Available online at www.sciencedirect.com

SCIENCE DIRECT®

Forest Ecology and Management 210 (2005) 25–37

Forest Ecology and Management

www.elsevier.com/locate/foreco

Monitoring forest dynamics using satellite imagery—a case study in the natural reserve of Changbai Mountain in China

Qi-Jing Liu [a,*], Xuan-Ran Li [a,b], Ze-Qing Ma [a,b], Nobuo Takeuchi [c]

[a] *Institute of Geographical Sciences and Natural Resources Research, The Chinese Academy of Sciences, A11 Datun Road, Chaoyang District, Beijing 100101, China*

[b] *Graduate School of Chinese Academy of Sciences, Yuquan Road, Beijing, China*

[c] *Center for Environmental Remote Sensing, Chiba University Yayoi-cho 1–33, Inage-ku, Chiba City 263–8522, Japan*

Received 5 June 2003; received in revised form 27 January 2005; accepted 7 February 2005

Abstract

This study intended (1) to develop a quantitative method to describe vegetation succession or change by remote sensing approach, and (2) to test the capability in clarifying the stability or instability of natural forests in landscape scales. With special attention on the coniferous forest, the attempt was conducted on the natural reserve of Changbai mountain in northeast China by using multi-temporal TM images. Two simple parameters were derived to represent succession rate or change extent. One was the mean change of radiance, and another was the number of pixels with changed reflection property. As conclusion, TM imagery is effective for detecting vegetation changes. The results also demonstrated that the so called climax is not a pure stand, which is generally assumed to be exclusively dominated by climax species, but rather a complex of shifting mosaic. The pioneer patches are permanent units in the forest community. This method is considered applicable for assessing the developing status or behavior of plant communities in large scales, like a life zone, under disturbance of global warming, especially for long-time span.

Keywords: Change detection; Climax; Disturbance; Boreal forest; Succession

1. Introduction

Vegetation succession has been a major topic in plant ecology (Glenn-Lewin et al., 1992), which is always related to the concept of climax. The climax consists of numberless patches which are always in dynamics. The patches with different composition form the mosaic pattern of the vegetation. Each patch, mature or premature, is a structural unit of the entire community.

To clarify the changes caused by either natural or human factors, community investigation in the field is

---

[*] Corresponding author. Tel.: +86 110 6485 6517; fax: +86 110 6488 9027.

E-mail address: liuqj@igsnrr.ac.cn (Q.-J. Liu).

0378-1127/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2005.02.025

useful for small scales, like patches or gaps. For large scales like landscape and regional levels, however, the field data of a ‘‘point’’ is less robust in representing the dynamics trend of an ‘‘area’’.

Plant ecologists may conclude the succession trend of a community by the data from field survey, i.e. the composition of succeeding trees under canopy is considered the future of the vegetation (Lertzman, 1992; Runkle, 1981; Lorimer et al., 1988), which is a general way for community ecology. However, the plot from which the data are collected is in fact a tiny unit of the community, which is a stage for just that patch. Therefore, it is debatable to represent the dynamics of a forest community by the successional trend of a plot which covers merely one or several hectares.

In other words, an area, with one or several hectare, of forest community we refer to is often a point, comparing to the ecosystem. Such points may show dramatic changes with time, while at landscape level, the phase of an ecosystem may present relatively stable. This view of point is supported by the fact that most original forest is characterized by the mosaic structure. Each patch, as a unit of the mosaic, is different from others in successional stage. When a gap, represents the declining phase, is filled by gapfillers, new gaps elsewhere are created by disturbance. Thus the mosaic is seemingly shifting (Clark, 1991; Lorimer, 1989; Foster and Reiners, 1986). It is a common sense that gaps are permanent existence in forest ecosystems, which have an important role in maintaining the spacial diversity (Bormann and Likens, 1979).

To demonstrate the equilibrium or dynamics, field investigation is essentially important, but for large scales of field investigation, such studies are difficult for the impossibility in labor, cost, and time.

Satellite remote sensing provides a meaningful method for detecting vegetation or land cover changes (Howarth and Wickware, 1981; Jensen and Toll, 1982; Quarmby and Cushnie, 1989; Singh, 1989; Mouat et al., 1993). By comparing the images taken in different time, the changes in landscape level can be easily detected (Jarvis, 1994). The main methods are image overlay, image difference, principal component analysis (Muchoney and Haack, 1994; Sunar, 1998), and post-classification difference (Chavez and Mackinnon, 1994; Miller et al., 1998).

Image ratio can also be applied to change detection, the changed parts appear either bright or dark, and the areas of no-change get a value of near unity (Prakash and Gupta, 1998). However, for changed pixels whose initial radiances are various, the different change extents may show the same ratio. In converse, the same fluctuation of absolute value may appear different ratios among pixels.

Images acquired on different dates appear various in spectral reflectance due to several reasons, e.g. the different sun elevation angles, changes in atmospheric conditions, variation in sensors and land cover changes. Therefore, atmospheric corrections are important for image comparison. For change detection, relative correction is frequently used. Based on a reference image, other images are corrected by establishing regression functions between images (Oguma and Yamagata, 1997).

Image normalization is another effective method for relative atmospheric correction, which modifies images by mean values and standard deviations of digital numbers (Higashi, 1990; Prakash and Gupta, 1998).

The study area is the most important natural landscape remaining in China’s temperate/boreal climate. Many studies had described the structure and composition of the natural vegetation (Chen et al., 1964; Wang et al., 1980; Liu et al., 1998; Chen and Bradshawb, 1999) as well as the succession of the main forest communities by field investigation (Okitsu et al., 1995; Liu, 1997).

A common phenomenon is that there is a large proportion of non-climax patches scattering in the old growth forest. In the mixed forest of the mountain area, the pioneer patches are dominated by broadleaved tree species, and in the subalpine coniferous forest zone, the patches in building stages are dominated by larch (*Larix olgensis*). Theses pioneer or non-climax patches are likely to be replaced by climax species, based on traditional succession theory. In other words, the pioneer patches would disappear during succession. But the question is that how has the pioneer population been maintained? What is the reason for the existence of the mosaic pattern? Can we assess the changes with a quantitative way?

