MAPPING THE SUSCEPTIBILITY OF LODGEPOLE PINE FOREST TO MOUNTAIN PINE BEETLE ATTACK IN COLORADO, USA

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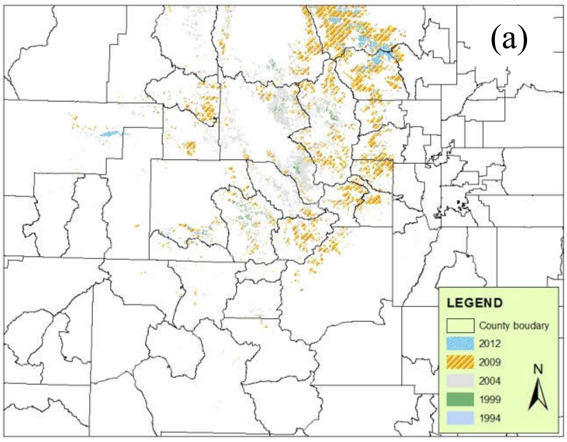
SUMMARY
Lodgepole pine forest (LPP) is common forest type in Colorado. It has been attacked by many kinds of beetle and disease mostly mountain pine beetle (MPB). Forest structure and climate condition are considered as two main factors that strongly influence to LPP by MPB. In order to evaluate vulerable levels of LPP to MPB in Colorado, the pine susceptibility index (PSI) was generated from forest characteristics such stand age (A), diamter at breat height (DBH), basal area (BA) and tree density (SPH). Maps of susceptibility of this foret type based on forest age, basal area, tree density and combination of all stand structure factors were created.
Keywords: Diameter at breast height, forest structure, lodgepole pine, mountain pine beetle, susceptibility, susceptibility index.

I. INTRODUCTION

Mountain pine beetle (MPB) is the most aggressive insect affecting mature pines in western North America (Safranyik and Wilson 2007). Within a year of successful attack, the infested tree is dead, and the next generation of beetles flies to new host trees. MPB is always present in Colorado's pine forests, normally attacking weak and injured mature trees (Colorado Forest Service Report, 2006). However, when forest and weather conditions are suitable for population growth, large outbreaks can occur. This may happen about every 10 to 30 years (Hicke and Jenkins 2008). Under epidemic conditions beetle populations mount mass attacks that overwhelm the defenses of healthy trees and result in high mortality rates of the host species population over thousands of hectares (Safranyik and Wilson 2007). The most recent MPB vast attack in the 2000s across western U.S. and Canada is the largest outbreak in Colorado's recorded history. The damaged area of lodgepole pine by MPB rocketed from 2000 to 2008 (>450,000 ha) and then plunged to insignificance within four year afterward. Climate and MPB in Colorado have crossed an elevational threshold that has not been seen before. Until the recent warmer weather, mountain pine beetles have not been able to withstand the cold temperatures above 2896m. But at the USDA Forest Service's Fraser Experimental Forest (elevation 2740 – 3902m), some of Colorado's oldest lodgepole pine trees are now being killed by these beetles. Although these stands have been at a susceptible age for over two centuries, they have not been impacted by mountain pine beetle until the current outbreak (Colorado Forest Service Report, 2006). Weather and host stand conditions are considered the two most dominant factors influence MPB outbreaks (Shore and Safranyik, 1992; Carroll et al., 2003). Stand conditions vary slowly in time with stand development whereas weather has much higher temporal variability, stand conditions set the stage for an outbreak, and suitable weather conditions may actually trigger the epidemic (Hicke and Jenkins 2008). The extent of recent MPB outbreaks has been linked to warmer and drier conditions in Colorado forest and to the existence of large populations of old beetle-susceptible trees (Gartner and Veblen). However, little is known about how these two factors actually affected the magnitude and direction of the MPB outbreak widespread in Colorado since susceptibility of lodgepole pine trees to MPB attack is influenced by complex interactions between climate and stand structure, which are dynamic in time. Although, recent research has focused on identifying stand structure and climate susceptibility to infestation in large scales (Shore and Safranyik 1992; Hicke and Jenkins 2008), it is of a greater important to epidemic control and forest management if susceptibility studies are done for local forests and used to predict outbreak spreading.



