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Forest ecosystem health assessment and analysis in China

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Abstract: Based on more than 300 forest sample plots surveying data and forestry statistical data, remote sensing information from the NOAA AVHRR database and the daily meteorological data of 300 stations, we selected vigor, organization and resilience as the indicators to assess large-scale forest ecosystem health in China and analyzed the spatial pattern of forest ecosystem health and influencing factors. The results of assessment indicated that the spatial pattern of forest ecosystem health showed a decreasing trend along latitude gradients and longitude gradients. The healthy forests are mainly distributed in natural forests, tropical rainforests and seasonal rainforests; secondarily orderly in northeast national forest zone, subtropical forest zonation and southwest forest zonation; while the unhealthy forests were mainly located in warm temperate zone and Xinjiang-Mongolia forest zone. The coefficient of correction between Forest Ecosystem Health Index (FEHI) and annual average precipitation was 0.58 (p<0.01), while the coefficient of correlation between FEHI and annual mean temperatures was 0.49 (p<0.01), which identified that the precipitation and temperatures affect the pattern of FEHI, and the precipitation's effect was stronger than the temperature's. We also measured the correlation coefficient between FEHI and NPP, biodiversity and resistance, which were 0.64, 0.76 and 0.81 (p<0.01) respectively. The order of effect on forest ecosystem health was vigor, organization and resistance.

Key words: ecosystem health; forest; assessment; spatial pattern; correlation analysis; China

1 Introduction

During recent two decades, the idea of "health" as an appropriate paradigm to assess the condition of ecosystems, is watchword of contemporary ecosystem management. The phrase "forest ecosystem health" has been used with increasing frequency in the context of forestry and natural resource management. Many scientists give the definitions from socio-economic and ecological perspectives (Rapport, 1992; USDA Forest Service, 1993; O'Laughlin, 1996; Allen, 2001). Forest health is a condition where biotic and abiotic influences of the forest (i.e., insects, diseases, atmospheric deposition, silvicultural treatments, harvesting practices) do not threaten management objectives for a given forest now or in the future (McIntire, 1988). That is, a forest is considered to be healthy if management objectives are satisfied, and unhealthy if they are not. While other researchers define forest health from ecosystem perspectives, emphasize the basic ecological processes that create and maintain forest conditions to potentially satisfy a range of diverse objectives, e.g., a forest in good health is a fully functioning community of plants and animals and their physical environments; a healthy forest is an ecosystem in balance. If we define forest health from ecosystem perspective in terms of resiliency, balance, and function, unhealthy is associated with declines in biological diversity, loss of primary productivity, reversal of successional patterns, widespread and severe diseases,

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and loss of nutrient capital (Rapport, 1992). A comprehensive definition of forest health is a condition wherein a forest has the capacity across the landscape for renewal, for recovery from a wide range of disturbances, and for retention of its ecological resiliency, while meeting current and future needs of people for desired levels of values, uses, products, and services (Dale, 2000).

Although the definitions of forest health range between utilitarian and ecosystems, of course, some forest health principles are generally agreed upon. A healthy forest is resilient; i.e. it has the ability to respond quickly to natural and human-induced disturbances, such as fire, diseases and insect pests, and climate changes, air pollution, and timber harvesting, and recover to some desired conditions or states. A healthy forest is also sustainable, it is capable of meeting people's present needs and aspirations without compromising the ability to meet those of the future. A healthy forest ecosystem possesses a full range of ecosystem services, such as detoxification of chemicals, water purification, production of game species, and reduced soil erosion, offer wildlife habitats (Rapport, 1998). Kolb *et al*. (1994) stated that a healthy forest ecosystem had the following characteristics:

–The physical environment, biotic resources, and trophic networks to support productive forests during at least some seral stages;

–Resistance to catastrophic change and/or the ability to recover from catastrophic change at the landscape level;

–A functional equilibrium between supply and demand of essential resources (water, nutrients, light, growing space) for major portions of the vegetation; and

–A diversity of seral stages and stand structures that provide habitat for many native species and all essential ecosystem processes.

