and global positioning system technology. To identify insect and disease activity, the observer looks for characteristic signatures to distinguish the tree species and the type of damage that has occurred. Characteristics that observers use to determine the host tree species include: the shape of the tree's crown, slope position, elevation and aspect. Variation in the color of the tree's foliage indicates the presence and type of insect or disease activity (http://www.fs.fed.us/r6/nr/fid/as/as-facts.shtml). Aerial survey data for 2010 was obtained for the state. Causal agents identified on the aerial survey were placed in four broad classes: bark beetles, defoliators, decline complexes and multi-damage. Causal agents associated with the four classes are listed below:

Bark beetles:

- Roundheaded pine beetle (*Dendroctonus adjunctus).*
- Mountain pine beetle *(Dendroctonus ponderosae).*
- Douglas-fir beetle (*Dendroctonus pseudotsugae).*

- Spruce beetle (*Dendroctonus rufipennis).*
- Pine engraver (*Ips pini).*
- Ips spp.
- Pityophthorus spp.
- Douglas-fir engraver (*Scolytus unispinosus)*
- Fir engraver (*Scolytus ventralis)*

Defoliators:

- Large aspen tortrix (*Choristoneura conflictana)*
- Western spruce budworm (*Choristoneura occidentalis)*
- Coleotechnites spp.

Decline Complexes/Dieback/Wilts:

- Sudden aspen decline.

Multiple-Damage:

- Subalpine fir mortality.
- Five-needle pine decline.
- Pinyon pine mortality.

Presence of Forest Types and Causal Agents in Colorado and Jalisco

The raster layer of vegetation types for Colorado was converted to binary surfaces indicating the presence/absence of a given forest type in the state. The frequency of raster cells in which a given forest type was dominant was determined for each of the 20 climate zones. Frequency as used in this paper is defined as number of times a given forest type was dominant in a given climate zone. In the case of Jalisco, the frequency of sample plots in which a given forest type occurred was tallied for each of the 12 climate zones.

Multiplying the frequencies by 0.09 for the Colorado data provides an estimate of the area (ha) dominated by a given forest type in each climate zone. Dividing the area of a given forest type by the area of the climate zones provides an estimate of the probability of observing that forest type in each climate zone. Frequencies and probabilities were summarized in a 4 x 5 Climate Transition Matrix (CTM) representing the response in the probability of observing a given forest type to a change in climatic conditions. The rows of the matrix correspond to the temperature zones and the columns the precipitation zones. In the case of Jalisco, a 3 x 4 Climate Transition Matrix was used.

A similar procedure was used to summarize the abundance of the disease and insect activity in Jalisco and Colorado. The aerial survey data layers in Colorado and the field data in Jalisco were intersected with the climate raster layers to obtain estimates the proportion of forested areas or the number of sample plots affected by the various causal agents within each climatic zone. This information was summarized in the Climate Transition Matrices.

Influence of Climate on the Distribution of Forest Types and Causal Agents in Jalisco and Colorado

To understand the role of climatic condition on the distribution and abundance of forest types and causal agents, linear and polynomial regression analysis were applied to the frequency and probability data. Linear and polynomial regression analysis were applied to patterns in the frequency and probability of the forest types and causal agents as a function of the temperature (T=1,2,3 for Jalisco, and T=1,2,3,4 for Colorado) and precipitation (P=1,2,3,4 for Jalisco and P=1,2,3,4,5 for Colorado) zones. A natural logarithm transformation was used to stabilize the variability in the frequencies and probabilities across climate zones, while the integers (1, 2, 3, 4, 5) were used to identify the temperature and precipitation zones in the model. The linear relationship between the integers used to represent the temperature and precipitation zones and the average temperature and precipitation associate with each zone is property of the histogram equalization technique used in defining the zones (Table1 and 2). The regression model that minimized the AIC was taken as the final form of the regression models.

Moran's I was used to test the null hypothesis that the frequency and probability data for forest types and causal agents were spatially independent across climate zones. Moran's I is a global test for spatial autocorrelation for continuous data. It is based on cross-products of the deviations from the mean and is calculated for n observations on a variable x at spatial locations i, j as:

$$I = \frac{n}{S_0} \frac{\sum_i \sum_j w_{ij} (x_i - \overline{x})(x_j - \overline{x})}{\sum_i (x_i - \overline{x})^2},$$

Where $\bar{x}$ is the mean of the x variable, w_{ij} are the elements of a spatial weights matrix describing the spatial proximity of the n observations , and S_0 is the sum of the elements of the weight matrix: $S_0 = \sum_i \sum_j w_{ij}$ (Moran, 1950).

A rook's move was used to define the spatial adjacency matrix describing the spatial relationship among 12 climate zones for Jalisco and 20 climate zones for Colorado. A cross-correlation statistic (Czaplewski and Reich, 1993) was used to test all pair-wise combinations of forest types and causal agents for spatial cross-correlations. The spatial weight matrix based on the rooks move was used to define the spatial adjacency matrix used to test for the spatial cross-correlation.

RESULTS

Distribution of Forest Types in Jalisco by Climate Zone

Temperature and to some extent precipitation significantly influenced the distribution of forest types in state of Jalisco (Table 5). Except for the cloud forests, *mezquite* and palms, forest types showed a curvilinear relationship with the temperature and precipitation zones. The cloud forests showed a negative relationship to temperature and precipitation preferring a warm, dry climate. In contrast, both the *mezquite* and palms showed a positive relationship with temperature and precipitation with both preferring a hot, wet climate. Based on the distribution of sample plots observed within the temperature zones (Figure 3 and 4), 53% of the sample plots classified as tropical deciduous occurred in the warm temperature zone (T2). Sample plots of sub-tropical deciduous (49%), cloud forest (50%), oak (49%), pine and oak (54%), and pine (50%) also dominated the warm (T2) temperature zone. *Mezquite* (67%), palm (40%), xerophytic (46%), and juniper (83%) occurred primarily in the hotter temperature (T3) zone, while fir preferred both the mild (T1-50%) and hot (T3-50%) temperature zone. The Climate Transition Matrices used in this analysis are summarized in Appendix A.

While not significant, precipitation did influence the distribution and abundance of forest types in the state (Table 5). For example, the tropical deciduous and sub-tropical deciduous forests occurred primarily in the wet precipitation zone (P4), while the pine forest type preferred the moist zone (P2). The fir forest type preferred both the moist (P2) and damp (P3) zone. The distribution and abundance of *mezquite*, palm, xerophytic, oak, pine-oak and juniper forest types increased with increasing precipitation, while the cloud forest decreased with increasing precipitation.

Distribution of insect and diseases in Jalisco by climate zone

Temperature and precipitation influenced the overall distribution of causal agents in Jalisco (Table 5, Appendix A). In general, there was more activity of causal agents in the warm (T2) temperature zones compared to the mild (T1) and hotter (T3) temperature zones (Figure 5). In contrast, the various causal agents were more active in the wetter precipitation zones compared to the drier regions (Figure 6). Individual causal agents showed less of a trend with the temperature and precipitation zones (Figure 5 and 6). For example, the distribution of wood decay (63%), insects (60%), fungi (69%), fire (75%), dwarf mistletoe (72%), defoliators (61%), wood borers (100%), and bark beetles (70%) occurred primarily in the warm (T2) temperature zone, while wind damage (85%) occurred primarily in the hotter (T3) temperature zone. The distribution of wind damage, fire and dwarf mistletoe increased with increasing precipitation. Wood decay and defoliators preferred the damp (P3) precipitation zone, while the insects and fungi occurred primarily on sample plots in the wet (P4) precipitation zone.

Spatial Relationships between Forest Types and Causal Agents in Jalisco

Influence of climate on the spatial distribution of causal agents and forest types were evaluated using measures of spatial autocorrelation and cross-correlation statistics (Table 3). Moran's I statistic indicated that the palm, xerophytic, tropical deciduous, sub-tropical deciduous, oak, pine-oak, fir, and pine forest types were spatially independent of climatic conditions in the state, while the *mezquite*, cloud forest and juniper forest types exhibited a significant positive spatial autocorrelation with climate zones (Table 3). Only wind, dwarf mistletoe and bark beetles showed a significant positive spatial autocorrelation across climate zones (Table 3).

Numerous significant cross-correlations were observed among the causal agents, the most important being the bark beetles (Table 3). The spatial distribution and abundance of bark beetles across climate zones was significantly similar to the patterns observed for wind damage, wood decay, fungi, fire, dwarf mistletoe and wood borers. In addition, the spatial distribution and abundance of dwarf mistletoe across climate zones were significantly similar to those observed for wood decay and fungi. No other significant correlations were observed among causal agents.

With respect to forest types the *mezquite* and juniper forest types showed the strongest cross-correlation with other forest types. The spatial distribution and abundance of the *mesquite* forest type across climate zones was significantly cross-correlated with the spatial distribution and abundance of the palms, xerophytic and cloud forest types. The spatial distribution and abundance of junipers were spatially cross-correlated to the spatial distribution of the pine, cloud forests and xerophytic forest types. The pine forest type was spatially cross-correlated to the tropical semi-deciduous forest type. A few significant cross-correlations were observed between forest types and causal agents (Table 3). The most notable were between bark beetles, wind and dwarf mistletoe and the *mesquite* and xerophytic forest types.

Distribution of major forest types in Colorado by climate zone

Temperature and to some extent precipitation are important ecological drivers that influence the distribution of forest types throughout the mountains of Colorado (Figure 7 and 8). Significant curvilinear relationships were observed between the probability of observing a forest type and the temperature and precipitation zones (Table 6). The major forest types occurred in two of the four temperature zones and three of the five precipitation zones (Apendix B). Aspen (77%), spruce (92%), lodgepole pine (73%), bristlecone pine (99.5%), fir (50%), limber pine (94%), willow (88%) dominated the mild (T2) temperature zone while piñon -juniper (97%), ponderosa pine (65%), oak (70%), shrubs (65%), lodgepole pine (27%) and fir (50%) occur primarily in the warmer temperature (T3) zone.