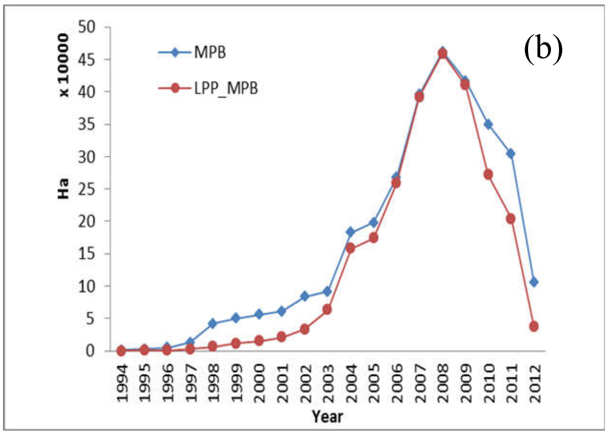


Figure 1. (a) Map of lodgepole pine area damaged by MPB from 1994 to 2011; (b)Total damaged area by MPB and total lodgepole pine damaged area by MPB

The objectives of this paper are to create susceptibility maps of lodgepole pine to MPB attacks in Colorado forest during the period from 2001 to 2010 based on pine structure and to identify the pine structure on Colorado's MPB epidemic spreading based on resulting susceptibility maps.

II. METHODS

In order to create susceptibility maps, we implemented the most updated models, namely Shore's Pine Susceptibility model and GIS interpolation tools. Hotspot analysis of Lodgepole pine infested area reveals the changes in epidemic extent and directions. The timeframe of this study presents the duration of the outbreak. Detail methods and data sources are presented below.

a. Data source:

We used the most recent Forest Inventory and Analysis database (FIADB version 5 2013) downloaded from Forest Inventory and Analysis (FIA) online inventory (http://apps.fs.fed.us/fiadb-downloads/datamart.html). The Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service provides the information needed to assess America's forests. The program surveys plots on public and private lands across the United States and stores information for most of the trees in each plot in its database (FIADB). FIADB consists of periodic and annual inventories with annual data for Colorado are available from 2002.

Annual data for Colorado forest from 2002 to 2011 was included. Our susceptibility analysis was limited to plots of lodgepole pine forest type containing live trees ≧ 2.95'' (7.5 cm) DBH that have recorded stand ages. We developed SQL queries (see appendix) to extract data from FIADB, compute PSI for each plot and project the results onto ArcMap 10.1. We then performed interpolation from our data to create interpolated susceptibility map. The map was then overlaid with Colorado Forest Service's sketched maps of MPB infested Lodgepole pine area, hotspot maps and climate susceptibility maps from

2001 to 2010 to compare and explain infestation trends. The FIADB's parameters used in our analysis are showed in the appendix.

b. Pine susceptibility index (PSI):

We used the Pine Susceptibility model developed by Shore et al. (2006) to calculate the PSI of lodgepole pine to Mountain Pine beetle attack based on the Pine structure:

$$PSI = P^* \times D \times A$$

Where: P* is the rescaled value of P, the percentage of susceptible lodgepole pine basal area within a stand, A is the age factor, and D is the density factor.

The original equation comprises one more factor for location (L), which is computed based on elevation and coordinates of the target stand. This is to capture the general effects of climate and is useful in cases where comparisons between broadly different locations such as states are applied. Since we focused only on Colorado, this effect was constant (L=0.3) and was omitted from the equation. Instead, we decided to depict the effects of climate with a more complex model.

The PSI's factors are calculated as follow:

$$P^* = \frac{100.0}{[1 + \exp(-(P - 22.7)/5.3)]}$$

Where:

$$\mathrm{P} = \frac{\text{basal area of pine } \geq \ 5.9'' \mathrm{DBH}}{\text{basal area of all species } \ \geq \ 2.95'' \mathrm{DBH}}$$

$$0 \leq P^* \text{ and } P \leq 1$$

DBH is tree diameter at breast height. The original unit of DBH used in Shore's equation was centimeter (cm), but here we used equivalent unit of inch. P reflects the proportion of a stand's total basal area that is composed of susceptible pine. It indicates the susceptibility of an entire stand regardless of species (e.g., percentage of all trees that are susceptible to attack). That is, if all the lodgepole pine within a stand were killed by mountain pine beetle, but the lodgepole pine was only a small fraction of the stand, the stand would be rated with low susceptibility (Hicke and Jenkins 2008). As a result, P* was introduced to address this problem (Shore et al. 2006).