China is poor in forest resources. The current forest area in China amounts to 158.9 million ha, with a forest coverage rate of 16.6%. The standing timber inventory reaches 12.5 billion m^3, while the man-made forest area is 46.7 million ha with a volume of 1 billion m^3. Annual standing growth is 419.1 million m^3 with a mean annual increment of 2.6 m^3/ha (State Forestry Administration, 2000). The present age structure of forests skews towards young ages, the young stands and half-mature forests account for 71.4% (77.4 million ha), while mature and over-mature forests account for only 18.4% (20.1 million ha), which is disadvantaged to forest health. Forest health has been negatively impacted by forest fires, disease and insect pests. There is an annual average of 13,000 forest fires covering more than 833,000 ha in area and forest diseases and insect pests occur in 4.4 million ha every year. Thus, forest fires, diseases and pests caused a forest volume decrement of 10 million m^3, as well as degrading timber quantities (State Forestry Administration, 2001). Forest health is also impacted by air pollution, especially by acid rain. Acid deposition has a great negative influence on forests, acid rain causes an annual average timber loss of 1.2 million m^3 in seven southern provinces (Zhejiang, Jiangsu, Fujian, Anhui, Jiangxi, Hunan and Hubei), and the direct and indirect economic losses are US$752.5 million (Feng *et al*., 1999).

The objective of this study is to develop indicators for forest ecosystem health assessment, to describe the spatial pattern of forest health, and to examine the linkage between forest ecosystem health and environmental factors.

2 Develop indicators to assessment forest ecosystem health

Owing to the complexity of ecosystems, especially forest ecosystems, it is clear that we cannot measure all aspects of ecosystems. Instead, we have to select a few variables that will represent key components of forest health. These representative elements are indicator-variables that we choose to monitor, reflecting what we consider to be important, based on what is feasible to measure (Ferris, 1999). Indicators are quantitative or qualitative variables which can be measured or described and which when observed periodically demonstrates trends (Dale *et al*., 2001). Ecosystem indicators track the magnitude of stress, habitat characteristics, exposure to the stressors, or ecological responses to exposures. If the objective is to monitor effects of forest management, indicators should be more sensitive to habitat perturbations than to environmental factors and occur at high enough densities to be sampled with statistical precision (Szaro and Balda, 1982). Assessment indicators should represent key information about structure, function, and composition of ecosystem, need to capture the complexities of the ecosystem but maintain sufficiently simplexity for being easily and routinely monitored.

How to develop the indicator is a principal problem to evaluate ecosystem health. Keddy *et al*. (1993) list three steps for developing useful indicators: selecting appropriate variables; setting critical limits; and testing indicators. Indicators should be closely related to maintenance of essential ecosystem processes and functions, indicate changes in entire communities rather than selected species, be measured easily and respond quickly to stresses and perturbations. In selecting compositional indicators, it is important to consider their relationships to specific habitat parameters or, if they are generalists, their ability to utilize a range of conditions and habitats. Dale *et al*. (2001) suggest that ecological indicators should meet the following criteria:

Easily measured

Sensitive to stresses on system

Responding to stress in a predictable manner

Anticipatory: signify an impending change in the ecological system

Predicting changes that can be averted by management actions

Integrative: the full suit of indicators provides measures of coverage of the gradients across the ecological systems

Having a known response to natural disturbances, anthropogenic stresses, and changes over time

Having low variability in response

Therefore, we identified three overarching attributes of ecosystem health: vigor, resilience, and organization.

Vigor refers to energy or activity. In an ecosystem context, it refers to a throughput of energy that can be measured in terms of nutrient cycling and productivity. Organization refers to ecosystem complexity, the characteristic varies from system to system but generally tends to increase with secondary succession in terms of number of species and variety and intricapy of interactions. Resilience refers to the capacity of a system to cope with stress and to bounce back when the stress diminishes. This capacity, elsewhere referred to as "counteractive capacity", is measured by the system's capacity to return after a perturbation. Generally, greater resilience leads to healthy ecosystem (Rapport, 1998).

3 Assessment models and methods

3.1 Forest ecosystem health assessment model

The forest ecosystem health assessment model is described as follows

$$\mathrm{FEHI} = w_1V + w_2O + w_3R \tag{1}$$

where FEHI represents forest ecosystem health index, V represents vigor, O represents organization, and R represents resistance, w_1, w_2, w_3 are weights for V, O, R respectively. Moreover, we select forest ecosystems' NPP to reflect vigor, Gleason biodiversity index reflect organization, and the capacity of resisting diseases and insect pests reflect resistance.