Zheng et al. (1997) reported the rates and patterns of landscape change of forest, the resource, between 1972 and 1988 by using satellite imagery, in which the imagery was classified into two broad cover types (forest and non-forest) for investigating the decrease of forest cover by timber harvest. However, few reports dealt with the ecological process of plant communities at landscape level. This study is the first attempt to show the ecological features of the forest communities by remote sensing approach, which takes all of a certain forest within the reserve as a community continuum.

Change detection has mainly been used for land cover monitoring, but the application to vegetation succession, an ecological issue, is less concerned. For the study area, this is a new approach to study the natural dynamics of vegetation, i.e. the stability and alteration of plant ecosystems.

The aim of this study is (1) to assess the feasibility of satellite imagery for monitoring landscaper-level vegetation dynamics in coniferous forest in northeast China, and (2) to apply the method to reveal the hypothesis that the forest in this region follows a trajectory to the relatively uniform composition with predominance of shade tolerant species such as spruce and fir, the so called climatic climax, or whether the forest is maintained in a more ‘‘shifting mosaic’’ arrangement where the presence of pioneer species is maintained by natural disturbances.

2. Study area and methods

2.1. Study area

Study area is in the Changbai Mountain Natural Reserve which is located on the border between China and North Korea, and the coordinates are 127°42′/41°41′– 128°17′/42°26′ (Fig. 1). The area of the reserve is 2000 km^2. The ranges of the reserve are 60 km south–north and 40 km east–west. The highest elevation is 2734 m above sea level (asl).

Based on species composition, the vegetation is vertically classified into four zones (Wang et al., 1980; Liu et al., 1998), consisting of mixed forest, coniferous forest, birch forest, and tundra. From 600 to 1100 m asl, it is occupied by mixed forest. The coniferous forest is distributed in the subalpine, from 1100 to 1700 m asl. From 1700 to 2000 m, the vegetation is named as mountain birch zone. But this is mainly on the northern slope. The western slope is almost lack of birch zone, apart from some forest strips along valleys. This study, as a case of succession monitoring by remote sensing technique, focuses on the subalpine coniferous forest, which is dominated by spruce (*Picea jezoensis var. komarovii, P. koraiensis*) and fir (*Abies nephrolepis*). These species are commonly considered as climax components in the subalpine zone. However, there is a considerable proportion of pioneer species like larch (*Larix olgensis*) and mountain birch (*Betula ermanii*). For comparison, the change of mixed forest and birch forest were also selected for the study.

To demonstrate the effectiveness of this method in monitoring vegetation recovery after timber harvest, a small area of clear-cut forest outside the reserve was also selected.

2.2. Remote sensing data

Two cloud-free TM images (resolution 30 m by 30 m) were used for the study, which were acquired on 19 November 1984 and 7 November 1997, respectively. The path/row is 116/31. Sun elevation was 26° in the 1984 image, and 31° in the other one. The size of the subset image covering the reserve was 1995 columns by 2842 lines (approximately 5100 km^2), and the geo-extents were 127°34′10″– 128°18′20″E and 41°41′10″– 42°26′50″N. The phenology in these two dates is considered identical, i.e. all species were in dormant phase.

An image processor of PCI (PCI Ltd.) was used for data analysis. Geometric correction was performed by using the fourth polynomial method, and the error (root mean square, RMS) was controlled within one pixel. For each image, more than 100 ground control points (GCP) were picked.

The original purpose is to detect the gaps created during certain period. Since gaps or deciduous patches are easy to discriminate from other types in leafless time, and snow on the forest floor is also expected to enhance the contrast between communities in different stages or composition, winter images were therefore selected for the study. Images were taken in the same season with an interval of 13 years. These dates are near-anniversary, and the difference of sun elevation was not so large, hence the effects of shadows on image differencing were neglected.

Digital numbers of the images were used to represent the spectral reflectance or radiance of the cover types. To compare vegetation changes, atmo-

