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Geographical Review of Japan
Vol. 78, No. 5, 276-288, 2005

Relationships between Vegetation Change and Geomorphic Conditions in Suburban Forests of Japan: Analysis by Means of Digital Aerial Photogrammetry and Geographical Information Systems

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Abstract: The relationships between successional vegetation change and geomorphic conditions were analyzed by using a high-resolution digital terrain model (DTM) and a time series of converted digital vegetation maps combined within a geographical information system (GIS). The results of the analysis confirmed that the pattern of vegetation change is a function of geomorphic conditions (measured in terms of spatio-statistical values of various parameters and time series of those values). Current geoecological studies are usually carried out by means of detailed field observations with high spatial resolution, and the results of our study suggest that a GIS can easily deal with such data over a large area and long time period.

In the study area, unforested sites were reforested using Japanese red pine (*Pinus densiflora*) as part of the forest rehabilitation work that occurred in the early 1950s. After that, two main patterns of vegetation change from pine forest to deciduous broadleaved forest occurred. In one type, the deciduous broadleaved forest reappeared quickly. In the other, the pine forests remained for a long time. Stands that underwent relatively rapid succession were found on north-facing gentle slopes close to large bodies of water. Stands that did not undergo rapid succession were found on steeper, warmer, and drier slopes (often south-facing slopes farther from bodies of water). The rate of forest succession towards deciduous broadleaved forest is a function of these geomorphic conditions. This suggests that forest succession is influenced by intermediate factors controlling by geomorphic conditions of site, such as soil moisture and soil thickness.

Key words: vegetation change, geomorphic conditions, suburban forest, digital aerial photogrammetry, geographical information system, digital terrain model

Introduction

What are now suburban forests were originally artificial rural forests, managed for agriculture and firewood production. After the fuel revolution of the 1960s, however, these forests were no longer managed. Thus, it is likely that the vegetation of these forests has changed over time. The value of suburban forests close to cities and that have high levels of biodiversity was reevaluated after the 1980s from the viewpoint of providing various urban amenities (Kuramoto 2001). Thus, it has become important to gather information on suburban forests to support urban planning, including preservation of the forests.

Geoecological studies of suburban forests and their species are usually done by means of topographic surveys with high spatial resolution, small quadrats, and line-transect investigations (e.g., Suzuki 1974; Suzuki et al. 1985; Koizumi et al. 1988; Koizumi 1995). The results of these studies indicate that the microclimate, soil conditions, and disturbance regimes that result from micro-scale landforms have influenced vegetation patterns in suburban forests.

It has become necessary for urban planning, including the preservation and practical use of suburban forests, to evaluate the natural environment of these forests. To support these activities, it has thus become necessary to establish a suitable method for analyzing the natural environment of suburban forests over wide areas, but with high spatial resolution. The techniques and methods used to support this analysis have advanced as computer technology has improved, and these methods are now ready for wider use. In particular, analysis using geographical information systems (GIS) will play an important role in solving these problems, because GIS can quantitatively relate the values of individual parameters to various other spatio-temporal properties.

Several examples of such analyses of the relationship between land use and the natural environment already exist. Hashimoto and Kimura (1997), for instance, found that agricultural land use in the Tokachi Plain on Hokkaido was determined by geological, geomorphic, and climatic conditions. Other studies have also examined the relationship between vegetation and geomorphic conditions; for example, Hirano (1998) demonstrated a decline of the beech (*Fagus* spp.) forest around the summit of Mt. Hinokiboramaru in the Tanzawa Mountains of central Japan. The decline was obvious on the gentle slope along the ridge around the summit and on the southern slope above an altitude of 1500 m.

The technique of vegetation classification by means of airphoto interpretation was formerly used for forest measurement (e.g., Taniguchi 1961; Watanabe 1970); however, this technique required high levels of manual labor. Automatic interpretation of aerial photographs has progressed gradually as a result of studies such as that of Kadmon and Haraki-Kremer (1999). Satellite remote-sensing techniques using indices such as NDVI have also gradually improved the interpretation of vegetation patterns.

In this historical context, forest monitoring research using remote sensing (e.g., Tsuyuki, 1995) and GIS-based research (e.g., Bessho et al., 2001) have recently been done to study vegetation change in suburban forests. In these studies, however, the relationships between vegetation change and features of the underlying landforms that were responsible for the observed changes were not discussed quantitatively, because the patterns of vegetation and landform in the suburban forest were too complex to be evaluated using the low-resolution digital data ordinarily provided by existing surveys.