The distribution of lodgepole pine, limber pine, and piñon-junper showed a curvilinear relationship with precipitation; lodgepole pine preferring the moist precipitation zone (P3). Aspen, ponderosa pine, spruce, oak, mixed shrub, bristlecone pine, fir, and willow exhibited a linear relationship with respect to precipitation. The distribution of ponderosa pine, aspen, oak, shrubs and fir decreased with increasing precipitation, while the presence of spruce, bristlecone pine and willow increased with increasing precipitation.

Distribution of insect and disease in Colorado by climate zone

Temperature and precipitation are important factors that influence the spread and distribution of insects and diseases in the forests of Colorado (Figure 9 and 10). Significant curvilinear relationships were observed between the probability of observing a causal agent and the temperature and precipitation zones (Table 6). Most insect infestation and disease were found in two of the four temperature zones and three of the five precipitation zones (Appendix B). The distribution of bark beetles (55%), decline complexes (75%), defoliators (82%), multi-damage (94%), occurred primarily in the mild (T2) temperature zone followed closely by the warmer temperature zone: bark beetles (45%), decline complexes (25%), defoliators (18%), and multi-damage (6%). Bark beetles preferred the moist precipitation zones (P3) while defoliators preferred the damp precipitation zone (P4). The distribution of decline complexes decreased with increasing precipitation while the presence of multi-damage increased with increasing precipitation.

Spatial Relationships between Forest Types and Causal Agents in Colorado

Estimates of spatial autocorrelation and the cross-correlation statistics for all variables are given in Table 4. Moran's I statistic indicated that the aspen, fir, oak, piñon-juniper, ponderosa pine, and mixed shrub were spatially independent of the climate zones in Colorado (Table 4), while bristlecone pine, limber pine, lodgepole pine, spruce, willow and all causal agents (e.g., bark beetle, decline complexes, defoliators and multi-damage) exhibited a significant positive spatial autocorrelation with climate zones (Table 4). Significant positive spatial cross-correlations were observed between bristlecone pine, limber pine, lodgepole pine and spruce. Significant positive spatial cross-correlations were also observed between bark beetles, multiple-causes and defoliators. The most important cross-correlations between forest types and causal agents included bristlecone pine, limber pine, spruce and lodgepole pine and the bark beetles, decline complexes and damage caused by multiple agents (Table 4).

DISCUSSION

Results of this study indicate that temperature and precipitation have a significant influence on the distribution and abundance of forest types and forest insects and diseases in both Jalisco and Colorado. Climatic conditions influence the dynamics of forested landscapes in many ways. Forests thrive in a variety of climatic conditions, ranging from wet tropical forests to the forests of the dry boreal regions in the northern latitudes. The vegetative transition from deserts to grasslands to forests is commonly determined by moisture conditions. Temperatures influence not only the length of the growing season, but the geographic distribution of individual species. As temperatures increase, this could result in a shift in the geographic ranges of some tree species. Habitats of some types of trees are likely to move northward or to higher altitudes. Other species may be at risk locally or regionally if conditions in their current geographic range are no longer suitable (CCSP, 2008). Increasing variability in temperature and precipitation patterns may also have a detrimental effect on forests. Plants rely on a certain range in seasonal temperature and precipitation for proper function in their various life stages. Extremes in variation outside of an acceptable range can damage individuals resulting in mortality or their functions are impaired (Bassow et al., 1994).

Temperature directly affects insect movement, development, resource consumption, fecundity, generation frequency and time, onset, pattern, and extent of dispersal, and phenology (Bale et al., 2002; Logan et al., 2003).Temperature indirectly affects host population health, stress, and susceptibility (Dukes at al., 2009); dynamics of symbiotic organism, resistance chemical in potential host trees (Ayres, 1993). Precipitation indirectly affects the water status of potential host trees and may influence susceptibility (Heliovaara and Peltonen, 1999).

The use climate zones provide useful perspective on the effects of temperature and precipitation on forest and insect dynamics and distribution. Determining the species environment relationship is an important issue in ecology (Guisan and Zimmermann, 2000) and the climatic zones provide opportunity for quantifying the relationship between forest insect population and environment factors. The relationships between temperature and precipitation within different zones and insect abundance can be used as a basis for predicting abundance of forest insects in zones with similar climatic conditions elsewhere in the state. Furthermore, the information characterizing insect abundance within the various climatic zones should provide information on how the insect population would change under different scenarios of changing temperature and/or precipitation.

Insect infestations occur where a susceptible host population occurs simultaneously with an aggressive insect population within a suitable environment. The environment serves to catalyze such interactions. In this study, for example, the probability of observing bark beetles both in Colorado and Jalisco was highest in the warmer, wet regions, while the probability of observing leaf defoliators was highest in the cooler, wet regions within both states. Both temperature and precipitation show geographic patterns that are influenced and often determined by the local and regional geography and both can change with time. As a consequence, insect distribution can depend on these factors.

The evidence is strong but mostly circumstantial for climate driven changes in the behavior and distribution of a handful of insects and diseases in the two states. There is, however, enough evidence to suggest that this effect is probably more widespread and will probably become more apparent in time. Aukema et al. (2008) concluded that dispersed local populations and temperature played a major role in dynamics of the current mountain park beetle outbreak in British Columbia. Low winter temperatures have been shown to reduce beetle populations levels to non-outbreak levels (Wygant, 1940; Swaine, 1925), while warm summer temperatures have been found to alter development rates and impact the phenology timing affecting synchrony of emergence (Logan et al., 1998). Low precipitation creates drought stress that has often been associated with physiological changes in host trees resulting in enhanced susceptibility (Beal, 1943; Amman, 1973; Matson and Haack, 1987; Berryman et al., 1989; Lorio, 1993). Juday (1998) describes the spruce beetle outbreaks in south-central Alaska during the 1990s as "the largest ever documented from an insect outbreak in North America", and claims that climate was the driving factor. Berg et al. (2006) linked the 1990s spruce beetle outbreak to a series of years from 1987 to 1997 that showed a higher than average summer temperature. Models of the impacts of climate change on insect abundance have been developed for a small hand full of insect pests. These models are all driven by hourly temperature data. Mechanistic models applicable to Alaska have been developed only for spruce beetle (Hansen et al., 2001a, b) based on temperature impacts on voltinism. Results suggest that the Climate Transition Matrix is a useful concept for examining the influence of temperature or precipitation on insect abundance and for predicting what might happen to the insect population under various environmental change scenarios.

Our limited understanding the influence of large scale temperature and precipitation patterns on insect pests in North America restricts our ability to predict future impacts of these agents on forest health. The climatic zones approach described here provides a unique perspective on the behavior of temperature and precipitation, and offers a promising approach to predicting what forest insect pests will do under a changing climate.

One of the limitations of this approach has to do with the quality of the data used to develop the Climate Transition Matrices. The linear and spatial correlations observed between climate zone and the distribution and abundance of forest types and causal agents were weaker in Jalisco than those observed in Colorado. This may be due to the type of data used in the analysis. In Jalisco, the only source of information available on the distribution and abundance of forest types and causal agents were from a set of permanent sample plots located throughout the state. The variability associated with the sample plots made it difficult to statistically quantify the relationship between the distribution and abundance of forest types and causal agents to climatic conditions. In contrast, in Colorado a vegetation map was available which provided detailed information of the distribution of forests types across climate zones. Aerial survey data was also available providing complete coverage of the state with respect to the area damaged by the various causal agents, thus making it possible to quantify the influence of climatic conditions on the distribution and abundance of the causal agents.

The forests in North America are predicted to experience strong changes in climatic conditions in the near future due to global warming: mean temperatures are projected to increase by 3^{o}C towards the end of this century as well as a redistribution of rainfall (Brienen et al., 2010). Trees in some regions may be particularly sensitive to climatic changes, especially to drying. Lower rainfall and/or higher temperatures increase water stress and may slow tree growth and raise mortality rates (Condit et al., 2004). Forests are strongly affected by a number of disturbances, including fire, drought, insects, diseases, and severe storms. Under the climate changes, insect and pathogen outbreak will likely increase in severity. As forest ecosystems change and move in response to climate changes, they will become more vulnerable to disturbances. However, inferences on the likely impact of climatic changes on the distribution and abundance of forest types and causal agents are impossible to make without a thorough understanding of the influence of climatic conditions on the distribution and abundance of the forest types and causal agents. The models developed in this study are a first step in understanding the impact of climate change on the spatial relationship between the distribution and abundance of the forest types and causal agents in North America. Distribution models like those developed here greatly add to the assessment of the relative importance of climatic factors on forest health and in doing so, offer arguments for which forest types should or should not be harvested, what forest types deserve priority in their management, and which forest types might be significantly impacted by climate change. The distribution models can help decision makers identify the locations of especially sensitive forest types to climate change; estimate and predict the impact of these changes on ecosystem services; and prioritize and decide on the best kinds of management options and where to implement them.

Table 1. Summary statistics of average temperatures (T) and precipitation (P) in Jalisco, Mexico by climate zone.

Climate Zone	Min	Mean	Max	CV%
	---------- Precipitation (mm) ----------			
P1 – Dry	30.0	56.8	109.0	14.1
P2 – Moist	35.0	66.5	125.0	11.9
P3 – Damp	39.0	77.1	118.0	10.4
P4 – Wet	38.0	93.2	158.0	18.0
	---------- Temperature (C^o) ----------			
T1 – Mild	2.9	12.0	18.9	7.7
T2 – Warm	8.6	15.0	23.1	11.5
T3 – Hot	12.4	20.6	25.7	5.9

Table 2. Summary statistics of average temperatures (T) and precipitation (P) in Colorado by climate zone.

Climate Zone	Min	Mean	Max	CV%
	---------- Precipitation (mm) ----------			
P1 – Arid	3.2	12.9	16.7	16.2
P2 – Dry	14.1	21.9	26.0	10.9
P3 – Moist	22.2	32.8	43.9	12.0
P4 – Damp	40.0	45.5	52.8	5.7
P5 – Wet	49.2	58.6	79.6	8.2
	---------- Temperature (C^o) ----------			
T1 – Cool	-6.0	-3.1	-2.6	14.2
T2 – Mild	-2.6	2.0	4.3	85.5
T3 – Warm	4.3	8.3	11.1	24.1
T4 – Hot	11.1	11.6	14.7	3.9

Table 3.Spatial autocorrelation and cross-correlation analysis of forest types and causatives in Jalisco, Mexico.