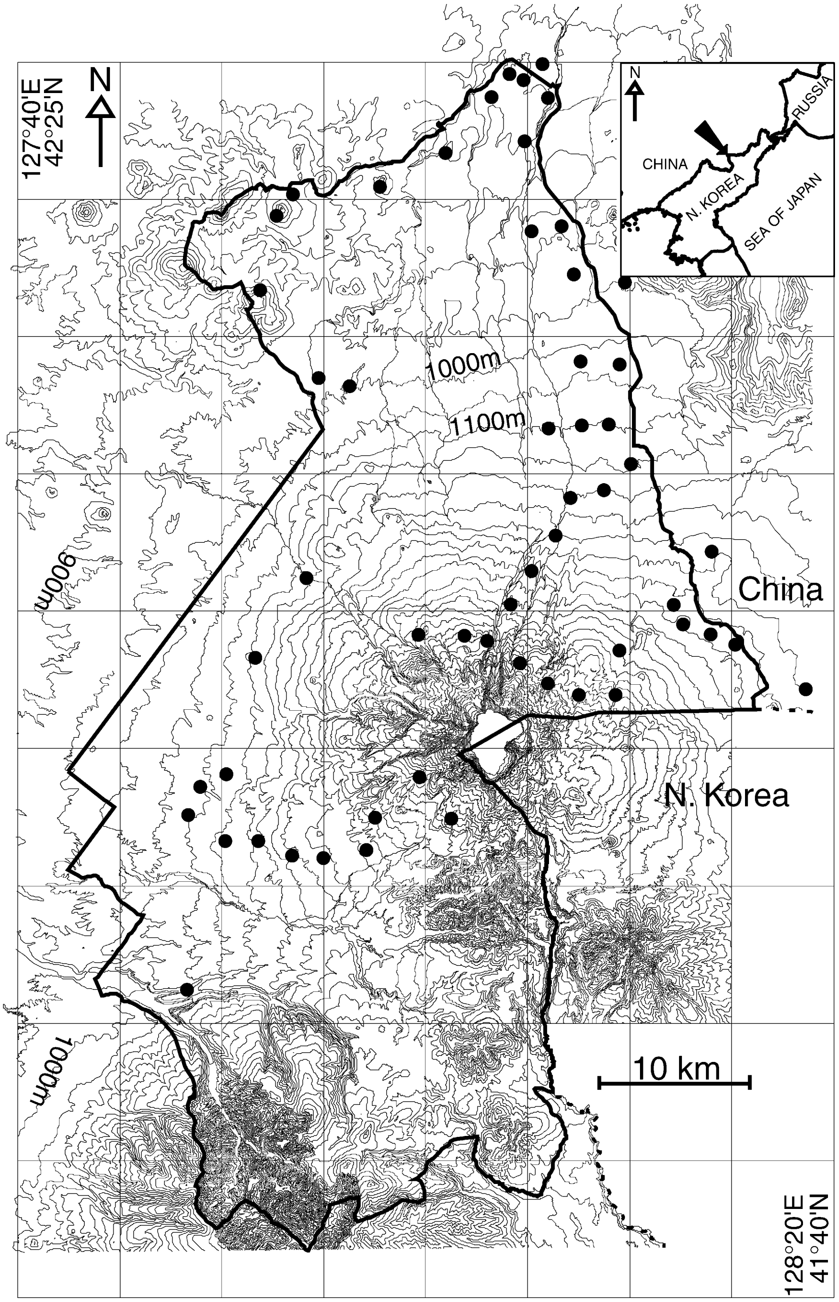

Fig. 1. Location and contour map of the Changbai Mountain Natural Reserve. Black balls represent the sample plots.

spheric correction is necessary. For the purpose of this study, relative correction (Oguma and Yamagata, 1997) was conducted. The image in 1984 was assigned as reference data, based on which the 1997 image was relatively corrected. Objects like concrete, asphalt, water and snow were chosen to establish linear regression equations between the two images. A total of 94 pixels was selected for the analysis. Coefficients

Table 1
Regressive coefficients of Landsat TM image between 19 November 1984 and 7 November 1997 for relative radiometric correction

Band	a	b	R
1	−19.6	1.08	0.99
2	−3.47	0.87	0.99
3	1.32	1.01	0.99
4	−2.97	1.29	0.99
5	0.67	1.08	0.99
7	0.50	0.67	0.99

$V\prime_{97} = a + bV_{97}$, and R is correlation coefficient.

of regression are shown in Table 1. Following are the regressive functions for relative radiometric correction:

$$V_{84} = a + bV_{97} \tag{1}$$

$$V\prime_{97} = a + bV_{97} \tag{2}$$

where V_{84} and V_{97} are the digital values of 1984 and 1997, respectively. $V\prime_{97}$ is the estimated value of 1997.

After the correction, image subtraction was performed, i.e. V_{84}– $V\prime_{97}$. For this study, channel 4 (near infrared) was used to detect the changes, since shorter waves are more sensitive to atmospheric condition than other bands. Change values are from minus to plus. In this study, the former means vegetation decrease, and the latter represents increase. The value 0 means ‘‘unchanged’’, and we call this as ‘‘zero point’’. By setting a threshold for ‘‘changed’’ at 1.5 standard deviations from the zero point, the number of pixels was counted to represent the change extent. Similarly, the shift from zero point was also used to demonstrate the community dynamics or equilibrium. To avoid signed numbers during image process, the residual values were scaled to the range of 0–255, with the equation of $(V_{84} - V\prime_{97} + 255)/2$.

The composition of typical communities was investigated in the field during the late 1980s to the early 1990s in other research projects. The total number of plots (size ¿ 1000 m^2) investigated was more than 100. The threshold of digital values in the residual image for identifying open stand or gaps from forest were determined by checking cover types in the field.

3. Results

3.1. Change pattern in spectral radiance

In the original images (Fig. 2), the high values represent low vegetation coverage, such as bare land, clear cutting area, windfall, and so on. In reverse, those areas with low values (dark) were densely forested or conifer-species dominated.

In the 1997 image, there was a large area with high radiance in the western slope, which was created by a strong typhoon in 1986. There was another large open forest near the new windfall area, similar in size and shape, recorded in both images, which is considered as an old wind fall.

In northern slope, the birch-mixed coniferous forest can only be found above 1400 m, and primarily around 1600 m asl near the birch zone. Contrary to this, in the western slope, mountain birch forest showed a high proportion, the spruce-birch forest was very common from 1300 m, and the timber line was very low comparing to northern and eastern slopes. Birch is a pioneer species, and it usually colonizes open land or gaps. In other words, the forest in the western slope showed a secondary property, implies that the forest is strongly affected by natural disturbance.

In the residual image (Fig. 3), the forest vegetation that kept unchanged showed uniform or homogeneous. The degraded area presented very dark, while the recovering parts, in progressive succession, were bright.

The large area with black color on the western slope inside the reserve (Fig. 3) was degraded due to natural disturbance. The white color shows the progressive succession of vegetation. Outside the reserve, this color represents the revegetation after logging.

The logged areas in China’s side were primarily small blocks, because the cutting-regeneration regime was regulated by the government in late 1970s, which forbade large-area clear cutting, and only selective cutting or small-area ($\leq$5 ha) clear cutting could be adopted for the mixed forest in northeast China. Contrary to this, Korea’s side showed a large area of clear cutting, which was conducted in the 1970s. Thanks to artificial regeneration or plantation after cutting, these parts were in their building phase, and showed a decrease in reflectance.