To remedy this situation, we acquired a high-resolution (5-m-mesh) digital terrain model (DTM) and a time series of converted digital vegetation maps of suburban forests in the southeastern part of Seto City, Aichi Prefecture, central Japan. Data were obtained from aerial photographs by using a digital aerial photogrammetry technique (Sano 2000; Suzuki et al. 2001). The resulting high-resolution DTM adequately described the hill slopes of the suburban forest (Oguchi and Katsube 2000; Masaoka et al. 2003). Kimura et al. (2000) described the relationship between landforms and vegetation changes that occurred in 1949, 1977, and 1995 using these high-resolution digital data.

On the basis of this model, we identified the geomorphic conditions that determined vegetation change by using statistical values taken from a wide area. In this paper, we discuss how well our technique models the results of geoecological research using a high-resolution DTM and vegetation-type data from 1949, 1964, 1977, and 1995.

Data and Methods

The study area covered about 7.0 km^2 of the "Kaisho-no-mori" and "Hirokute-no-mori" forests in the southeastern part of Seto City (Figure 1). This area is west of Mount Sanage, which lies at the southwestern tip of the Kiso Mountain Range, and extends from the Sanage Mountains to the Nagakute hills. The Nagakute hills in the study area are divided into eastern and western parts by the flood plain formed by the Yata River and its tributaries. The eastern part of the Nagakute hills and Sanage Mountains (the "Kaisho-no-mori" area) are underlain by coarse- to medium-grained soils of granitic origin that have been well sheared and deeply weathered. The western part (the "Hi-

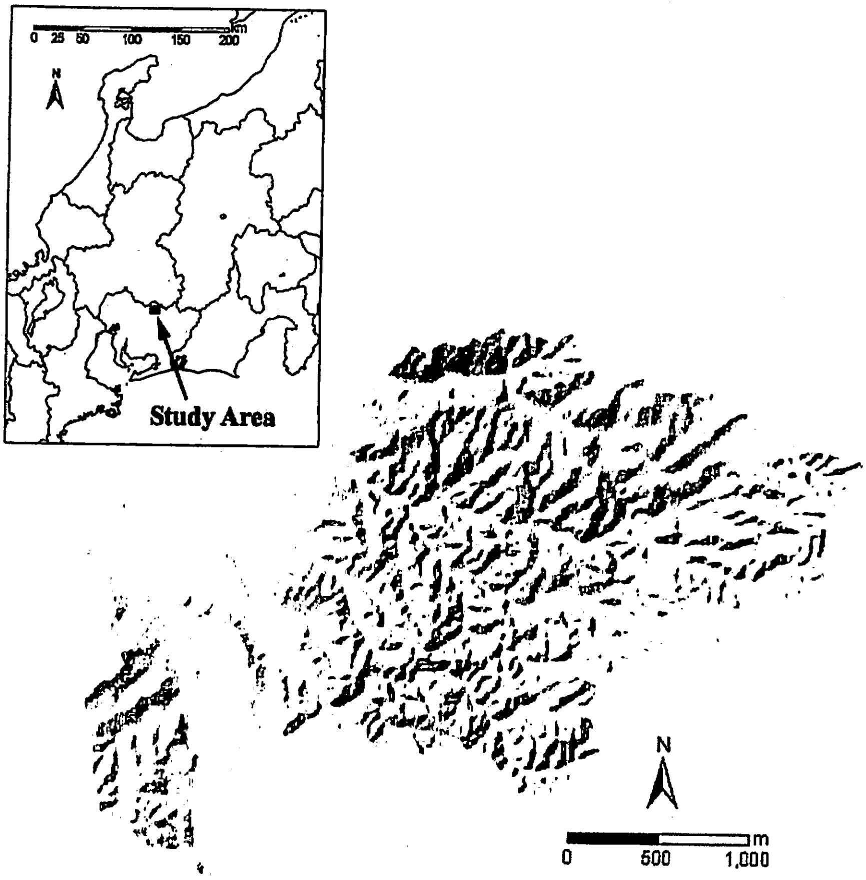

Figure 1. Shaded relief map of the study area.

rokute-no-mori" area) is underlain by a well-consolidated conglomerate of the Mizunami formation (Aichi Prefecture 1983). The "Kaisho-no-mori" area has a gentle northwest-facing slope with very shallow depressions and ridges. Just after the end of World War II, unforested terrain had expanded widely into the study area. This terrain is now rare along the ridge and the sides of the valley because of reforestation and recovery of the vegetation (Masaoka et al. 2003).

The study area represents the so-called "suburban forest", and is primarily hilly land covered by native deciduous broadleaved forest and artificial coniferous forest. The warmth index (Kira 1949) for this area, calculated from meteorological data recorded at nearby weather stations, is around 120 m·d. The potential natural vegetation of this area is laurel forest, but this kind of forest is currently limited in extent. The whole study area belongs to the same vegetation zone because the highest point reaches 408 m asl and the range in altitude spans only 320 m.