Causative Disease									Land											
Wind	Wood decay	Insect	Fungi	Fire	Dwarf mistletoe	Defoliators	Wood borer	Bark beetles	Mazquite	Palm	Xerophytic	Tropical-deciduous	Sub-tropical deciduous	Cloud forest	Oak	Pine-oak	Juniper	Fir	Pine	
0.201 ***	0.0052 NS	0.088 NS	0.119 NS	0.15 NS	0.24 NS	-0.030 NS	-0.12 NS	0.28 **	0.40 ***	0.07 NS	0.125 ***	0.026 NS	-0.045 NS	-0.19 NS	0.175 NS	0.048 NS	0.159 ***	-0.055 NS	0.234 NS	Wind
	-0.11 NS	0.106 NS	0.130 NS	0.029 NS	0.303 **	-0.046 NS	0.008 NS	0.295 **	0.255 *	0.05 NS	-0.011 NS	0.051 NS	-0.15 NS	-0.24 *	0.053 NS	-0.168 NS	-0.09 NS	0.034 NS	0.294 *	Wood decay
		-0.077 NS	0.13 NS	0.178 NS	0.108 NS	0.131 NS	-0.07 NS	0.06 NS	0.118 NS	-0.012 NS	-0.0007 NS	0.038 NS	0.05 NS	0.005 NS	0.10 NS	0.15 NS	0.047 NS	-0.008 NS	0.068 NS	Insect
			0.140 NS	0.144 NS	0.176 *	0.055 NS	-0.06 NS	0.171 *	0.154 NS	0.089 NS	0.146 NS	0.15 NS	0.08 NS	-0.09 NS	0.14 NS	0.031 NS	0.12 NS	-0.07 NS	-0.024 NS	Fungi
				0.14 NS	0.310 ***	-0.011 NS	-0.05 NS	0.336 ***	0.371 ***	0.17 NS	0.19 NS	0.117 NS	-0.021 NS	-0.25 *	0.15 NS	-0.033 NS	0.13 NS	-0.01 NS	0.166 NS	Fire
					0.215 ***	0.123 NS	-0.18 NS	0.21 ***	0.270 **	0.23 NS	0.381 ***	0.173 NS	0.189 NS	-0.14 NS	0.17 NS	0.15 NS	0.374 ***	-0.08 NS	-0.26 *	Dwarf mistletoe
						-0.009 NS	0.035 NS	0.19 NS	0.143 NS	0.024 NS	-0.02 NS	0.06 NS	-0.08 NS	-0.19 NS	0.038 NS	-0.15 NS	-0.099 NS	0.08 NS	0.20 NS	Defoliators
							0.082 NS	-0.24 *	0.313 ***	-0.195 NS	-0.22 NS	-0.06 NS	0.007 NS	0.18 NS	-0.083 NS	*0.02* NS	-0.18 NS	-0.009 NS	-0.03 NS	Wood Borer
								0.179 ***	0.28 **	0.25 *	0.36 ***	0.16 NS	0.197 NS	-0.10 NS	0.205 NS	0.216 NS	0.402 ***	-0.150 NS	-0.22 NS	Bark beetles
									0.52 ***	0.21 *	0.384 ***	0.069 NS	0.146 NS	-0.23 *	0.30 NS	0.26 **	0.48 ***	-0.10 NS	0.016 NS	Mazquita
										-0.21 NS	0.013 NS	-0.04 NS	0.032 NS	-0.05 NS	0.08 NS	0.09 NS	0.056 NS	0.081 NS	0.015 NS	Palm
											0.051 NS	0.067 NS	-0.046 NS	-0.142 NS	0.117 NS	0.006 NS	0.07 *	-0.10 NS	0.10 NS	Xerophytic
												0.12 NS	0.069 NS	0.037 NS	0.076 NS	0.024 NS	0.035 NS	-0.079 NS	-0.03 NS	Tropical deciduous
													-0.130 NS	-0.03 NS	0.014 NS	-0.14 NS	-0.16 NS	-0.105 NS	0.23 *	Sub-tropical deciduous
														0.23 *	-0.10 NS	-0.179 NS	-0.28 **	-0.12 NS	0.06 NS	Cloud-forest
															0.18 NS	0.11 NS	0.165 NS	-0.05 NS	0.18 NS	Oak
																-0.12 NS	-0.07 NS	-0.069 NS	0.35 ***	Pine-oak
																	0.094 **	-0.033 NS	0.27 *	Juniper
																		-0.21 NS	-0.06 NS	Fir
																			-0.08 NS	Pine

Spatial autocorrelation statistic on the diagonal and spatial cross-correlations statistic on the off diagonal. *** significant $\alpha = 0.05$. ** significant $\alpha = 0.1$. * Significant $\alpha = 0.15$. NS = not significant $\alpha > 0.15$.

Table 4. Spatial autocorrelation and cross-correlation analysis of forest types and causatives in Colorado

Aspen	Bristlecone pine	Fir	Gambel oak	Limber pine	Lodgepole pine	Piñon-Juniper	Ponderosa pine	Shrub mixed	Spruce	Willow	Bark beetles	Decline complexes	Defoliators	Multi-damage	
-0.02 NS	-0.11 NS	-0.048 NS	-0.076 NS	-0.14 NS	-0.13 NS	-0.04 NS	0.107 NS	-0.040 NS	-0.146 NS	-0.12 NS	-0.122 NS	-0.128 NS	-0.153 NS	-0.123 NS	Aspen
	0.22 **	-0.05 NS	-0.02 NS	0.283 ***	0.297 ***	-0.12 NS	0.072 NS	-0.123 NS	0.272 ***	0.27 ***	0.271 ***	0.232 **	0.302 ***	0.226 ***	Bristlecone pine
		-0.061 NS	-0.089 NS	-0.07 NS	-0.073 NS	0.08 NS	0.15 NS	-0.07 NS	-0.08 NS	-0.129 NS	-0.061 NS	-0.09 NS	-0.093 NS	-0.063 NS	Fir
			-0.12 NS	-0.04 NS	-0.05 NS	-0.11 NS	0.14 NS	-0.11 NS	-0.055 NS	-0.12 NS	-0.050 NS	-0.078 NS	-0.068 NS	-0.037 NS	Gambel oak
				0.29 ***	0.31 ***	-0.15 NS	0.12 NS	-0.14 NS	0.30 ***	0.25 **	0.290 ***	0.245 **	0.292 ***	0.2828 ***	Limber pine
					0.30 ***	-0.16 NS	0.18 NS	-0.157 NS	0.319 ***	0.15 NS	0.291 ***	0.1981 *	0.266 **	0.318 NS	Lodgepole pine
						-0.06 NS	0.086 NS	-0.062 NS	-0.16 NS	-0.118 NS	-0.15 NS	-0.150 NS	-0.168 NS	-0.135 NS	Piñon-Juniper
							0.141 NS	0.088 NS	0.097 NS	-0.11 NS	0.178 NS	0.084 NS	0.108 NS	0.074 NS	Ponderosa pine
								-0.05 NS	-0.157 NS	-0.123 NS	-0.145 NS	-0.14 NS	-0.164 NS	-0.132 NS	Shrub_Mixed
									0.35 ***	0.29 ***	0.338 ***	0.217 **	0.34 ***	0.323 ***	Spruce
										0.506 ***	0.127 NS	0.056 NS	0.235 **	0.411 ***	Willow
											0.28 ***	0.163 NS	0.254 **	0.309 ***	Bark beetles
												0.190 *	0.169 NS	0.164 NS	Decline complexes
													0.242 **	0.327 ***	Defoliators
														0.281 ***	Multi-damage

Spatial autocorrelation statistic on the diagonal and spatial cross-correlations statistic on the off diagonal. *** significant $\alpha = 0.05$. ** significant $\alpha = 0.1$. * Significant $\alpha = 0.15$. NS = not significant $\alpha > 0.15$.

Table 5. The significance (p-value) of temperature and precipitation on the distribution and abundance forest types and causal agents observed on the sample plots across climate zones in the state of Jalisco, Mexico. The functional form of the regression models were selected based on AIC.

Variable	p-value				Model AIC	
	Temp	Precip	$Temp^2$	$Precip^2$	Linear	Quadratic
			Causal Agent			
Bark beetles	0.120	0.170	0.126	0.069	23.01	18.17
Defoliators	0.863	0.079	0.791	0.094	36.81	35.99
Wood Borers	1.00	0.257			21.96	23.42
Dwarf Mistletoe	0.004	0.095	0.003	0.040	39.33	24.68
Fire	0.005	0.617	0.005	0.771	44.23	33.96
Fungi	0.007	0.659	0.005	0.416	43.33	32.35
Insects	0.060	0.979	0.066	0.805	34.48	32.21
wood decay	0.832	0.227			34.11	37.14
Wind	0.011	0.034			36.58	40.13
			Forest Type			
Cloud Forests	0.301	0.170			18.94	19.01
Mezquite	0.014	0.004			17.34	21.06
Oak	0.092	0.310	0.096	0.807	32.52	31.42
Palm	0.530	0.493			15.10	18.52
Pine	0.147	0.461	0.182	0.409	30.92	30.68
Pine-Oak	0.058	0.495	0.077	0.478	38.64	36.33
Tropical Deciduous	0.068	0.851	0.046	0.661	34.77	31.28
Sub-tropical deciduous	0.177	0.657	0.146	0.749	34.78	34.77
Xeriophytic shrubs	0.030	0.354	0.042	0.72	31.62	27.91

Table 6. The significance (p-value) of temperature and precipitation on the distribution and abundance forest types and causal agents across climate zones in the state of Colorado. The functional form of the regression models were selected based on AIC.