3.1.1 Vigor (V) measurement We use remote sensor technique to measure NPP. Net Primary Productivity (NPP) has connection with leaf area index (LAI), and NDVI can sensitively reflect the change of LAI, as study the relationships of LAI, NPP and NDVI, we conclude the following relations:

$$\mathrm{LAI} = -4.6332 - 86.2804\mathrm{Ln}\ (1 - \mathrm{NDVI}) \tag{2}$$

the linear correlation of NPP and LAI:

$$NPP = 3.1951 + 0.7773LAI \quad (3)$$

so, the linear correlation of NPP and NDVI:

$$NPP = -0.6394 - 67.064Ln(1 - NDVI) \quad (4)$$

Concrete models and methods see references of Zheng *et al*. (2000).

3.1.2 Organization (O) measurement We use Gleason biodiversity index (D) to reflect forest ecosystem organization, which reflects forest community biodiversity richness and biodiversity spatial distribution (Ma, 1994; Zhang, 1995).

$$D_o = S_o/\mathrm{Ln}A \quad (5)$$

where D_o represents forest community Gleason biodiversity index in sample plot, S_o is the amount of floral species in sample plot, and A is the area of sample plot.

3.1.3 Resistance (R) measurement It is difficult to directly measure the resistance and resilience, we apply an indirectly approach to measure resistance instead. In this study we select the resistance capacity to control forest diseases and insect pests. Generally, healthier forests have greater ability to resist diseases and insect pests, which leads to less occurrence frequency and intensity of the diseases and insect pests, while less healthy forests lead to lower ability of resistance. Therefore, we select the stress of diseases and insect pests to reflect the resistance (R). The method of measurement is the following:

$$R = (1 - P) \times 100 \quad (0 \leq R \leq 100) \quad (6)$$

where R represents forest ecosystem resistance, and P represents forest ecosystem diseases and insect pests occurrence intensity.

3.2 Data collection

The remote sensing information used in this research is derived from the NOAA AVHRR database provided by the Data Center of the Earth Resources Observation System under the United States Geology Survey Agency. The image size is 5004*2168 pixels with an 8 km resolution and Goode projection. For the case study in China's NPP, channels 1 and 2 data from 1991 to 1997 were taken in every ten-day interval. Survey plots data comprise plot area, composition of forest communities, the number of plant species and arborous layer species. These data include more than 300 sample plots distributed in typical forests throughout the country, which were supplied by Chinese Academy of Forestry and Chinese Ecosystem Research Network (CERN). Forestry statistical data contain the number of annual forest fire and fire-covered areas, forest disease-pest areas and harm intensity, forest resources and plantation forest areas changes, supplied by Chinese Forestry Statistical Yearbook. The daily meteorological data of 300 observatories, supplied by National Climate Center, were employed in this research, including the annual mean temperature, and annual average precipitation.

4 Results

4.1 The spatial FEHI distribution in China

The Forest Ecosystem Health Index, or FEHI, is calculated to the nearest whole number and ranges from 0 for an "unhealthiest" forest ecosystem, to 100, for a "healthiest" forest ecosystem (Figure 1).

From the results of FEHI assessment model and data, the spatial distribution of FEHI showed a decreasing trend from southern China to northern China. The distribution may have close relationship with the distribution of vegetation. The highest value was found in the southwest of China, tropical rainforests and tropical monsoon rainforest regions, including southeastern Tibet, southwestern Yunnan, and most parts of Hainan. In these regions there are highest forest ecosystem health indexes, and forest ecosystems are the "healthiest"; the rather higher value regions cover subtropical forest zone where as conditions of precipitation, radiation and temperature are abundant, forest can quickly recover from disturbances. However, since the subtropical zone is the key artificial forest area in China, the existence of vast expanse of pure pine forest and pure fir forest in particular exerts great impact on the outbreaks of diseases and insect pests. Many of the perturbations maintain healthy forest functions and species diversity over time. However, outbreaks are often seen as harmful to forest health. Insect pests and disease events near developed area may provoke secondary disturbances, such as wildfire; in forest area of Northeast China, the extremely low temperature limits forest physiological and ecological development. Forest biodiversity and productivity are rather low, which result in low health index; while in warm temperate deciduous broad-leaved forest and Xinjiang-Mongolia forest areas, FEHI is the lowest and the health status is the "poorest" because of forest standing conditions and forest structures.