Vegetation and land-use data for the study area were obtained from aerial photographs from four periods.[1] Vegetation data were interpreted on the basis of aspects of the land cover, color, shapes of trees, and characteristics of the crowns of each species. Data were compiled as polygons in the GIS. Nomura and Nakajima (2000) distinguished 16 types of vegetational community and land-use, and we regrouped these into nine categories based on the kind of pieces and human impacts[2] (Table 1).

The 5-m-mesh DTM data for the background vegetation and land-use data were generated from a 1 : 2500-scale land-use planning map, and were revised on the basis of field observations. The study area, which included many small areas of undulating terrain, could not be successfully described by the 50-m-mesh DTM created by the Geographical Survey Institute (Oguchi and Katsube 1999). Thus, a high-resolution DTM such as the 5-m-mesh model in the present study is needed to show how geo-

Table 1. Description of vegetation and land-use categories
(revised from Nomura and Nakajima, 2000)

Category	Vegetation and land-use
A	Fir and hemlock forest
B	Evergreen broad-leaved forest
C	Deciduous broad-leaved forest
D	Pine tree forest
E	Bamboo tree forest
F	Cedar and cypress forest
G	Bare ground
H	Residuals and artificial pond
I	Cultivated field and cleared section

morphic conditions establish the framework for vegetation change. Geomorphic attributes of each part of the mesh, including the coordinates of position, slope gradient, slope aspect, profile curvature, and distance from a body of water, were then generated from the high-resolution DTM.[3] Last, vegetation maps of each community created from the original polygon data were transformed into a 278 637-point dataset with the same positions as those in the DTM.

Changing Patterns of Vegetation and Land-use

After considering all the data points within the study area, we found that significant changes in vegetation and land-use had occurred between the times the four sets of aerial photographs were taken. Figure 2 shows the distribution over the study area of each pattern of vegetation and the resulting land-use changes between the four photographic periods. (The pattern identifiers used in this figure are explained in Table 2. In this table, each of the four letters in the column labeled "Change" represents the vegetation community present in the corresponding airphoto survey.) We chose the 14 most frequently occurring patterns of change, which comprised 61.3% of the total number of points. The most common pattern (15.7% of the total) was Cu (unchanged type C), in which vegetation category C was present in all four airphoto surveys. This is the most representative vegetation type in this area because deciduous broadleaved forest was retained as a coppice to separate neighboring houses. The second most common vegetation type was IC (8.4%), in which vegetation changed from category I to category C. (This type includes three patterns of change: ICCC, IICC, and IIIC.) The remainder of Table 2 shows the other vegetation types that comprised 61.3% of the classified vegetation change in the study area, in order of decreasing abundance.

Our aim was to clarify the relationship between vegetation change and the geomorphic conditions in each point, but in areas where people have caused vegetation change through activities such as cutting down the forest or reforesting formerly unforested land, such activities can be expected to dominate any effects that might arise from the underlying geomorphic conditions of point. Similarly, we treated residential activity as an exception because it was not suitable for analysis as a contributor to natural vegetation change. Therefore, we focused our analysis on the IC, GC, IDC, and GDC types of vegetation and land-use change because we believed that these types would be most representative of natural vegetation transitions. We used a typical large forest as our basis for comparison.

Results and Discussion

In discussing natural vegetation change within the study area, it is best to consider the relationships between a series of vegetation changes and the underlying geomorphic conditions. We first compare the IC and IDC types and the GC and GDC types because both initial vegetation types (I and G) are unforested and both undergo the same pattern of succesion (culminating in vegetation type C). Although the members of these two pairs of change patterns share similar initial conditions (I or G) and end in the same category (C), they differ in whether they experienced an intermediate stage in category D (pine forest). Pine trees were planted on unforested terrain in this area in the late 1950s (Aichi Prefecture 2000). After the IDC and GDG areas had been neglected for many years, the advent of the pine forests improved the soils and benefited the natural environment, and typical forest (category C) gradu-