Variable	p-value				Model AIC	
	Temp	Precip	$Temp^2$	$Precip^2$	Linear	Quadratic
			Causal Agent			
Bark Beetles	<0.001	0.355	0.001	0.752	82.81	71.52
Decline Complex	0.003	0.158	0.002	0.329	73.93	64.12
Defoliators	0.002	0.573	0.002	0.966	71.24	61.76
Multiple Causes	0.006	0.774	0.005	0.351	66.34	58.60
			Forest Type			
Aspen	0.025	0.026	0.036	0.077	121.15	115.82
Bristlecone Pine	0.018	0.982	0.010	0.510	97.74	92.33
Fir	0.007	0.009	0.012	0.026	121.55	112.24
Gamble Oak	<0.001	0.009	<0.001	0.014	123.76	108.31
Limber Pine	0.002	0.454	0.001	0.881	101.69	91.63
Lodgepole Pine	<0.001	0.160	<0.001	0.505	123.61	104.35
Piñon-Juniper	0.030	0.021	0.137	0.019	122.28	116.60
Ponderosa Pine	0.001	0.017	0.001	0.043	126.25	112.31
Shrubs	0.031	0.004	0.050	0.015	119.14	111.38
Spruce	0.017	0.106	0.011	0.369	120.24	114.70
Willow	0.066	0.463	0.023	0.846	103.36	100.21

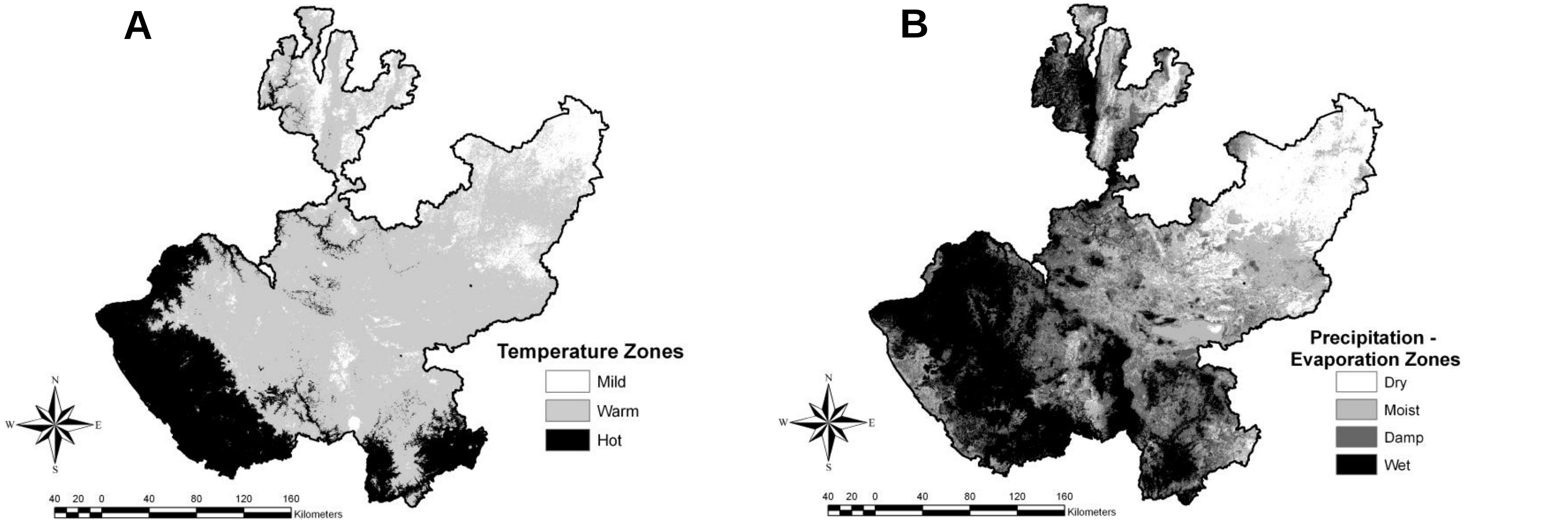

Figure 1: Climatic zones in Jalisco based on A) Temperature and B) Precipitation.

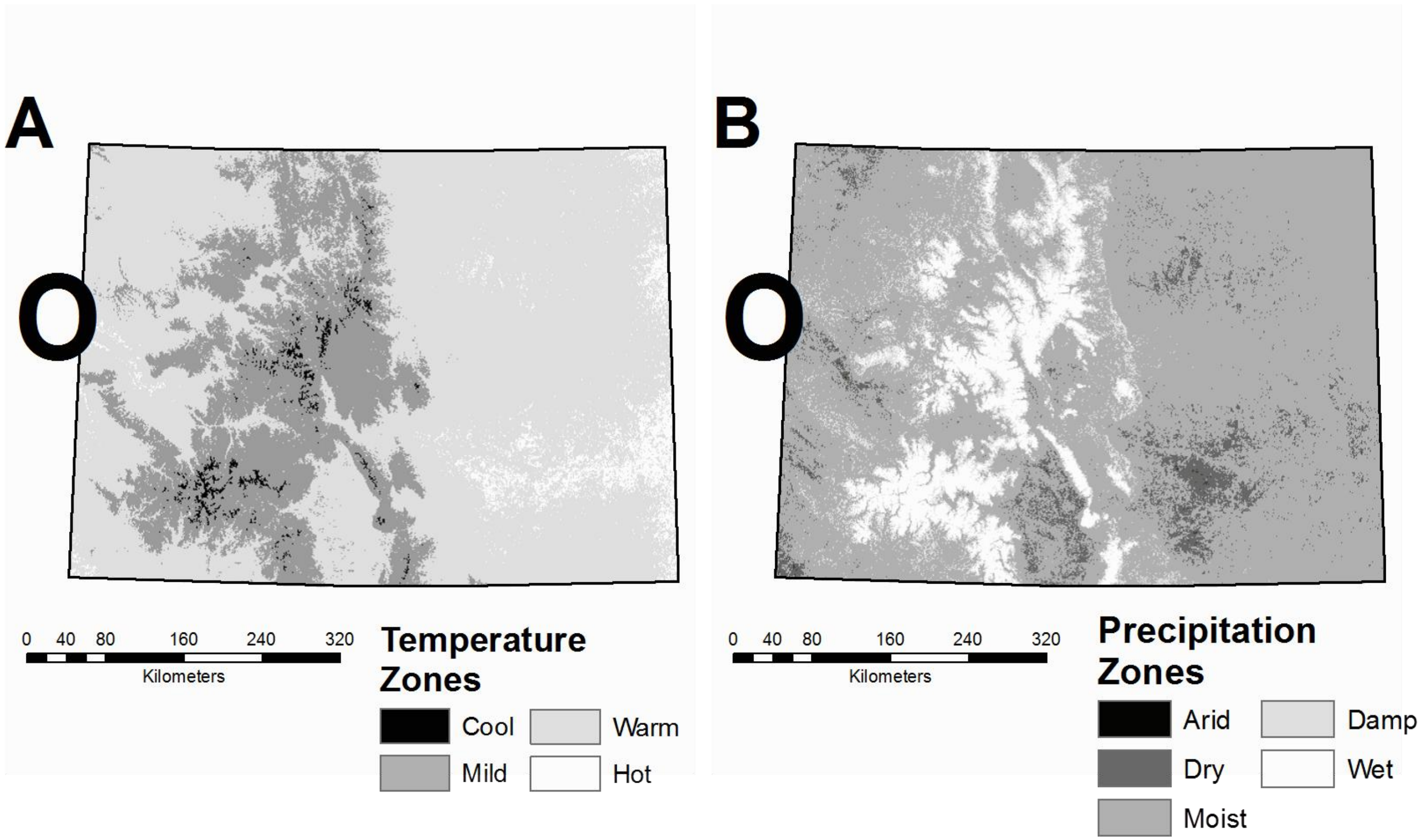

Figure 2: Climatic zones in Colorado based on A) Temperature and B) Precipitation

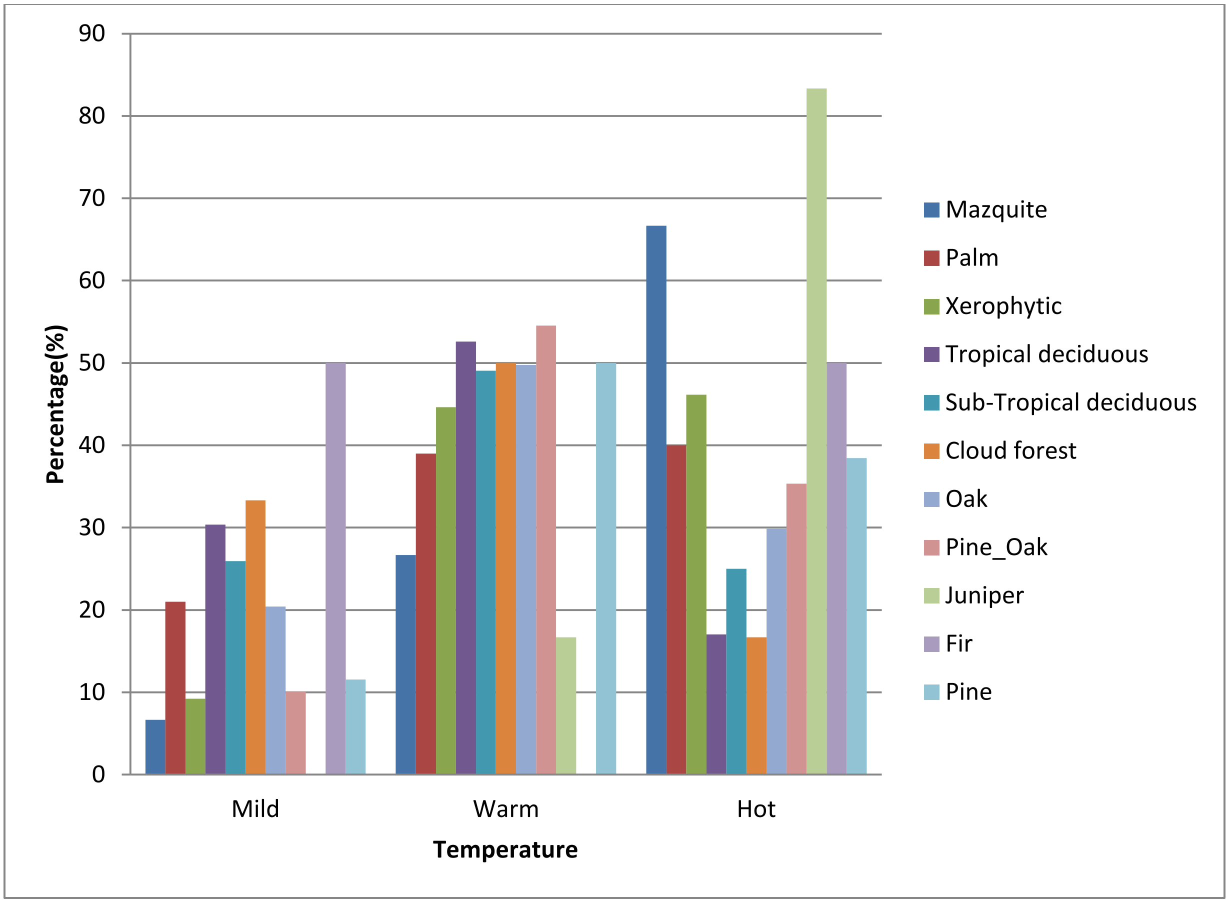

Figure 3: Distribution of major forest types in Jalisco, Mexico by temperature zone.