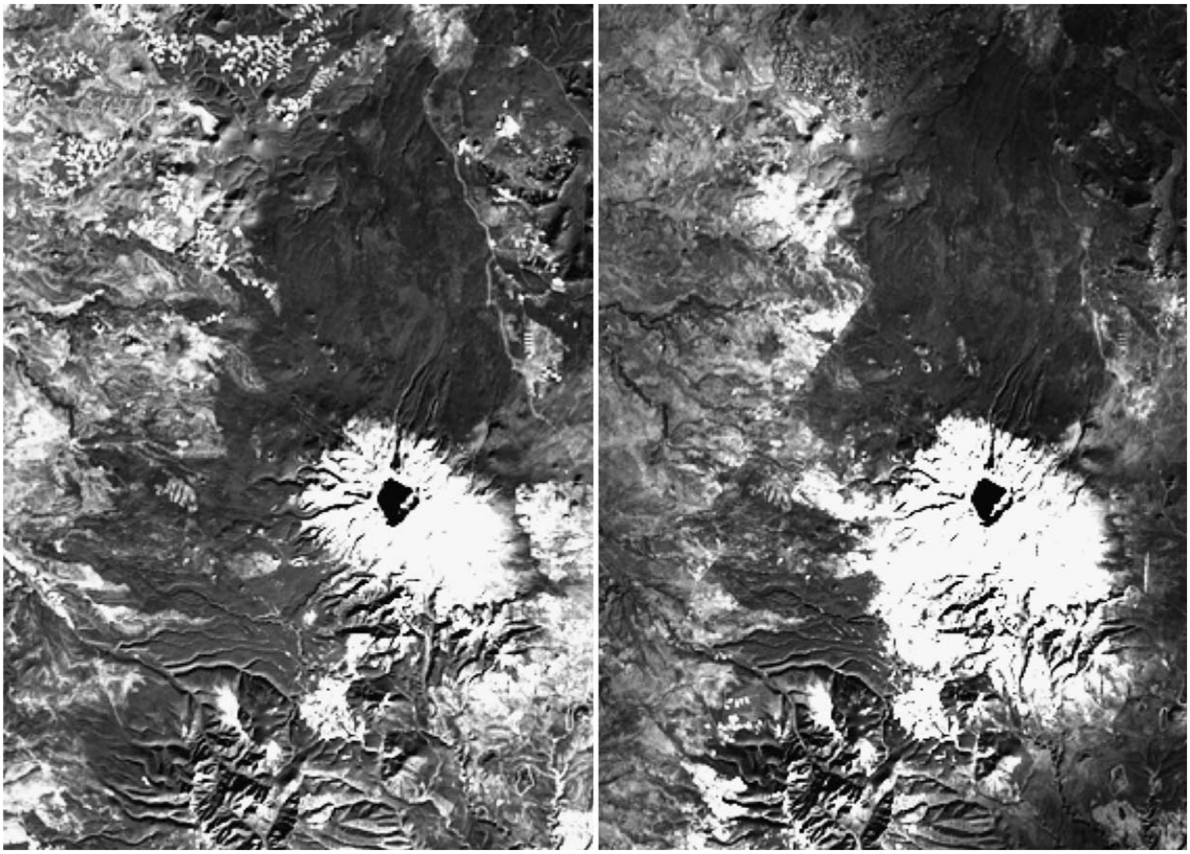

Fig. 2. Landsat TM band 4 showing the change in 13 years of period. Ground size 60-km by 85-km. Left 1984; right 1997.

The vegetation that changed from forest to bare land or gaps showed the lowest digital values, and the forest increased in stem density or coverage presented positive. The higher extent it changed, the larger absolute value it was, and this implies the precipitate change in coverage or species composition. On the other hand, the lower absolute values mean the gradual shift. The former was mainly represented by forest fall or logging, and the latter was by individual death or fall.

In the coniferous forest, pixels in degrading areas showed significant changes in radiance, about 29.62% of pixels showed smaller than −100, while those in growing stage were gentle in radiance change that few pixels (0.27%) went larger than 100 (Fig. 4). This is consistent with the general rule of plant community dynamics, that the change is gradual in progressive succession, and precipitate in degrading caused by disturbance. As a whole, the coniferous forest presented a little degrading, implies the results of disturbance.

As mentioned earlier, the forest outside the reserve had been cut prior to the mid-1980s (Zheng et al., 1997). After cutting, most of the cut area was covered by artificial forest, mainly larch, and the vegetation increase was well represented in spectral radiance, that the residuals ranged in 10–100, with the maximum pixel-number at about 40. In contrast, the radiance change in the windfall area showed a degrading property, that the residuals ranged in −200 to 10, with its peak value at about −60. This pattern is consistent with the original images (Fig. 2).

The typhoon in 1986 also caused a large area of fall in the birch forest. The fallen area was vertically near