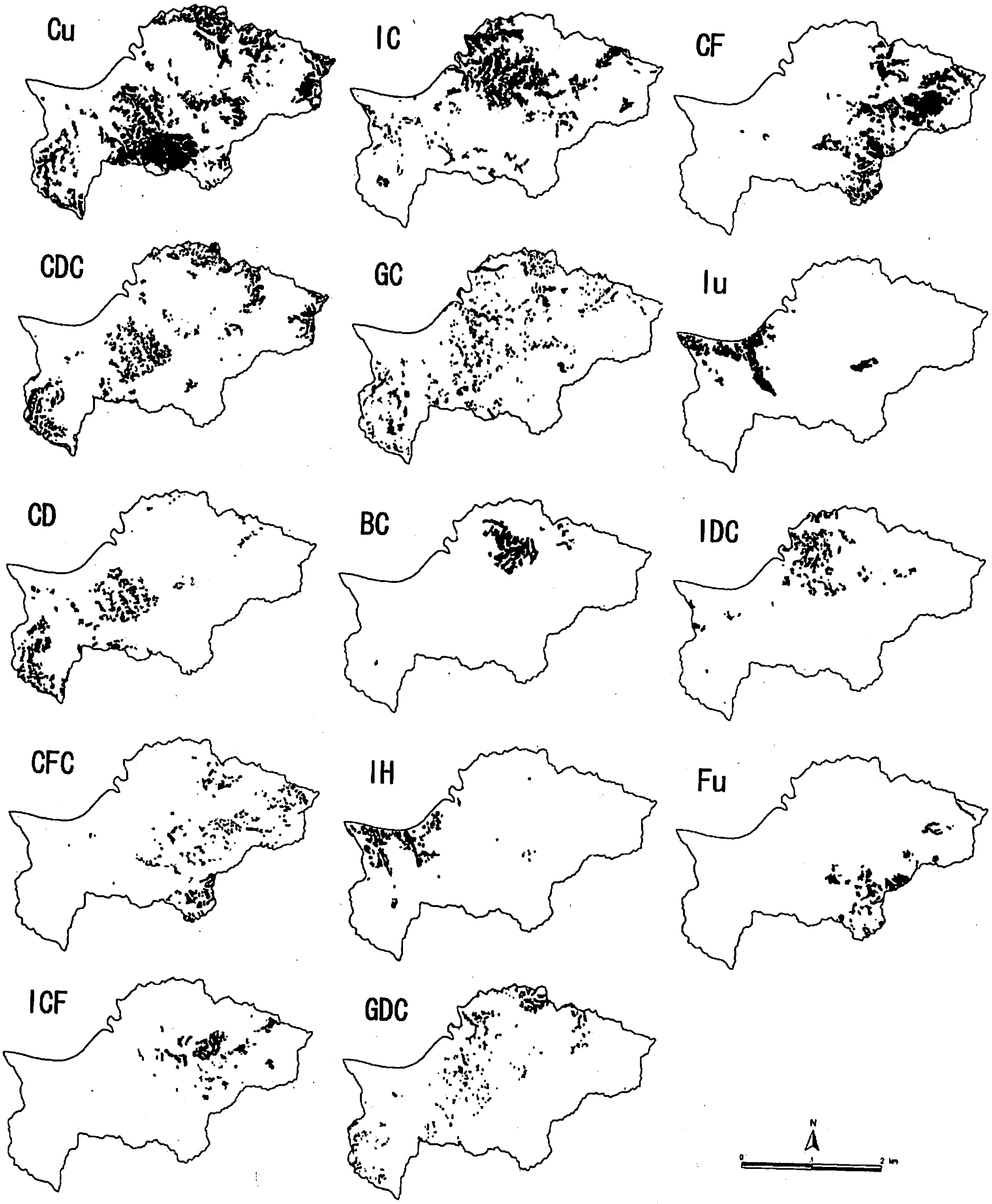

Figure 2. Distribution of each type of vegetation change. Letters represent the pattern of vegetation types defined in Table 2.

Table 2. Numbers and labels for each type of vegetation change and proportion. "Change" indicates the vegetational community (as defined in Table 1) during each of the four air photo surveys (1949, 1964, 1977 and 1995)

No.	Type	Change	Sub-total	Total	Total %	Accum.%
1	Cu	C C C C	43478	43748	15.7	15.7
2	IC	I I I C	351	23313	8.4	24.1
		I I C C	982			
		I C C C	21980			
3	CF	C C C F	3479	21838	7.8	31.9
		C C F F	8031			
		C F F F	10328			
4	CDC	C C D C	7808	15518	5.6	37.5
		C D D C	2772			
		C D C C	4938			
5	GC	G G G C	1098	9909	3.6	41.1
		G G C C	2406			
		G C C C	6405			
6	Iu	I I I I	9721	9721	3.5	44.6
7	CD	C C C C	3288	8660	3.1	47.7
		C C D D	2079			
		C D D D	3293			
8	BC	B B B C	0	6061	2.2	49.9
		B B C C	0			
		B C C C	6061			
9	IDC	I I D C	3	6047	2.2	52.1
		I D D C	1718			
		I D C C	4326			
10	CFC	C C F C	2069	5498	2	54.1
		C C F C	1719			
		C F C C	1710			
11	IH	I I I H	1733	5472	2	56.1
		I I H H	2332			
		I H H H	1407			
12	Fu	F F F F	5076	5076	1.8	57.9
13	ICF	I I C F	187	4948	1.8	59.7
		I C C F	2559			
		I C F F	2202			
14	GDC	G G D C	932	4554	1.6	61.3
		G D D C	909			
		G D C C	2713			

ally replaced the pine trees. On the other hand, areas classified as IC and GC made the transition to category C without the planting of pines (or, at any rate, if such planting did occur, the vegetation had changed to category C by 1965). Thus, polygons classified as IC and GC became, as a result of some geomorphic mechanism or mechanisms, suitable for the establishment of deciduous broadleaved forests without the need for an intermediate stage of pine forest. As shown below, we analyzed the mechanisms by which such geomorphic conditions influenced vegetation change.