$$A = \begin{cases} 0.1 & ; \quad age < 40 \\ 0.1 + 0.1\left[\dfrac{(age - 40)}{10}\right]^{1.58\ 5} & ; \quad 40 \leq age \leq 80 \\ 1.0 & ; \quad 80 < age \leq 120 \\ 1.0 - 0.05\left[\dfrac{(age - 120)}{20}\right] & ; \quad 120 < age \leq 510 \\ 0.1 & ; \quad age > 510 \end{cases}$$

$$D = \begin{cases} 0.0824\left(\dfrac{SPH}{250}\right)^{1.58\ 5} & ; \quad SPH < 650 \\ 1.0 - 0.7\left(3 - \dfrac{SPH}{250}\right)^{0.5} & ; \quad 650 \leq SPH \leq 750 \\ 1.0 & ; \quad 750 < SPH \leq 1500 \\ \dfrac{1.0}{\left[0.9 + [0.1 \exp\left(0.4796\left(\dfrac{SPH}{250 - 6}\right)\right)]\right]} & ; \quad SPH > 1500 \end{cases}$$

Basal area (m^2/ha) is defined as the cross sectional area of a tree at breast height; age is the stand age; SPH is stems per ha.

Inputs to the Pine Susceptibility model include stand age, stem density (SPH) and basal area (BA). Stand age can be acquired directly from Condition (COND) table in the database. We calculated other variables using the following equations:

$$\mathrm{SPH} = \sum_i \left[\frac{TPA\_UNADJ(i)}{CONDPROP(i)}\right]$$

$$\mathrm{BA} = \sum_i \left[\pi\, x\, \left(\frac{DIA(i)}{2}\right) x\, \frac{TPA\_UNADJ}{CONDPROP(i)}\right]$$

Prior to this study, Hicke and Jenkins 2008 used Resources Planning Act (RPA) inventory database to conduct a similar analysis. However, they used older database and broader susceptibility estimates for every County in Western US. Their estimates were also plot-based but the results were then scaled up to County-level by multiplying with expansion factors. Each County was assigned with only one susceptibility index. Our analysis is more site-specific where continuous susceptibility indexes were assigned to Colorado Lodgepole pine forest.

c. Mapping Pine Susceptibility index:

The calculated PSIs were stored in excel tables along with plot numbers and there coordinates. We then projected data from the tables onto ArcMap 10.1 as points. Pine susceptibility is an index calculated based on the intrinsic conditions of a stand regardless of the external factors. Interpolation for the pine susceptibility requires the data points to stay in a certain range for the best spatial correlation. Due to the limited number and the dispersion of yearly data, and the fact that unlike climate susceptibility which alters frequently with changes in climate conditions, pine susceptibility is more stable and slowly changes with stand development, we assumed that a five year period would not be long enough for a stand to significantly change its intrinsic conditions regardless of external disturbances and so the susceptibility index of a plot measured within that period is considered representative during the period. Therefore, we integrated data points from 2002 to 2006 and from 2007 to 2011 to produce two susceptibility maps that represent the two periods.

Since our susceptibility data type is proportion, it is most appropriate to perform probability Kriging interpolation because of no normality assumption. We assumed 0 – 0.1 is very low susceptibility, 0.1 – 0.5 is susceptible and ≥ 0.5 is highly susceptible based on the rationale made by Shore et al. 2006, and performed probability Kriging interpolation with threshold exceeding 0.1 and output the rescaled susceptibility which is the probability of a predicted value to be greater than 0.1 (or to become susceptible). Therefore, locations with higher probability will be more susceptible.

III. RESULTS

Figure 2 and 3 shows the maps of Lodgepole pine susceptibility to MPB attacks based on pine structure for the period of 2002 – 2006 and 2007 – 2011, respectively. We only included the forested area that has lodgepole pine in our susceptibility map. The susceptibility map was made based on interpolation using real values of the surrounding neighbors to predict values for the unknown locations. Every point in the map was assigned with a specific value. The total sample numbers were 357 and 284 with standardized mean difference between sampled and predicted values of 0.004 and -0.012, and standardized root mean square of 0.98 and 0.94 for 2002-2006 and 2007-2011 Kriging interpolation, respectively.