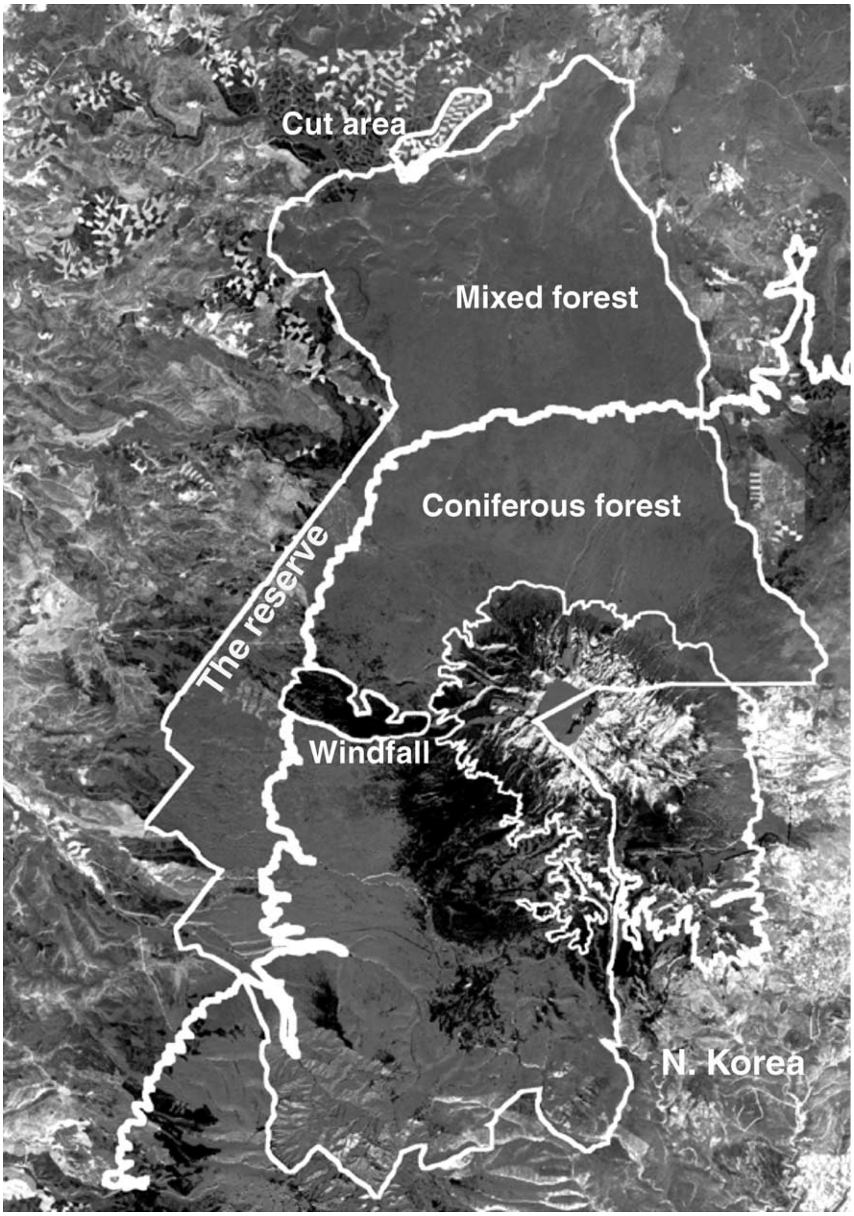

Fig. 3. Residual image of near infrared (band 4) between 1984 and 1997. Dark: vegetation decreased; bright: vegetation increased.

the timber line, and its large size implies that the distribution of timberline is partly controlled by strong wind.

The mixed forest in the mountain area may be less affected by large disturbance. But this forest is also considered to be kept by patch shift (patches emerge or merge due to species replacement), because regeneration of the climax tree species like Korean pine (*Pinus koraiensis*) was very poor under its own canopy, in contrast with tremendous seedlings in the secondary forest established after large disturbance, according to our field investigation.

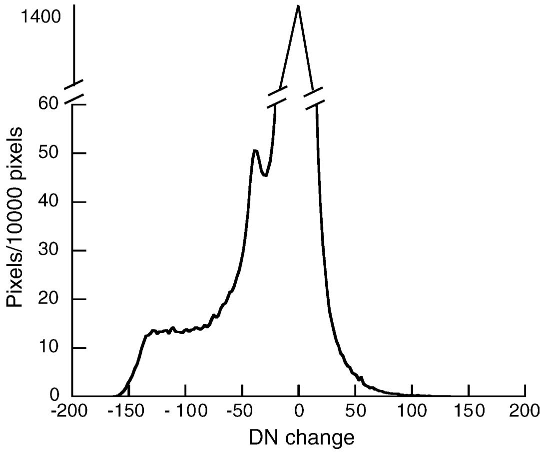

Fig. 4. Radiance change of TM band 4 in the coniferous forest. Minus: vegetation decreased; plus: vegetation increased.

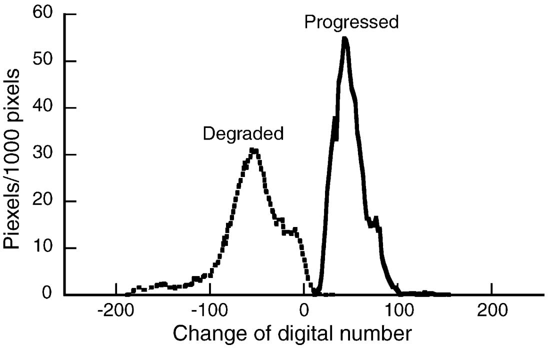

Fig. 5. Radiance change in result of disturbance and restoration. Left: decrease by windfall; right: increase by afforestation outside the reserve.

Based on Fig. 5, the change extent can be expressed by a ratio of changed value to the potential maximum change of 255, which is defined as change rate. In this study, the coniferous forest showed a declined value of −9.2, and its change rate was −0.0361. As comparison, the mixed forest and birch forest were −0.0075 and −0.0596, respectively. By extracting the windfall area in the western slope, the ratio was −0.21, and that of the cut area was 0.19. We call this change rage as succession index, representing the speed or magnitude of vegetation dynamics (Table 2).

Similarly, the number of pixels that fell in −1.5 STDs represents the degraded extents, and that in 1.5 STDs for increased levels. With this criteria, about 8.4% of the coniferous forest showed decrease and less than 2% presented increase.

The change pattern also showed a trend that the disturbance was heavier towards higher altitude. The mixed forest was under other forest types, and few pixels with radiance change over 1.5 STDs in both directions. The birch forest, in reverse, had nearly 10% of pixels with radiance change less than −1.5 STDs.

Focusing on the windfall area in the coniferous forest, the change rate of radiance was −0.21, and 72% of the pixels decreased less than −1.5 STDs, the highest ratio among all cases. These figures reveal the high change extent that the property of the extracted area was thoroughly different from its original status. By investigating the structure of the windfall area, there were few trees left standing on the ground. During 2 or 3 years after the typhoon in 1986, the fallen logs were removed from the site for commercial purpose, and no artificial regeneration was conducted. Ten years after the event, the area was covered by young trees of birch and poplar, as well as some shrubs. During the winter, the forest was leaf-off and the crown density was very small, the ground is usually covered by snow in this season. Therefore, the reflectance was significantly higher than predisturbance.