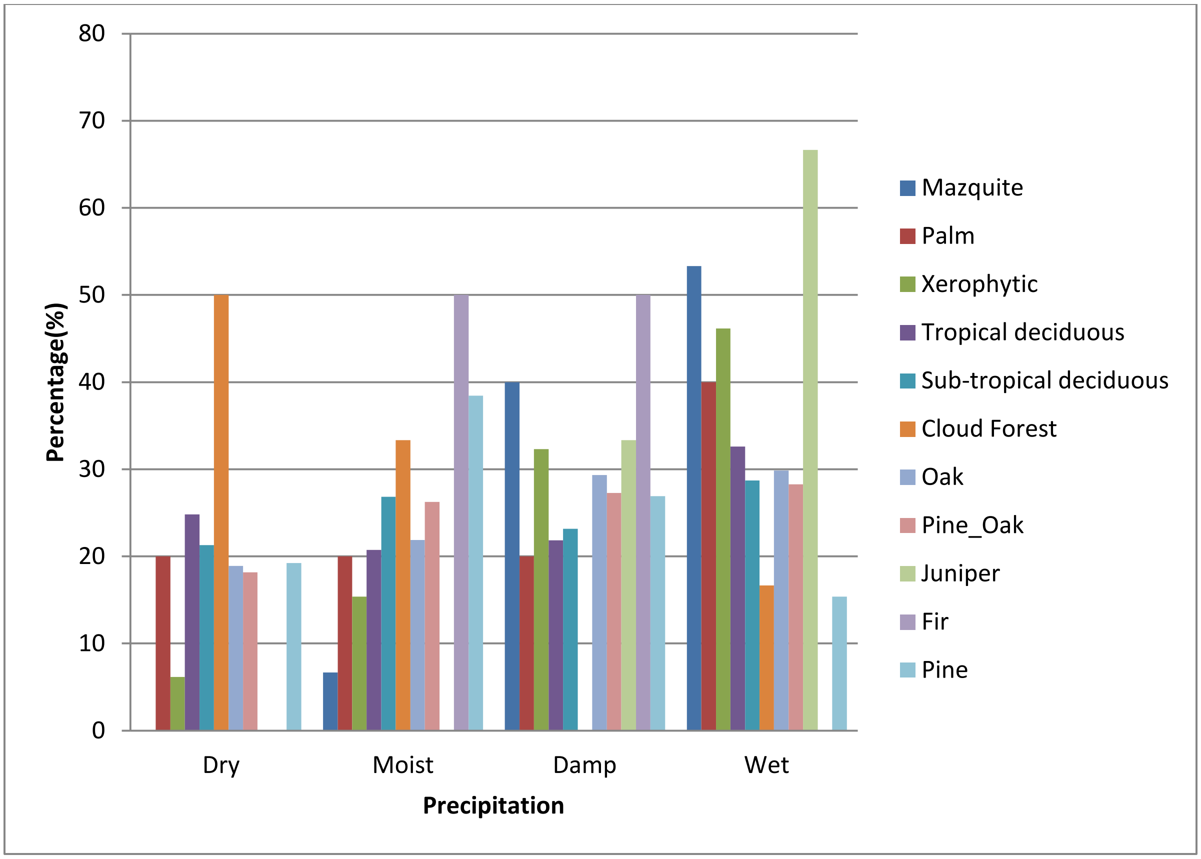

Figure 4: Distribution of major forest types in Jalisco, Mexico by precipitation zone.

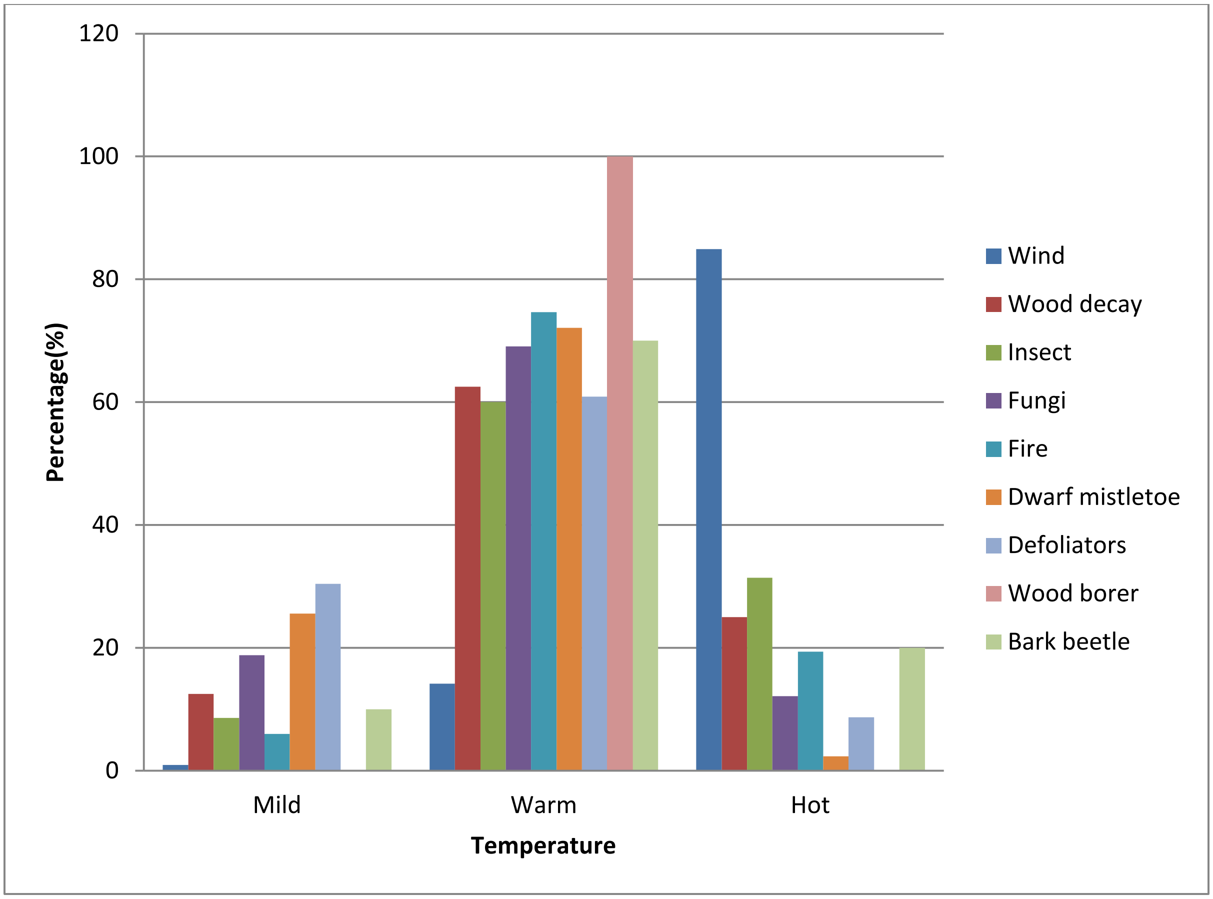

Figure 5: Distribution of insect and disease in Jalisco, Mexico by temperature zone.