Due to the fact that the rescaled pine susceptibility index is the probability of a predicted value to be susceptible, we defined 0.5 as the middle point and so values that are greater than 0.5 will be considered high susceptibility and the opposites considered as low susceptibility. To make the map finer, we defined two more natural breaks and categorized the susceptibility indexes into 5 main groups, namely low (0 - 0.1), fair (0.1 – 0.3) moderate (0.3 – 0.5), high (0.5 –0.7) and very high susceptibility (≥ 0.7). These categories are created for better interpretation of the output; further experiments are needed for more precise grouping.

The 2002-2006 map shows that most of lodgepole pine forest is fairly to moderately susceptible to MPB attack, and the "high" and "very high" susceptible lodgepole pine areas are concentrated in the North Central of Colorado. As a result, we might expect a high spreading rate of MPB in the red and darkish red area of the map. There might be the invasion of MPB to the less susceptible area once the pest population grows crowded.

The highly susceptible area shrinks to Font Range forest of Colorado in the 2007-2011 map (the upper right corner) and to small areas in the North and South Central (Figure 2) leaving the highly susceptible area of 2002-2006 period low to fairly susceptible. As mentioned, infested lodgepole pine trees die one or two years after the infestation, we might infer that the region in North Central of Colorado forest that has a change in colors from yellow or red to green is the outbreak area in 2002-2006. Most of the trees in that area might have been killed and so the Pine susceptibility reduced significantly. Due to the high susceptibility in the Font Range forest, we might also infer that there would be higher pest activities in that region compared to other areas during this period. Climate susceptibility is needed for further inferences.