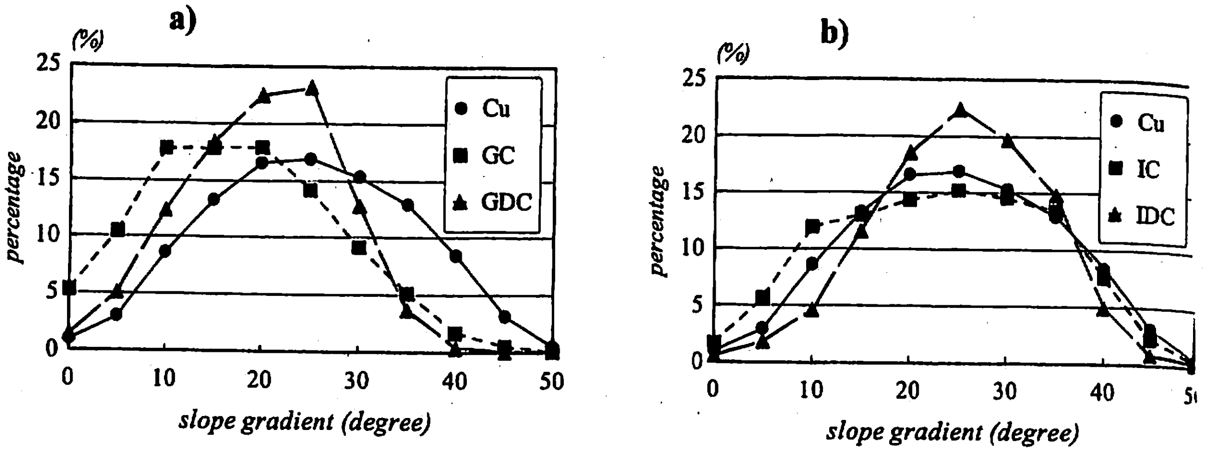

Figure 3. Slope gradient for each type of vegetation change.
a) GC, GDC, and Cu community types; b) IC, IDC, and Cu community types

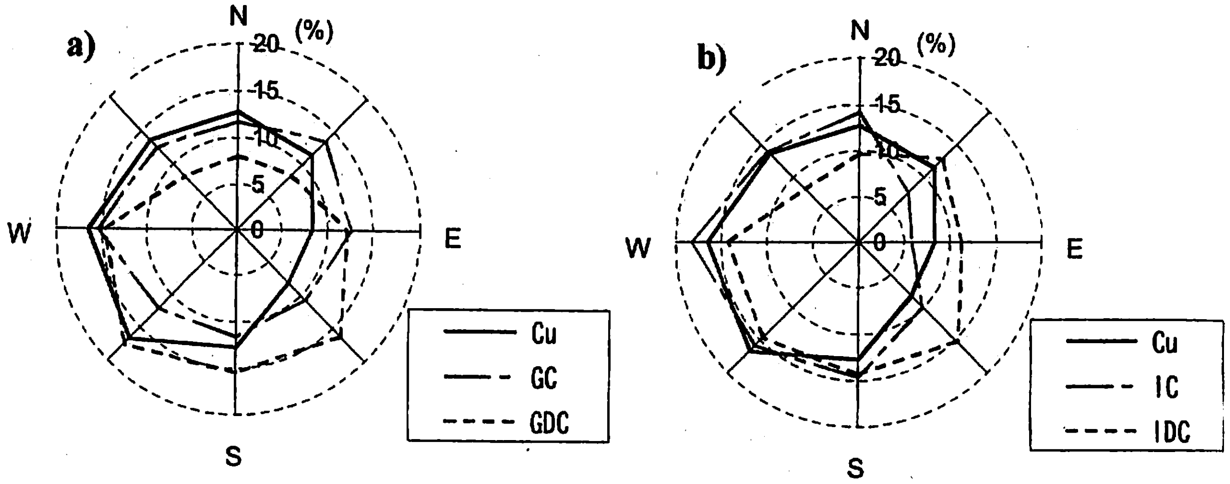

Figure 4. Slope aspect for each type of vegetation change.
a) GC, GDC, and Cu community types; b) IC, IDC, and Cu community types

Geomorphic conditions responsible for IC, IDC, GC, and GDC patterns

The distribution patterns of the IC, IDC, GC, and GDC community types appear in Figure 2. The results of the analysis of the geomorphic conditions for these four types are shown as a function of slope gradient (Figure 3), slope aspect (Figure 4), and distance from bodies of water (Figure 5).