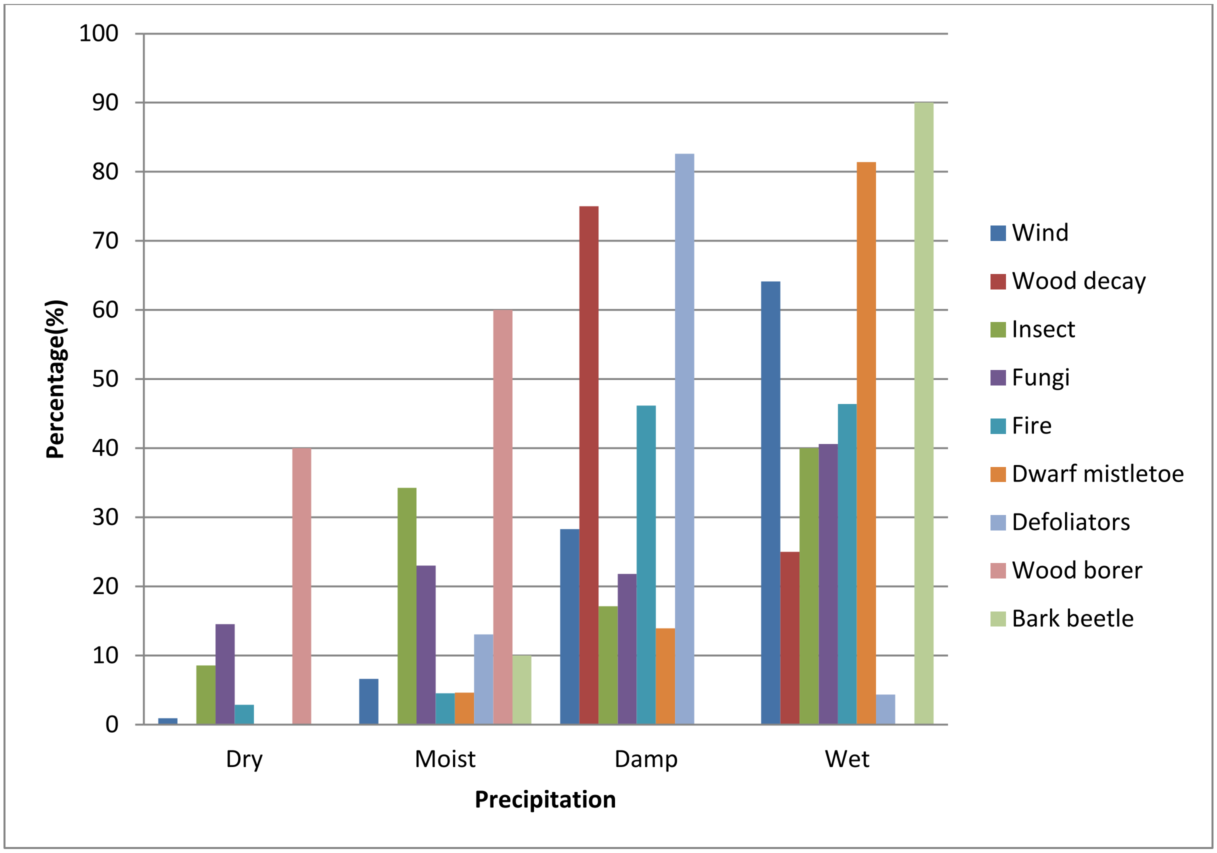

Figure 6: Distribution of insect and disease in Jalisco, Mexico by precipitation zone.

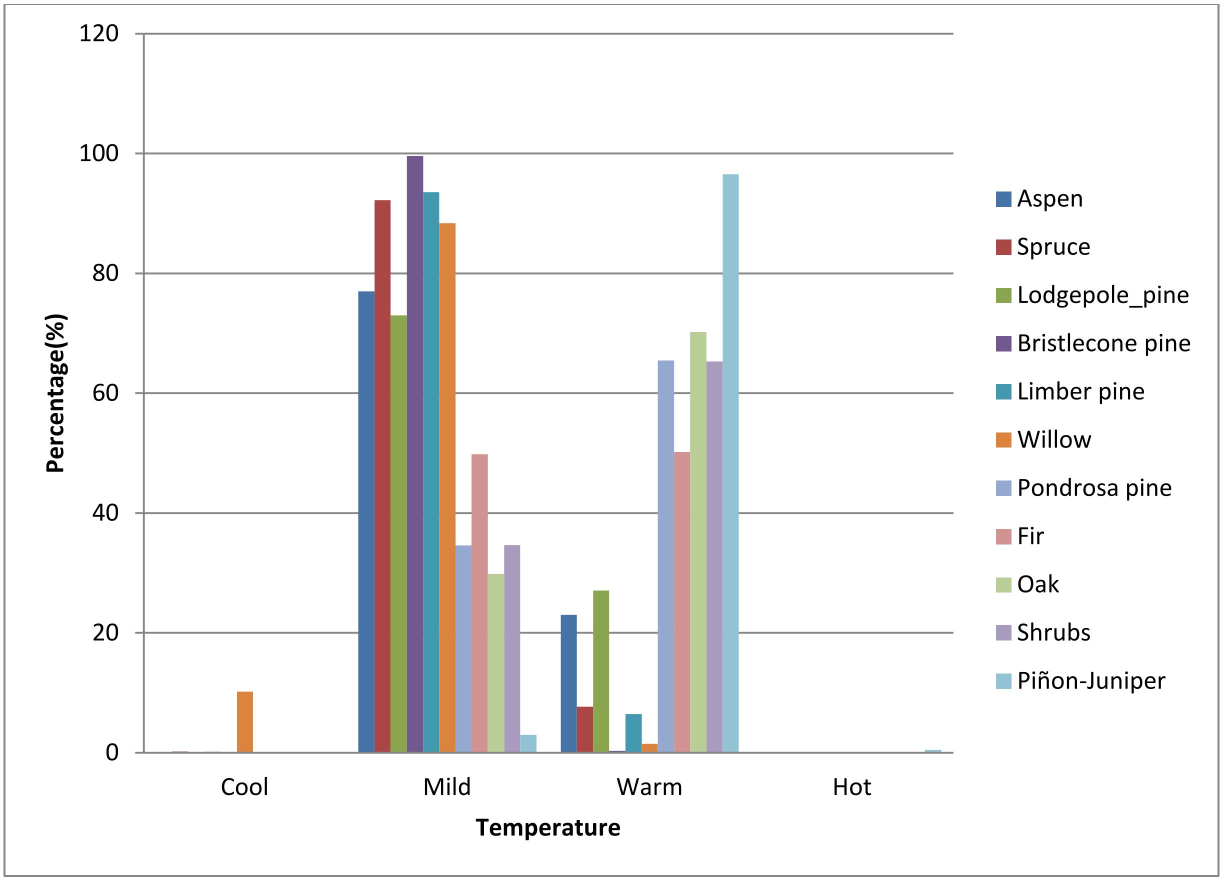

Figure 7: Distribution of major forest types in Colorado by temperature zone.