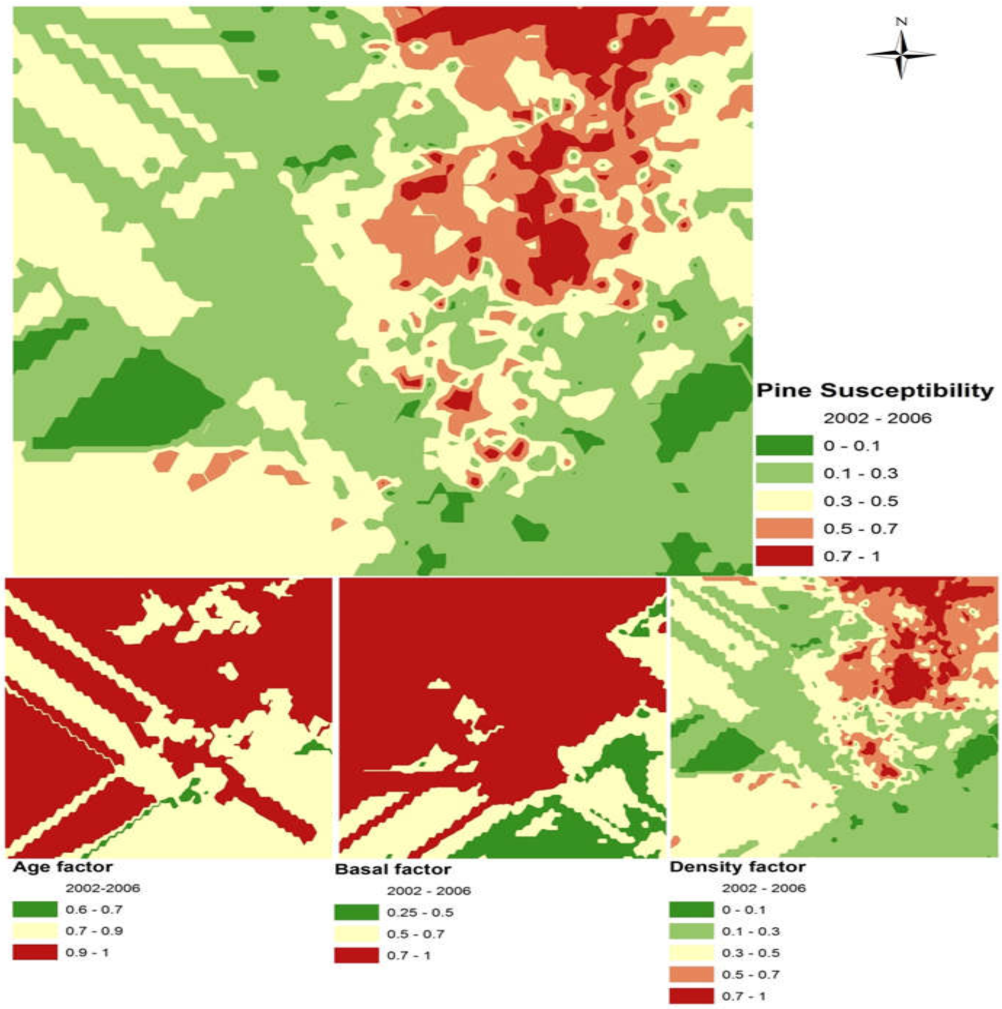


Figure 2. Map of Lodgepole pine susceptibility to Mountain Pine Beetle (with contributing factors) in Colorado forest from 2002 – 2006

We also created the interpolation maps for contributing factors to Pine Susceptibility Index in order to better understand what determined the magnitude of susceptibility index in different areas (Figure 2 and 3). We found that lodgepole pine basal area and age factor were high in most of the research region. However, density factor was the limiting one with higher values concentrated in North Central and overcrowded Front Range forests in 2002-2006 map, in mostly Front Range forests in 2006-2011 map, and much lower values in the West and South Central of Colorado making these areas less susceptible to MPB.