Figure 3 shows the frequency distribution of the slope gradient for each vegetation type. The mean slope and its standard deviation for IC were 20.9°±10.8°, versus 22.7°±8.4° for IDC, 15.2°±9.5° for GC, and 17.4°±7.8° for GDC. The slope gradients for IDC and GDC were slightly steeper than those for IC and GC, respectively. On the steeper slopes, surface soil is eroded more easily, and the thinner layer of soil is more vulnerable to drying. Deciduous broadleaved trees (category C) prefer wetter environments than pine trees (Saitoh 1973), and for this reason IC and GC community types may prefer the gentler slopes. On the other hand, after pine trees (category D) have become established on a site, the soil is protected against erosion, soil moisture is retained better, even on steeper slopes, and the site conditions become suitable for succession to stands of deciduous broadleaved trees. For this reason, IDC and GDC community types gradually appear on the steeper slopes.

Figure 4 shows the distribution among eight compass directions of slope aspect for each of the vegetation patterns. IDC and GDC were more commonly found at locations with a

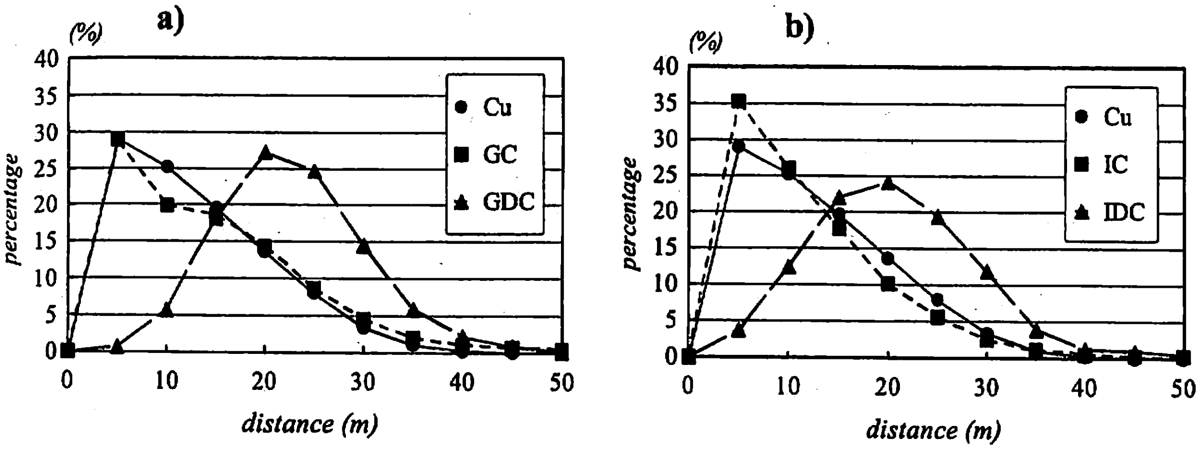

Figure 5. Distance from bodies of water for each type of vegetation change.
a) GC, GDC, and Cu community types; b) IC, IDC, and Cu community types

southern or eastern aspect than were IC and GC. In contrast, IC and GC were more commonly found at locations with northern and western aspects. Generally speaking, direct insolation on south-facing slopes in summer dries the soil, especially when there is little ground cover (as is the case in categories I and G). Because pines are more tolerant of dry conditions, people plant such sites with pines. It is relatively difficult for deciduous broadleaved forests to establish themselves directly on these sites, but once a pine forest has become established, less direct insolation reaches the soil. Soil moisture is then retained in the pine forests, creating moister soil conditions that eventually allow deciduous broadleaved trees to become established. Conversely, direct insolation is weaker on typical north-facing slopes and soil moisture is lost more slowly. Soil moisture would thus be retained better even on unforested sites (categories I and G), and deciduous broadleaved trees that require relatively higher levels of soil moisture would become established more quickly and directly on these slopes.

The distribution of distances from bodies of water appears in Figure 5. The mean distance and standard deviation was 45.5±15.0 m for GDC, 41.0±16.4 m for IDC, 29.9±21.1 m for GC, and 24.8±17.4 m for IC. Although the variation was large, the *t*-test indicated significant differences between IC and IDC, and between GC and GDC. It is reasonable to hypothesize that long distances from bodies of water mean drier conditions. If this is correct, locations with IDC and GDC patterns were drier. The discussion of geomorphically determined soil moisture is then similar to that for slope gradient and slope aspect. IC and GC areas are closer to bodies of water than are IDC and GDC areas, and are more likely to support deciduous broadleaved trees. Thus, category C communities would develop more easily on these sites.