Table 2
Radiance change of the main forest types in TM band 4 as the results of disturbance or restoration

Items	Mixed	Conifer	Birch	Windfall	Logged
N pixels	753885	1216812	106861	28357	15121
Change mean	−1.9	−9.2	−15.2	−55.7	49.6
Change rate	−0.0075	−0.0361	−0.0596	−0.2100	0.1900
STD	8.2	29.0	35.3	34.7	17.0
N% of > −1.5STDs	3.8442	8.3835	9.5227	72.3455	0.0066
N% of < 1.5STDs	3.7286	0.5207	1.8491	> 0.0001	41.4126

Change mean: change of radiance in mean value; change rate: change mean/255, STD: standard deviation of radiance change; *N*%: number of pixels in percent.

In contrast, the logged area outside the reserve was in its restoring period, and it presented a rapid increase that the change rate was 0.19. In accordance with this, over 41% of the pixels showed an increase larger 1.5 STDs (Table 2).

4. Discussion

4.1. Vegetation changes through spectral reflectance

Spectral reflectance is sensitive to structure and life-form composition of plant communities, and this can be detected by satellite imagery. This study demonstrates that gaps or open stand can be easily detected. As we found during field investigation, tiny gaps are frequently created by wind disturbance and other factors like snow breakage, because snowfall in high altitudes is heavy, and the evergreen canopies are vulnerable, comparing to the deciduous species like larch and mountain birch. Such motion was well represented in the residual image.

The composition in life form level was well reflected in the imagery, that the sharp increase in reflectance for those patches of declining and, in reverse, pixels that increased in tree density showed gradual changes in spectral property. This is very useful for verifying the dynamics of plant communities.

4.2. Vegetation succession in the subalpine

Spruce-fir forest is the climax in the subalpine. Based on the eco-characteristics of the climax tree species, the forest is stable, that spruce and fir are shade tolerant and the seedlings can regenerate under canopy. Contrast to this, larch has a narrow range of adaptability, and it is difficult to regenerate under a shading canopy area. By investigating a plot with a size of about 1 ha, usually the larger one for field work, the forest may be predicted with different trends of succession. This is because the plot size is too small to represent the overall dynamic regime of a plant community.

It is a great puzzle for ecologists that there exists a large proportion of larch forest with few seedlings under canopy layer. This is often explained as the result of volcanic eruptions (Okitsu et al., 1995). But the last major eruption was identified to be 1600 years ago (Liu et al., 1993), and the population may have experienced several generations. On the other hand, we found many large areas of young larch forest dominated with young individuals, and the age of the largest tree is estimated about 150 years. Apparently, such patches were the result of natural disturbance. Hence, the mechanism of the population maintenance is difficult to explain with the view point of volcanic activities. It is concluded that the community structure is maintained by climatic factors, rather than volcanic activities.

Previous studies show that, in natural forest ecosystems, there is a balance between gapmaking and gapfilling (Lertzman, 1992; Lorimer et al., 1988). The forest patches in different phases have different composition in canopy layer, but the regeneration layer is similar in all cases, especially the larch forest which is located in the coniferous the forest zone. We investigated some plots that were dominated by larch, and the result showed that the young individuals (DBH < 16 cm) accounted for more than 50% (Liu et al., 1998).

The succession of coniferous forest in the subalpine can be represented as: bare land → larch → coni-oniferous forest → bare land. This is the case in a patch. The forest is composed of numberless such patches which are in different phases, roughly, gap phase, building phase, and climax or mature phase. Because gaps are always made by permanent climate factors, the forest is maintaining a mosaic structure, and it can never reach the pure status of uniform composition, the pure coniferous forest.

4.3. The differentiation of vegetation in the subalpine

The composition of forest in the subalpine was different among slopes. The eastern slope was dominated by larch, the northern slope by coniferous forest and birch forest, the western by birch-spruce forest, and the southern slope was similar to the western slope.

Here we focus on the vegetation in the western slope. The windfall area had a wide range, from the southern to the western slopes. The direction was from the south to the north, and then turned to the west, which was likely to be affected by topography. It hit on a high ridge and then turned its way along the valley to the lower areas.

The vegetation history is considered longer in the western slope than in the eastern slope, but the timberline was lower in the western slope. This is considered the result of wind activity. The prevailing wind in the mountain is WSW (Zhang et al., 1980), and the forest is always under the control of wind. It is very common that the coniferous forest in the eastern slope was mixed with mountain birch. Mountain birch is a pioneer species in the coniferous forest zone, and its dominance tends to decrease during succession. Also, birch is a wind-resistant species, and it can be kept in forest for long time.

The northern slope is relatively gentle in topography, and the pioneer species appeared thin in density, and the diversity in landscape level showed lower than southern slope (Liu et al., 2002).

4.4. *The concept of the climax vegetation*

Climax is initially defined as the vegetation with great stability, in which the species composition has reached an equilibrium with present climate (Glenn-Lewin et al., 1992), and it is also called climatic climax. Another concept is an improved version of climax, the combination of biota, soil and climate factors, which is called biogeoclimatic complex (Kojima, 1981; Pojar et al., 1987). This is similar to the Clement's theory in relation with the stability of species composition.

The climax theory has been criticized according to the fact that species composition is also controlled by trophic factor and natural disturbance. Moreover, vegetation itself is always in shift due to individual replacement, like generation turnover. On this point of view, the equilibrium is never reached.

The concept of compositional equilibrium may be applied at a range of spatial scales. For example, for a species-rich forest in compositional equilibrium, the relative importance of species inevitably change at spatial scales corresponding to groups of a few trees on a very small area (e.g. $<25\ \mathrm{m}^2$) but may remain approximately constant at stand or landscape scales.

As mentioned earlier, the coniferous forest zone on the subalpine consists of numberless patches which are always in dynamics. The equilibrium, in landscape or larger scales, encompasses the dynamics, in smaller scales. The patches with different composition form the mosaic pattern of the vegetation. Each patch, mature or premature, is a structural unit of the entire community, just like a cell versus the tissue. This mosaic structure with shifting patches can be defined as the climax in the subalpine.

The mixed forest was distributed in the lower elevations, and the windfall effects are considered small in extent, comparing to the subalpine forest. This means that fine scales of gaps are the major driving force for its dynamics.