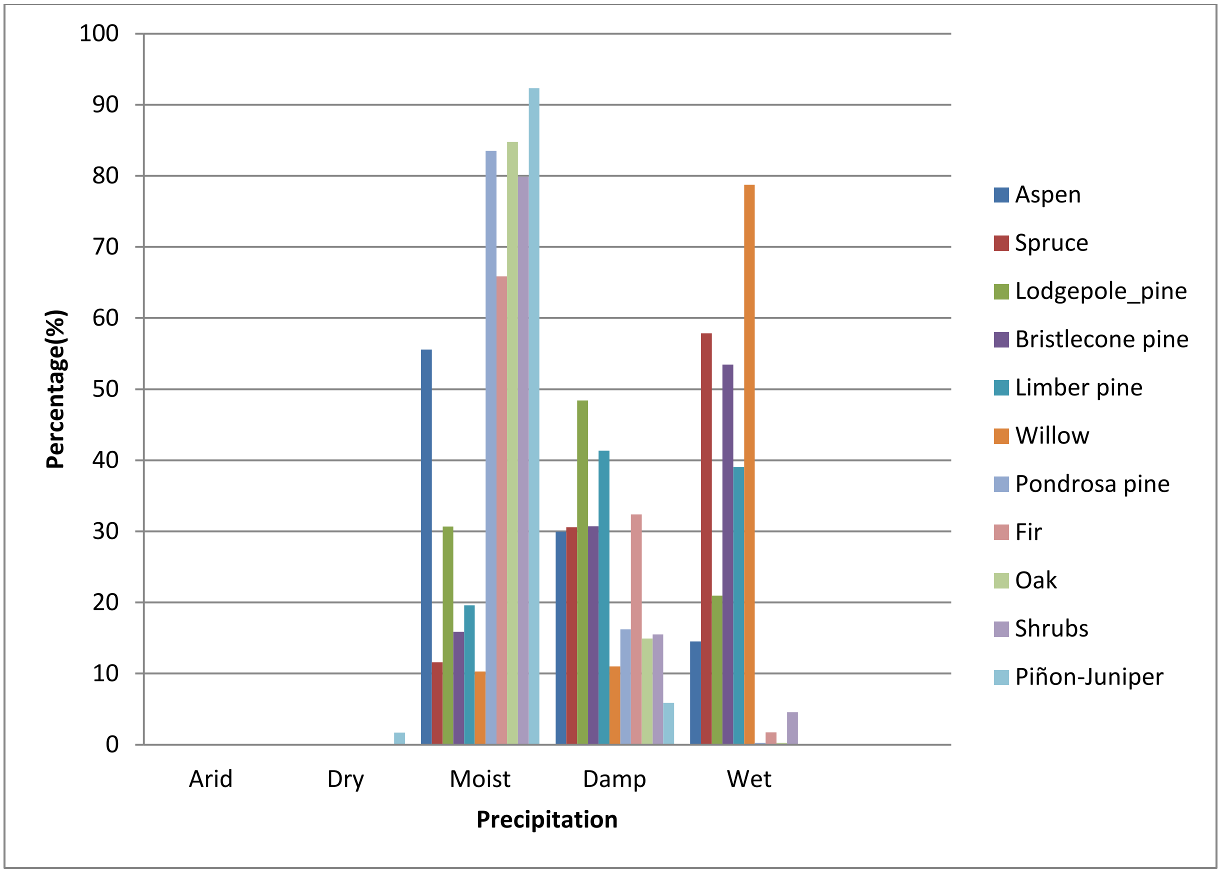

Figure 8: Distribution of major forest types in Colorado by precipitation zone

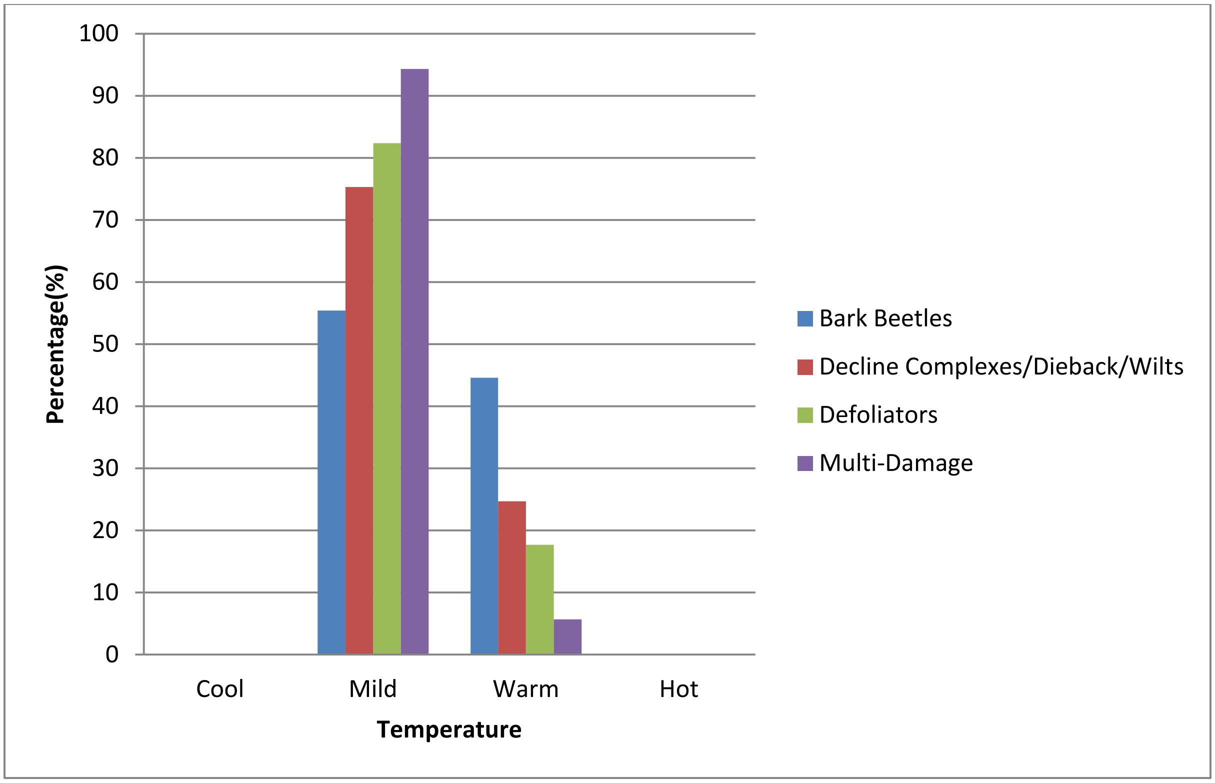

Figure 9: Distribution of insect and disease in Colorado by temperature zone.

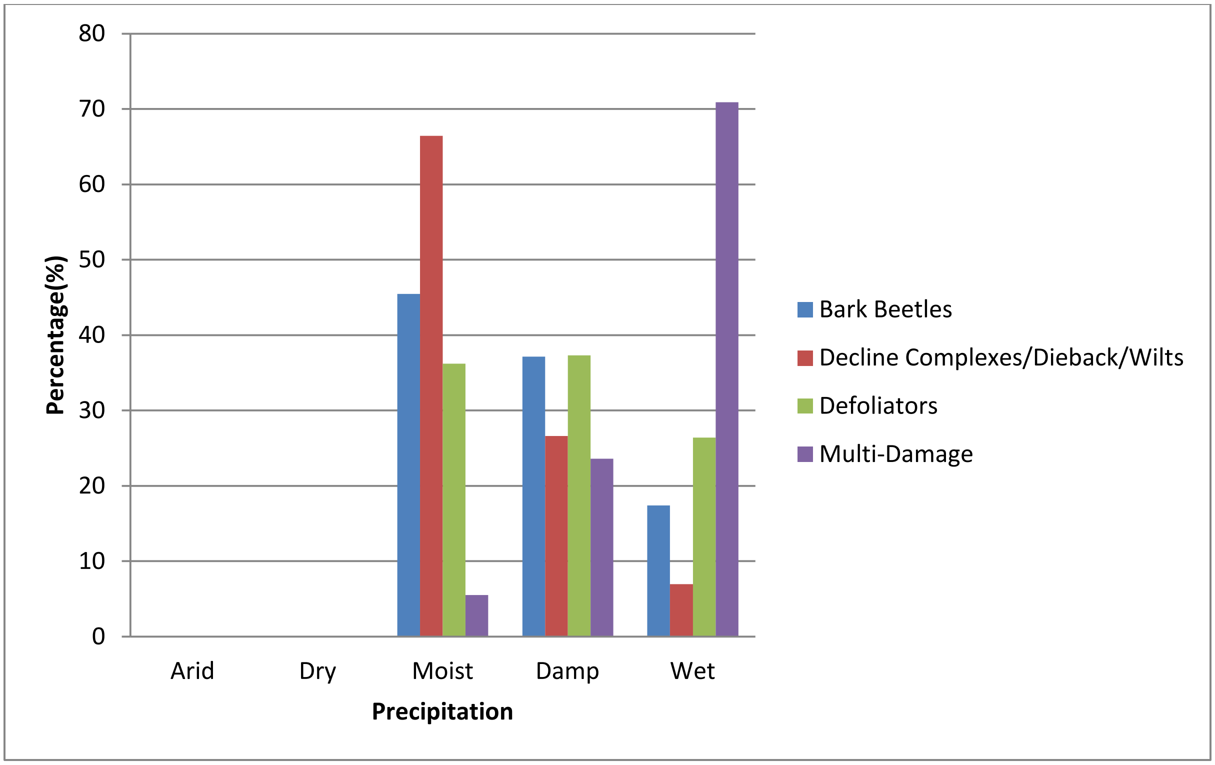

Figure 10: Distribution of insect and disease in Colorado by precipitation zone.

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APPENDIX A

Table A1. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees that have been attacked by bark beetles within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	0	0	1	1
2	0	1	0	6	7
3	0	0	0	2	2
Total	0	1	0	9	10

Table A2. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with damage due to wood borers within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	0	0	0	0
2	2	3	0	0	5
3	0	0	0	0	0
Total	2	3	0	0	5

Table A3. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with crown loss due to leaf defoliators within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	3	4	0	7
2	0	0	14	0	14
3	0	0	1	1	2
Total	0	3	19	1	23

Table A4. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees infected with dwarf mistletoe within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	1	1	9	11
2	0	1	5	25	31
3	0	0	0	1	1
Total	0	2	6	35	43

Table A5. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with fire damage within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	1	4	4	16	25
2	11	11	185	105	312
3	0	4	4	73	81
Total	12	19	193	194	418

Table A6. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with fungal infections within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	5	12	4	10	31
2	19	26	31	38	114
3	0	0	1	19	20
Total	24	38	36	67	165

Table A7. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with some form of insect damage within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	1	0	1	1	3
2	2	12	3	4	21
3	0	0	2	9	11
Total	3	12	6	14	35

Table A8. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with wood decay within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	0	2	0	2
2	0	0	10	0	10
3	0	0	0	4	4
Total	0	0	12	4	16

Table A9. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with wind damage within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	1	0	0	0	1
2	0	2	9	4	15
3	0	5	21	64	90
Total	1	7	30	68	106

Table A10. Climate transition matrix (CTM) for the frequency of sample plots classified as having cloud forest that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	1	1	0	0	2
2	2	1	0	0	3
3	0	0	0	1	1
Total	3	2	0	1	6

Table A11. Climate transition matrix (CTM) for the frequency of sample plots classified as having fir trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	0	1	0	1
2	0	0	0	0	0
3	0	1	0	0	1
Total	0	1	1	0	2

Table A12. Climate transition matrix (CTM) for the frequency of sample plots classified as having juniper trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	0	0	0	0
2	0	0	1	0	1
3	0	0	1	4	5
Total	0	0	2	4	6

Table A13. Climate transition matrix (CTM) for the frequency of sample plots classified as having *mazquite* trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone 1	2	3	4	Total
1	0	0	1	0	1
2	0	0	1	3	4
3	0	1	4	5	10
Total	0	1	6	8	15

Table A14. Climate transition matrix (CTM) for the frequency of sample plots classified as having oak trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone 1	2	3	4	Total
1	20	8	5	8	41
2	16	26	35	23	100
3	2	10	19	29	60
Total	38	44	59	60	201

Table A15. Climate transition matrix (CTM) for the frequency of sample plots classified as having palm trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	0	0	1	1
2	1	1	0	0	2
3	0	0	1	1	2
Total	1	1	1	2	5

Table A16. Climate transition matrix (CTM) for the frequency of sample plots classified as having pine trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	2	1	0	0	3
2	3	6	1	3	13
3	0	3	6	1	10
Total	5	10	7	4	26

Table A17. Climate transition matrix (CTM) for the frequency of sample plots classified as having pine-oak trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone 1	2	3	4	Total
1	4	5	1	0	10
2	13	13	22	6	54
3	1	8	5	21	35
Total	18	26	28	27	99

Table A18. Climate transition matrix (CTM) for the frequency of sample plots classified as having tropic deciduous trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone 1	2	3	4	Total
1	32	14	10	26	82
2	34	37	35	36	142
3	1	5	14	26	46
Total	67	56	59	88	270

Table A19. Climate transition matrix (CTM) for the frequency of sample plots classified as having sub-tropic deciduous trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	11	7	5	5	28
2	12	16	17	8	53
3	0	9	3	18	27
Total	23	29	25	31	108

Table A20. Climate transition matrix (CTM) for the frequency of sample plots classified as having xerophytic trees that have been within the temperature and precipitation zones of Jalisco, Mexico.