Transition of the vegetation

In our analysis shown in chapter 3, the division for some community types was based on the transition of vegetation types over a 46-year period. The IC, IDC, GC, and GDC community types that were discussed in the previous section show probability distributions that reflect topology and an accommodation to natural environmental conditions when changes in the time series are considered in detail.

The number of sites with an ICCC pattern (21 980 points) is much greater than the number of IICC (982 points) and IIIC (351 points) sites (Table 2). This indicates that deciduous broadleaved forests formed as soon as cultivated fields were abandoned between 1949 and 1964. The change directly from category I to category C can be compared with the change from category I via category D (pine forest) to category C. Sites with an IDCC pattern were most common (4326 points), with IDDC next most common (1718 points) and IIDC uncommon (only 3 points). After the cultivated fields were abandoned between 1949 and 1964, pines were planted in this area, and the pine forests

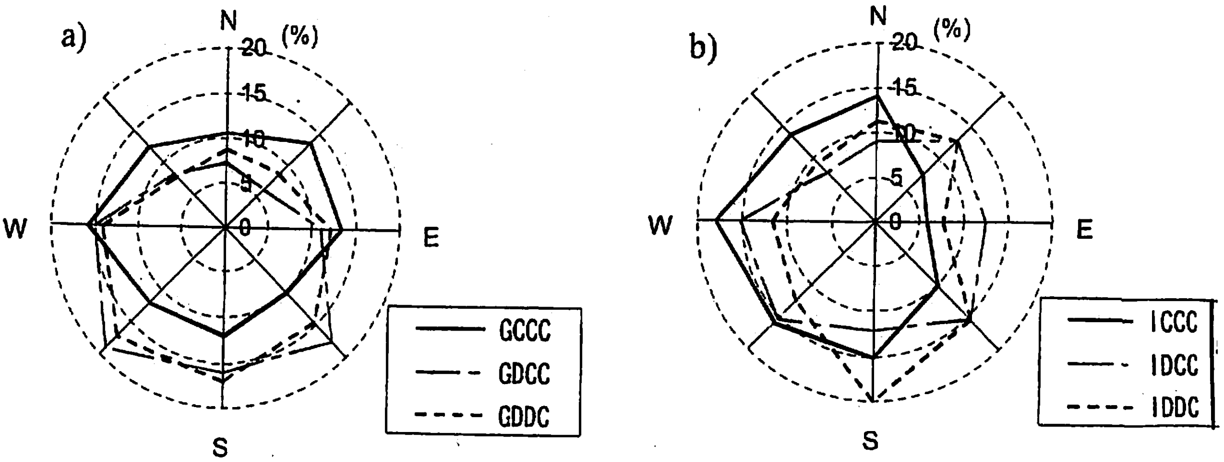

Figure 6. Slope aspect for each type of vegetation change.
a) GCCC, GDCC, and GDDC patterns of change; b) ICCC, IDCC, and IDDC patterns of change

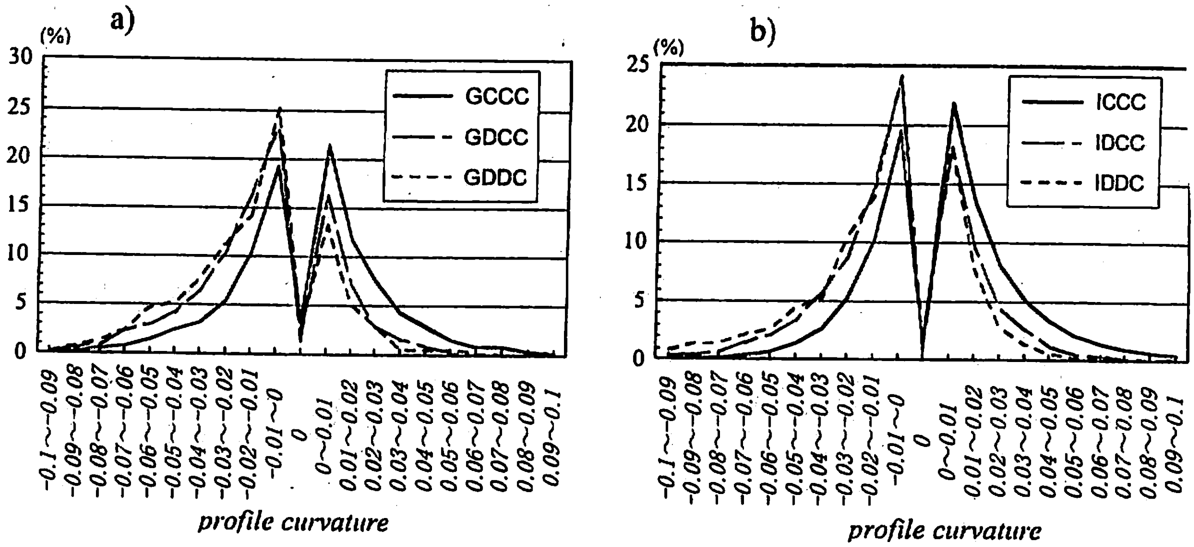

Figure 7. Profile curvature for each type of vegetation change.
a) GCCC, GDCC, and GDDC patterns of change; b) ICCC, IDCC, and IDDC patterns of change