4.5. *The shift of different forest patches*

The forest in subalpine is in fact a mosaic structure which is very common in virgin forest communities. Those consisting of pioneer species are in developing stage, and those exclusively dominated by climax species are in mature phase. It is presumed that the patches are shifting from/to each other's phase with time.

The changes are considered as the results of individual replacement. The changes in different phases are moving or floating from one place to another. The decreased values represent the increase of deciduous species or formation of tiny gaps, and the increased one represent the decrease of pioneer components.

The gap creating-filling process can be described by a simple model: the cycling time for gap formation is the function of the disturbance speed. Based on a given shifting rate, the turnover time for the entire forest is:

$$[\text{Turnover time}] = \frac{[\text{Community area}]}{[\text{Annual gap making}]} \tag{3}$$

In this section, we presume that the mosaic structure of the coniferous forest zone is kept by disturbance, and the gaps forming is counteracted by patch building. Following is the conceptual model of the succession process.

The coniferous forest is dominated by climax species, and is always disturbed by wind throw. After disturbance, the pioneer species invade the site, and the forest develops toward the climax. The total area of gaps is constant (Fig. 6), namely:

$$S_1 = S_2 = \ldots = S_n \tag{4}$$

where $S_1, S_2 \ldots S_n$ are the total area of gaps in different time.

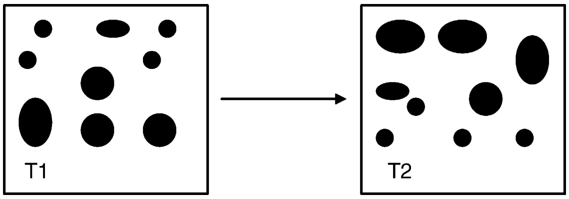

Fig. 6. A gap shift model showing the constancy of gap area. Left: gaps distribution in time T1, right: gaps distribution in time T2. The total area of gaps is constant.

Gaps created with intermediate size are benefited from the pre-regeneration and the improved energy environment, and would be closed soon after disturbance. But this process is much slower than gap formation that usually happens in a sudden.

Large open stand (> 10 ha) created by wind throw is very different from relatively small one. It is thoroughly cleared of saplings or large sized trees for regeneration or recovery. The seed rain can not reach this area easily, especially for those species with heavy seeds. Moreover, trees regenerate from seeds or seedlings may take more than 100 years to reach the canopy, and even longer for making a closed stand (Yang and Xie, 1994). Therefore, the recovery of this kind of sites from bare land to matured climax forest is very slow.

The frequency of large disturbance is not clear, and thus it is difficult to precisely estimate the role of large scale of wind fall in vegetation succession, especially the interval of turnover.

However, the adjacent wind throw area may reveal the frequency of typhoon. The old wind throw is now dominated by larch and birch, and the largest trees in the stand are estimated more than 100 years. Though the interval of such events is yet to be investigated, it can be deduced that windfall would revisit the same area, which is a regular activity controlling the vegetation style. However, since the behavior of wind varies among slopes, the prevailing wind is west–south–west (Zhang et al., 1980), as stated earlier, the disturbance regime is therefore considered different in relation with topography and slope aspect.

4.6. Accuracy of the discrimination

The mosaic structure of the forest has been identified by field survey, which was also revealed in the images. The method used in this study is effective for such studies. However, the spectral reflectance, although relatively corrected and the season was nearly the same, is affected by solar zenith, which was clearly identified for some areas that the shadows differed between the two images. This may not account for large proportion, since the topography of the forest area was relatively gentle. Another factor is the surface status of the cover types themselves may have performed a considerable effect on the spectral reflectance.

It was recognized that the land cover with lower vegetation coverage or less biomass is changeable in spectral reflectance, like sparse forest, grass land, and bare land, especially the latter. The ground surface is easy to be affected by weather, like rain (soil moisture), snow, etc. The images were received in winter, and the ground or forest floor may present some difference in reflectance due to the possible variation in snow cover. This can be implied by the fact that the bare land in 1984 image presented a little brighter than the 1997 one.

The wind fall detected in the southwestern slope was a thin birch-spruce forest, and its change in reflectance was even larger than the densely covered area of forest in the western slope.

Different from most studies dealing with vegetation changes caused by human activities, this study is on the ecological process in natural ecosystem, and it reveals that the method is effective to explore community dynamics in landscape level by remotely sensed data. The result demonstrated the hypothesis that (1) the entire vegetation as a statistical universe was stable, and (2) declining (gapmaking) and progressing (gapfilling) were coexistent.

However, as mentioned earlier, the reliability of detection is limited by image resolution, particularly for small gaps of patches. In fact, small gaps and pioneer patches are very important units in the ecosystem process, which were very common in the study area. This is expected to be improved by using higher resolution image. Data fusion with high resolution image would also be an effective approach.

For detecting vegetation change with more precise accuracy, factors like sun elevation and topography must be considered.

4.7. Potential application for assessing ecosystem change

In ecological sense, the status and behavior of the interested area can be evaluated by the method developed in this study. To demonstrate the stability or instability of a life zone, a large area is usually difficult to investigate or monitor by field plots, while satellite images record the change, even if tiny, with continuous data. More important, satellite remote sensing broaden the field of view of ecologists, and they are able to probe the statistical universe (population) other than merely an event (plot). For the case of vegetation dynamics under natural condition, long span of time is considered more reliable. The approach can be applied to (1) vegetation under global warming, and (2) vegetation under natural or anthropologic disturbance in different scales, and (3) change of other types of ecosystems, which is spectrally sensitive.

Acknowledgement

Sponsored by the National Key Basic Research Special Foundation of China (No. 2002CB4125).

References

Bormann, F.E., Likens, G.E., 1979. Pattern and Process in a Forested Ecosystem. Springer, New York, NY, 253 pp.

Chavez, P.S.J., Mackinnon, D.J., 1994. Automatic detection of vegetation changes in the southwestern United States using remotely sensed images. Photogrammetric Eng. Remote Sens. 60 (5), 571–583.