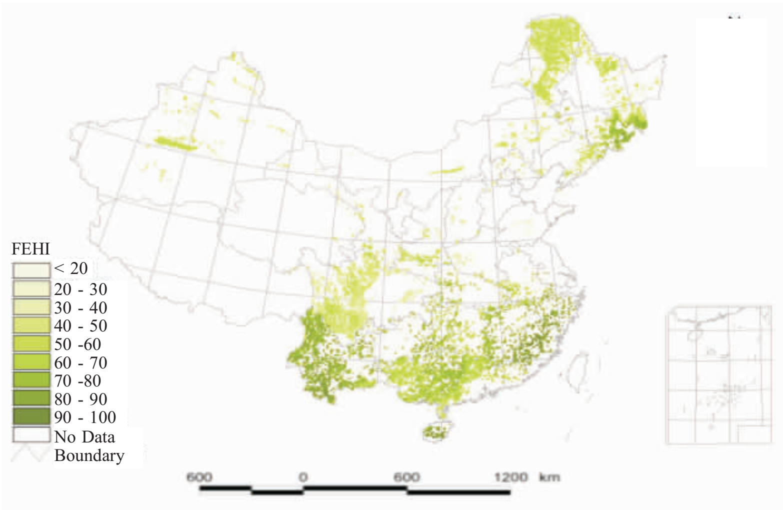

Figure 1 The spatial pattern for forest ecosystem health in China

Similar to Canada's forest ecosystem health survey and assessment approach (McLaughlin *et al*., 2000), we classify forest ecosystem health into 9 levels, and calculate the area proportion of each classification. Figure 2 illuminates that the proportion of the "healthiest" and "poorest" forests in China is small (being 3.9% and 11.1%, respectively), and most of the forests are in medium health status. The health status relates to landform, climate condition, forest species structure, exotic forest pest invasion, anthropogenic disturbances, as well as national law and policies.

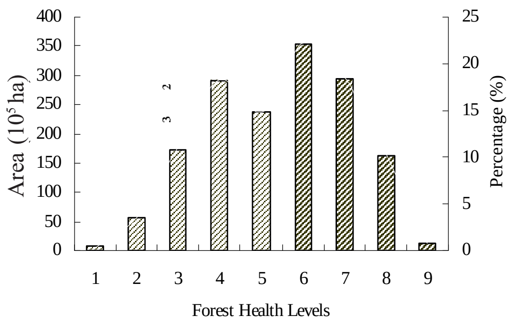

Figure 2 Forest area and percentage of each forest health classification

4.2 Forest Ecosystem Health's correlation analysis

4.2.1 Correlation analysis between FEHI and Vigor, Organization, and Resistance According to the spatial correlation analysis model, we calculate the correlation coefficient of two types of spatial data by GIS. The correlation coefficients (r) of FEHI and Vigor (V) is 0.64 ($p<0.01$). Similarly, FEHI was statistically correlated with Organization (O) and Resistance (R), forest ecosystem health improved as forest biodiversity increased ($r = 0.78$, $p<0.01$) and forest diseases and insect pests decreased ($r = 0.81$, $p<0.01$). In these three indicators, resistance has the greatest influence on forest ecosystem health because the disturbances, including forest diseases and insect pests, forest fire and acid rain have greatly impacted forest ecosystem health in China. The more of the frequency and the greater intensity of disturbance, the lower the FEHI. The influence of organizational structure on FEHI comes the second. The greater diversity leads to increased community complexity and stability, hence the health index is higher. Among the three varieties, Vigor has the smallest influence on FEHI, e.g. large areas of artificial forests, especially pure artificial forests, have high productivity, but are prone to disease and insect pest invasion and outbreak, resulting in ecosystem collapse.