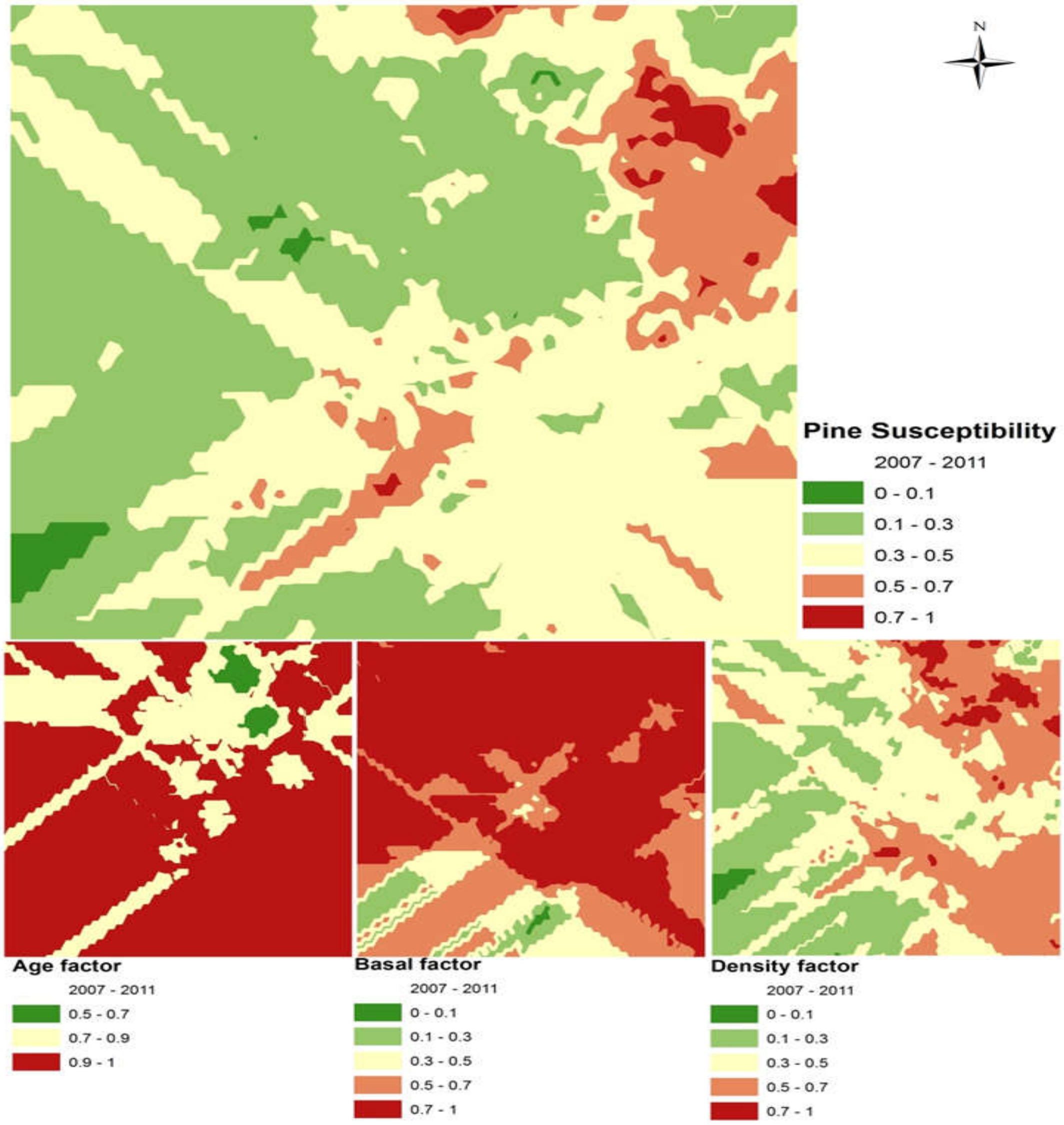


Figure 3. Map of Lodgepole pine susceptibility to Mountain Pine Beetle (with contributing factors) in Colorado forest from 2007 - 2011

IV. DISCUSSION

Mountain pine beetle impacted on lodgepole pine mostly concentrated in the North of state where the highest elevation and highest slope is. This would suggest that elevation, slope and latitude and longitude could have influence susceptibility through their effects on stand structure as well as climate regime. This agrees with Hopkins' stating that the higher elevation or more northerly latitudes or easterly longitudes the beetle's development cycle will be extended (Hopkins, 1919). Focus on damaged areas' trend, we found that it has been moving from the Southwest to the Northeast of Colorado State.

Both climate and stand condition influence MPB outbreak (Safranyik, 1978, Shore and Safranyik, 1992, Carroll et al., 2004). The higher density, the higher susceptibility of damage is. This could be cause of decreasing infestation area of MPB on LPP from 2009 to 2012.

Based on the trend of total damaged area changing by time from 1994 to 2012, information about this outbreak cycle can be inferred. Mountain pine beetle increased their impact on lodgepole pine from 1994 and then outbreak in 2000s due to the 2000 – 2004's drought. After 2007, their impact decreased with the decrease in climate susceptibility. As outbreak expand, stand-level susceptibility appear to have more influence on the subsequent spread of an outbreak; appropriate stand conditions will amplify the magnitude of the outbreak, create bigger hotspots and speed up the spread even in less-supportive climate conditions. Hotspot analysis showed the disappearing of MPB hotspot in 2011 (data not shown), but the forest fire in 2012 actually put the 2000's outbreak to an end.

There are no recorded effective control methods for MPB outbreak after MPB populations grew from endemic to epidemic levels. Therefore, it is very important to understand the susceptible conditions to MPP outbreaks in order to timely pay attention and employ appropriate managements to suppress the epidemic ignition or shorten the outbreak cycle. Our results are descriptive; however, the corresponding epidemic behaviors presented in this study can be useful for future predictions of outbreak for better forest managements and outbreak control.

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BẢN ĐỒ VÙNG NHẠY CẢM ĐỐI VỚI SÂU HẠI THÔNG (*DENDROCTONUS PONDEROSAE*) CỦA RỪNG THÔNG TẠI BANG COLORADO, HOA KỲ

Hà Quang Anh

Trường Đại học Lâm nghiệp

TÓM TẮT

Rừng thông là một trạng thái rừng phổ biến tại khu vực núi cao bang Colorado. Loại hình rừng này đã và đang bị xâm hại bởi nhiều loài sâu bệnh hại, chủ yếu là loài *Dendroctonus ponderosae.* Cấu trúc rừng và điều kiện khí hậu là những nhân tố có ảnh hưởng quan trọng tới mức độ tàn phá của *Dendroctonus ponderosae*. Để có thể đánh giá được những mức độ khác nhau về tính nhạy cảm của rừng thông đối với loài sâu hại *Dendroctonus ponderosae* ở Colorado, chỉ số nhạy cảm (PSI) được tính toán dựa trên cơ sở đặc điểm của lâm phần như: tuổi rừng, đường kính ngang ngực, tiết diện ngang và mật độ. Bản đồ về mức độ nhạy cảm của đối tượng nghiên cứu đã được xây dựng dựa trên đặc điểm của những nhân tố cấu trúc này.

Từ khóa: Bản đồ chỉ số nhạy cảm, cấu trúc rừng, chỉ số nhạy cảm, đường kính ngang ngực, sâu hại thông (*Dendroctonus ponderosae*), tiết diện ngang.

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