Chen, J., Bradshawb, G.A., 1999. Forest structure in space: a case study of an old growth spruce-fir forest in Changbaishan Natural Reserve, PR China. For. Ecol. Manage. 120, 219–233.

Chen, L., Bao, X., Li, C., 1964. Some structural characteristics of the main plant communities in the vertical zones of Changbai mountain. Acta Phytoecologica et Geobotanica Sinica 2 (2), 207–225 (in Chinese).

Clark, J.S., 1991. Disturbance and tree life history on the shifting mosaic landscape. Ecology 72, 1102–1118.

Foster, J.R., Reiners, W.A., 1986. Size distribution and expansion of canopy gaps in a northern Appalachian spruce-fir forest. Vegetation 68, 109–114.

Glenn-Lewin, D.C., Peet, R.K., Veblen, T.T. (Eds.), 1992. Plant Succession. Chapman and Hall, London, 352 pp.

Higashi, T., 1990. Extraction of expanded area of damaged stands by pine wilt disease using two Landsat TM data. J. Remote Sens. Soc. Jpn. 10 (3), 77–83 (in Japanese).

Howarth, P.J., Wickware, G.M., 1981. Procedures for change detection using Lansat digital data. Int. J. Remote Sens. 2 (3), 277–291.

Jarvis, C., 1994. Modelling forest ecosystem dynamics using multitemporal multispectral scanner (MSS) data. Adv. Space Res. 14 (3), 277–281.

Jensen, J.R., Toll, D.L., 1982. Detecting residential land-use development at the urban fringe. Photogrammetric Eng. Remote Sens. 48 (4), 629–643.

Kojima, S., 1981. Biogeoclimatic ecosystem classification and its practical use in forestry. J. Coll. Liberal Arts, Toyama Univ. 14 (1), 41–75.

Lertzman, K.P., 1992. Patterns of gap-phase replacement in a subalpine, old-growth forst. Ecology 73, 657–669.

Liu, Q.J., 1997. Structure and dynamics of the subalpine coniferous forest on Changbai mountain, China. Plant Ecol. 132, 97–105.

Liu, Q.J., Kondoh, A., Takeuchi, N., 1998. The forest vegetation and its differentiation under disturbance in a temperate mountain, China. Jpn. J. For. Res. 3 (2), 111–117.

Liu, Q.J., Takamura, T., Takeuchi, N., Shao, G., 2002. Mapping of boreal vegetation of a temperate mountin in China by multitemporal Landsat TM imagery. Int. J. Remote Sens. 23, 3385–3405.

Liu, Q.J., Wang, Zh., Wang, Sh., 1993. The effects of volcanic eruption on subalpine vegetation of Changbai mountain. Geologica Scienta Sinica 13 (1), 51–67 (in Chinese).

Lorimer, C.G., 1989. Relative effects of small and large disturbances on temperate hardwood forest structure. Ecology 565–567.

Lorimer, C.G., Frelich, L.E., Nordheim, E.V., 1988. Estimating gap origin probabilities for canopy trees. Ecology 69, 778–785.

Miller, A.B., Bryant, E.S., Birnie, R.W., 1998. An analysis of land cover changes in the Northern Forest of New England using multitemporal Landsat MSS data. Int. J. Remote Sens. 19 (2), 245–265.

Mouat, D.A., Mahin, G.G., Landcaster, J., 1993. Remote sensing techniques in the analysis of change detection. Geocarto Int. (2), 39–49.

Muchoney, D.M., Haack, B.N., 1994. Change detection for monitoring forest defoliation. Photogrametric Eng. Remote Sens. 60 (10), 1243–1251.

Oguma, H., Yamagata, Y., 1997. Study on effective observing season selection to produce the wetland vegetation map. J. Jpn. Soc. Photogrammetry Remote Sens. 36 (4), 5–16 (in Japanese with English summary).

Okitsu, S., Ito, K., Li, C.-H., 1995. Establishment processes and regeneration patterns of montane virgin coniferous forest in northeastern China. J. Veg. Sci. 6 (3), 305–308.

Pojar, J., Klinka, K., Meidinger, D.V., 1987. Biogeoclimatic Ecosystem classification in British Columbia. For. Ecol. Manage. 22, 119–154.

Prakash, A., Gupta, R.P., 1998. Land-use mapping and change detection in a coal mining area-a case study in the Jharia coalfield, India. Int. J. Remote Sens. 19 (3), 391–410.

Quarmby, N.A., Cushnie, J.L., 1989. Monitoring urban land cover changes at the urban fringe from SPOT HRV imagery south-east England. Int. J. Remote Sens. 10 (6), 953–963.

Runkle, J.R., 1981. Gap regeneration in some old-growth forests of the eastern United States. Ecology 62, 1041–1051.

Singh, A., 1989. Digital change detection techniques using remotely-sensed data. Int. J. Remote Sens. 10 (6), 989–1003.

Sunar, F., 1998. An analysis of changes in a multi-date data set: a case study in the Ikitelli area, Istanbul, Turky. Int. J. Remote Sens. 19 (2), 225–235.

Wang, Zh., Xu, Zh., Li, X., Peng, Y., Qian, J., Liu, Z., Yang, Y., Wei, Ch., Li, Y., 1980. The major forest types and community structure in northern slope of Changbai mountain. Res. For. Ecosyst. 1, 25–42 (in Chinese).

Yang, H., Xie, H., 1994. Study on the reconstruction of disturbance history of *Pinus koraiensis* mixed forest in Changbai mountain. Acta Phytoecologica Sinica 18 (3), 208–210 (in Chinese).

Zhang, F., Chi, Zh., Li, X., 1980. Preliminary analysis on the climate of Changbai mountain area. Res. For. Ecosyst. 1, 193–213 (in Chinese).

Zheng, D., Wallin, D.O., Hao, Z., 1997. Rates and patterns of landscape change between 1972 and 1988 in the Changbai Mountain area of China and North Korea. Landscape Ecol. 12 (4), 241–254.