4.2.2 Correlation analysis between FEHI and climate factors Forest ecosystem health was affected by forest community composition and structure, meanwhile climate factors also have impact on forest ecosystem health. We do know that climatic factor plays an important role in forest ecosystem health.

Different combinations of temperature and precipitation account for great variation in climatic conditions in different regions of China. Due to geographical locations, the eastern and southwestern parts of China are moist and wet. In contrast, the northwestern part of China is very dry. This influences the distribution of forest ecosystems and their health status. The spatial distribution of precipitation showed a decreasing trend from southeastern China to northwestern China, which has close relationship with the distribution of FEHI. Throughout the country annual mean precipitation was statistically correlated with FEHI. Forest ecosystem health status deteriorated as precipitation decreased ($r = 0.58$, $p<0.01$), which identifies that precipitation has great influence on forest health status. Precipitation is important limiting factor for forest types distribution and plant growth, and forest productivity non-linearly increased as annual mean precipitation increased (Feng *et al*., 1999), hence productivity is an important aspect of ecosystem health. Therefore, precipitation variety leads to the change of forest health index. In addition, precipitation also has impact on the distribution of forest types, and the biological diversity index was high where precipitation was abundant, while the forest biodiversity index was low where precipitation was scarce (Chen *et al*., 1997). Precipitation indirectly impacted the spatial pattern of forest ecosystem health by impacting the distribution of forest biodiversity.

Temperature is another important factor impacting forest ecosystem health. However, the effects of temperature were relatively small compared to precipitation effects. The correlation coefficient between FEHI and annual mean temperature is 0.49 ($p<0.01$). Forest ecosystem health index increased as annual mean temperature increased (the latitude decreased), temperature is one of the main factors that limited forest distribution and growth. Temperature's change affected forest health through influence on forest productivity. The forest productivity increased as annual mean temperature increased (the latitude decreased). At the same time, temperature can impact on forest health through influence on forest biodiversity, which reflected the forest biodiversity changes along latitude. The latitude pattern for biological biodiversity was attention-getting at the earliest (Huston, 1994). Several studies have found a decline in species richness of communities with a reduction in latitude from the equator to the polar (Darlington, 1959; Zhou and Yu, 2000). For most of the terrestrial plants, the biodiversity was low at the polar, the biodiversity increased as latitude decreased, and reach the maximal diversity in the tropical rainforest. Thereby, temperature change would directly or indirectly impact on forest ecosystem health.

5 Conclusions

The following conclusions can be drawn from the previous analysis and assessment.

(1) Forest ecosystem health assessment indicators. According to ecosystem health theories and characteristics of large-scale ecosystem, we select Vigor, Organization, and Resistance as the indicators to assess forest ecosystem health. Moreover, as China's forest ecosystems' diversity and complexity, we select forest ecosystems' NPP to reflect vigor, Gleason biodiversity index reflect organization, and the capacity of resisting diseases and insect pests reflect resistance when they are applied in China's forest ecosystems.

(2) Forest ecosystem health spatial pattern in China. The spatial pattern of forest ecosystem health shows a decreasing trend along latitude gradient and longitude gradient. The healthy forest is mainly distributed in natural forest, tropical rainforest and seasonal rainforest; secondarily orderly in northeast national forest zone, subtropical forest zonation and southwest forest zonation; while the unhealthy forest is mainly located in warm temperate zone and Xinjiang-Mongolia forest zone.

(3) Correlation analysis for forest ecosystem health. The coefficient of correction between FEHI and annual average precipitation is 0.58, while the coefficient of correlation between FEHI and annual mean temperature is 0.49, which identify that the precipitation and temperature affect the pattern of FEHI, and the precipitation's effect is stronger than the temperature's. The correlation coefficient between FEHI and NPP, biodiversity and resistance is 0.64, 0.76 and 0.81 respectively.

(4) In this study, we only assessed large-scale forest ecosystem health and analyzed the climatic factors on how to affect forest ecosystem health. Generally, forest ecosystem health depends on not only forest structure and function, climate condition, diseases and pests, but also soil condition, tree age, wildfire, acid rain, and other natural stressors and anthropogenic disturbances. Therefore, it is expected to further probe into the mechanism of ecosystem health at micro- and medium-scale ecosystems in future study.

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