Temperature Zone	Precipitation Zone				Total
	1	2	3	4	
1	0	1	1	4	6
2	4	8	10	7	29
3	0	1	10	19	30
Total	4	10	21	30	65

APPENDIX B

Table B1. Climate transition matrix (CTM) for the area of climate zones within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	9132	2618806	2,627,938
2	0	122115	32939010	15621033	24774960	73,457,118
3	40952	12178273	188479450	9880253	243413	210,822,341
4	115333	4068771	43	44	0	4,184,191
Total	156,285	16,369,159	221,418,503	25,510,462	27,637,179	291,091,588

Table B2. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees that have been attacked by bark beetles within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0	0
2	0	0	1007	1061	900	2968
3	0	0	1428	930	32	2390
4	0	0	0	0	0	0
Total	0	0	2435	1991	932	5358

Table B3. Climate transition matrix (CTM) for the joint probability of sample plots classified as having trees that have been attacked by bark beetles within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0	0
2	0	0	3.06E-05	6.79E-05	3.63E-05	0.000135
3	0	0	7.58E-06	9.41E-05	0.000131	0.000233
4	0	0	0	0	0	0
Total	0	0	3.81E-05	0.000162	0.000168	0.000368

Table B4. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with decline complexes, dieback and wilts within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0	0
2	0	0	1602	674	228	2504
3	0	0	607	211	3	821
4	0	0	0	0	0	0
Total	0	0	2209	885	231	3325

Table B5. Climate transition matrix (CTM) for the joint probability of sample plots classified as having trees decline complexes, dieback and wilts within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0	0
2	0	0	4.86E-05	4.31E-05	9.2E-06	0.000101
3	0	0	3.22E-06	2.14E-05	1.23E-05	3.69E-05
4	0	0	0	0	0	0
Total	0	0	5.19E-05	6.45E-05	2.15E-05	0.000138

Table B6. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with crown loss due to leaf defoliators within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0	0	0
2	0	0	483	537	467	1487
3	0	1	171	137	10	319
4	0	0	0	0	0	0
Total	0	1	654	674	477	1806

Table B7. Climate transition matrix (CTM) for the joint probability of sample plots classified as having trees with crown loss due to leaf defoliators within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0	0	0
2	0	0	1.47E-05	3.44E-05	1.88E-05	6.79E-05
3	0	8.21E-08	9.07E-07	1.39E-05	4.11E-05	5.59E-05
4	0	0	0	0	0	0
Total	0	8.21E-08	1.56E-05	4.82E-05	5.99E-05	0.000124

Table B8. Climate transition matrix (CTM) for the frequency of sample plots classified as having trees with multi-damage within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0	0
2	0	0	61	352	1230	1643
3	0	0	35	59	5	99
4	0	0	0	0	0	0
Total	0	0	96	411	1235	1742

Table B9. Climate transition matrix (CTM) for the joint probability of sample plots classified as having trees with multi-damage within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0	0
2	0	0	1.85E-06	2.25E-05	4.96E-05	7.4E-05
3	0	0	1.86E-07	5.97E-06	2.05E-05	2.67E-05
4	0	0	0	0	0	0
Total	0	0	2.04E-06	2.85E-05	7.02E-05	0.000101

Table B10. Climate transition matrix (CTM) for the frequency of sample plots classified as having aspen trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	1	1,565	1,566
2	0	99	3,901,171	2,432,693	1,449,900	7,783,863
3	0	354	1,698,703	588,652	9,901	2,297,610
4	0	0	62	10	0	72
Total	0	453	5,599,936	3,021,356	1,461,366	10,083,111

Table B11. Climate transition matrix (CTM) for the joint probability of sample plots classified as having aspen trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0.00011	0.000598	0.000707
2	0	0.000811	0.118436	0.155732	0.058523	0.333502
3	0	2.91E-05	0.009013	0.059579	0.040676	0.109296
4	0	0	1.44186	0.227273	0	1.669133
Total	0	0.00084	1.569309	0.442693	0.099796	2.112638

Table B12. Climate transition matrix (CTM) for the frequency of sample plots classified as having bristlecone pine trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0	168	168
2	0	0	22302	42875	74957	140134
3	0	0	3	348	51	402
4	0	0	0	0	0	0
Total	1	2	22308	43227	75181	140704

Table B13. Climate transition matrix (CTM) for the joint probability of sample plots classified as having bristlecone pine trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0	6.42E-05	6.41514E-05
2	0	0	0.000677	0.002745	0.003026	0.006447281
3	0	0	1.59E-08	3.52E-05	0.00021	0.000244758
4	0	0	0	0	0	0
Total	0	0	0.000677	0.00278	0.003299	0.00675619

Table B14. Climate transition matrix (CTM) for the frequency of sample plots classified as having fir trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0	128	128
2	0	131	1784017	809946	78873	2672967
3	0	257	1751340	928772	14244	2694613
4	0	3	13	2	0	18
Total	0	391	3535370	1738720	93245	5367726

Table B15. Climate transition matrix (CTM) for the joint probability of sample plots classified as having fir trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0	4.89E-05	4.88772E-05
2	0	0.001073	0.054161	0.05185	0.003184	0.110267266
3	0	2.11E-05	0.009292	0.094003	0.058518	0.161833728
4	0	7.37E-07	0.302326	0.045455	0	0.347780864
Total	0	0.001095	0.365779	0.191307	0.06175	0.619930735

Table B16. Climate transition matrix (CTM) for the frequency of sample plots classified as having gambel oak trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0	0
2	0	80	1647906	225652	1146	1874784
3	1	3194	3684811	712220	14588	4414814
4	0	42	8	0	0	50
Total	1	3316	5332725	937872	15734	6289648

Table B17. Climate transition matrix (CTM) for the joint probability of sample plots classified as having gambel oak trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0	0
2	0	0.000655	0.050029	0.014445	4.63E-05	0.065176
3	2.44188E- 05	0.000262	0.01955	0.072085	0.059931	0.151853
4	0	1.03E-05	0.186047	0	0	0.186057
Total	2.44188E-05	0.000928	0.255626	0.086531	0.059977	0.403086

Table B18. Climate transition matrix (CTM) for the frequency of sample plots classified as having limber pine trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0	0	0
2	0	0	16258	32262	34471	82991
3	0	0	1143	4407	183	5733
4	0	0	0	0	0	0
Total	0	0	17401	36669	34654	88724

Table B19. Climate transition matrix (CTM) for the joint probability of sample plots classified as having limber pine trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0	0	0
2	0	0	0.000494	0.002065	0.001391	0.00395
3	0	0	6.06E-06	0.000446	0.000752	0.001204
4	0	0	0	0	0	0
Total	0	0	0.0005	0.002511	0.002143	0.005154

Table B20. Climate transition matrix (CTM) for the frequency of sample plots classified as having lodgepole pine trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	757	757
2	0	97	2337133	3543403	2283507	8164140
3	0	144	1093083	1872333	59239	3024799
4	0	0	0	0	0	0
Total	0	241	3430216	5415736	2343503	11189696

Table B21. Climate transition matrix (CTM) for the joint probability of sample plots classified as having lodgepole pine trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	0.000289	0.000289
2	0	0.000794	0.070953	0.226835	0.09217	0.390753
3	0	1.18E-05	0.005799	0.189503	0.243368	0.438682
4	0	0	0	0	0	0
Total	0	0.000806	0.076753	0.416338	0.335827	0.829724

Table B22. Climate transition matrix (CTM) for the frequency of sample plots classified as having piñon-juniper trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	15	15
2	0	1724	585683	16039	2373	605819
3	464	297540	18209120	1182853	13351	19703328
4	1779	48558	46251	321	0	96909
Total	2243	347822	18841054	1199213	15739	20406071

Table B23. Climate transition matrix (CTM) for the joint probability of sample plots classified as having piñon-juniper trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	5.73E-06	5.7278E-06
2	0	0.014118	0.017781	0.001027	9.58E-05	0.03302121
3	0.01133	0.024432	0.096611	0.119719	0.054849	0.30694108
4	0.015425	0.011934	1075.605	7.295455	0	1082.92746
Total	0.026755	0.050484	1075.719	7.4162	0.054951	1083.26743

Table B24. Climate transition matrix (CTM) for the frequency of sample plots classified as having ponderosa pine trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	3	3
2	0	1347	4077291	497435	7502	4583575
3	0	1313	6989449	1654382	27020	8672164
4	0	1	0	7	0	8
Total	0	2661	11066740	2151824	34525	13255750

Table B25. Climate transition matrix (CTM) for the joint probability of sample plots classified as having ponderosa pine trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0	1.15E-06	1.14556E-06
2	0	0.011031	0.123783	0.031844	0.000303	0.166960363
3	0	0.000108	0.037083	0.167443	0.111005	0.315639199
4	0	2.46E-07	0	0.159091	0	0.159091155
Total	0	0.011139	0.160866	0.358378	0.111309	0.641691862

Table B26. Climate transition matrix (CTM) for the frequency of sample plots classified as having shrubs within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	1	4208	4209
2	0	155	1474491	314753	254564	2043963
3	0	2238	3235898	600970	10462	3849568
4	0	146	90	4	0	240
Total	0	2539	4710479	915728	269234	5897980

Table B27. Climate transition matrix (CTM) for the joint probability of sample plots classified as having shrubs within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0.00011	0.001607	0.001716
2	0	0.001269	0.044764	0.020149	0.010275	0.076458
3	0	0.000184	0.017168	0.060825	0.04298	0.121158
4	0	3.59E-05	2.093023	0.090909	0	2.183968
Total	0	0.001489	2.154956	0.171993	0.054862	2.383301

Table B28. Climate transition matrix (CTM) for the frequency of sample plots classified as having spruce trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	25	32552	32577
2	0	14	1830418	5176107	11520588	18527127
3	0	18	494686	965546	75558	1535808
4	0	0	1	0	0	1
Total	0	32	2325105	6141678	11628698	20095513

Table B29. Climate transition matrix (CTM) for the joint probability of sample plots classified as having spruce trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone					Total
	1	2	3	4	5	
1	0	0	0	0.002738	0.01243	0.015168
2	0	0.000115	0.05557	0.331355	0.465009	0.852049
3	0	1.48E-06	0.002625	0.097725	0.310411	0.410762
4	0	0	0.023256	0	0	0.023256
Total	0	0.000116	0.08145	0.431817	0.78785	1.301234

Table B30. Climate transition matrix (CTM) for the frequency of sample plots classified as having willow trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	132	131304	131436
2	0	2	119260	136485	883252	1138999
3	0	12	13174	5282	349	18817
4	0	0	0	0	0	0
Total	0	14	132434	141899	1014905	1289252

Table B31. Climate transition matrix (CTM) for the joint probability of sample plots classified as having willow trees within the temperature and precipitation zones of Colorado.

Temperature Zone	Precipitation Zone 1	2	3	4	5	Total
1	0	0	0	0.014455	0.050139	0.064594
2	0	1.64E-05	0.003621	0.008737	0.035651	0.048025
3	0	9.85E-07	6.99E-05	0.000535	0.001434	0.002039
4	0	0	0	0	0	0
Total	0	1.74E-05	0.003691	0.023727	0.087224	0.114658