were replaced by deciduous broadleaved forests relatively quickly. The pattern is different for the GC type, for which the number of sites with a GCCC pattern (6405 points) was greater than the numbers of GGCC (2406 points) and GGGC (1098 points) sites (Table 2). Some of the unforested ground created by deforestation would succeed naturally to deciduous broadleaved forests between 1949 and 1964. This transition is comparable to the natural succession from bare ground to deciduous broadleaved forest through an intermediate artificial pine forest.

Especially on unforested ground in the suburban forest of the Yata River watershed in the present study area, pine planting was repeated throughout the 1950s by the Aichi Prefecture government as an urgent project. This is why many areas of bare ground and abandoned fields were replaced by pine forests (category D). Sites with a GDCC pattern were most common (2713 points), with smaller amounts of GDDC and GGDC sites (909 and 932 points, respectively). Pine trees were planted on unforested ground from 1949 to 1964, after which natural succession accelerated. The transition from pine forest to deciduous broadleaved forest occurred relatively quickly, probably because the pine forest mitigated the relatively severe natural environment.

The difference in the patterns of transition between IC and IDC and between GC and GDC lies in whether an intermediate category D community existed. Though all the pine forests in this area were planted, we analyzed the natural environmental factors for sites in this category as a function of topography. The slope gradient was similar between IC and IDC and between GC and GDC, but IC and GC sites without intermediate category D communities were more likely to lie on north-facing slopes (Figure 6) and have a more positive profile curvature (Figure 7)—that is, these sites were concave upward and thus retained soil moisture better. IDCC and IDDC sites and GDCC and GDDC sites, which had an intermediate category D community, exhibited similar patterns of change, but the time series differed. Slope gradients and slope aspects were similar between IDCC and IDDC sites and between GDCC and GDDC sites. The IDCC and GDCC sites, which had a shorter intermediate period with category D communities than in the IDDC and GDDC sites, tended to have a positive profile curvature. This means the slope curve on these sites was convex upward, promoting runoff, but the points were nearer to streams, which kept soil moisture levels relatively high. The net result of these factors is that deciduous broadleaved forests become established on unforested ground and in abandoned fields because the soil moisture becomes wetter after pine forests have become established.

Succession (recovery) to C type forests inferred from geomorphic factors

In ecological studies, the relationship between topography and the distribution, growth, and succession patterns of the vegetation has been discussed (e.g., Ishizuka 1977; Kikuchi 2001). Although topography does not directly influence vegetation, we must pay attention to intermediate factors that are related to topography through geomorphic processes such as insolation, soil moisture regimes (Ishizuka 1977), and the disturbance regime (Koizumi 1992; Kikuchi 2001).

As described earlier, it is thus clear that the geomorphic attributes calculated from our DTM, such as slope gradient, slope aspect, profile curvature, and distance from bodies of water, correlate strongly with the type of vegetation change. Geomorphic conditions such as a steep slope gradient, south-facing convex slope, and long distance from bodies of water, control the vegetation change from planted pine forests to deciduous broadleaved forests. The most common results of these geomorphic conditions are as follow:

(1) The topsoil layer recovers more slowly on convex and steep slopes.

(2) Strong insolation tends to dry south-facing slopes faster, especially when there are thin topsoil layers.

(3) Moisture is more available near bodies of water at all times. As the distance from a stream increases, the soil tends to gradually grow drier.

Japanese red pine (*Pinus densiflora*) trees have relatively simple demands in terms of climate and soil, and can thus become established naturally on difficult sites. They are shade-intolerant trees and thus grow faster in exposed, dry areas than do broadleaved deciduous trees (Yoshioka 1959). In contrast, the oaks (*Quercus serrata*) that make up the deciduous broadleaved forest grow better than Japanese red pine under wetter conditions (Saito 1973). Almost all the bedrock in the study area is grus. In areas with thin soils overlying the bedrock, rain is retained only briefly in the soil layer, and immediately penetrates to the bedrock (Iwashita et al. 1994, etc.). This is why soils in the study area tend to be drier than soils that originated from weathering of sedimentary rocks such as sandstone and mudstone (Koide 1952).

As a result, the planted pine forests (category D) that replaced abandoned cultivated fields and deforested areas (category I and G) after the 1940s helped soils to recover, resulting in succession to deciduous broadleaved forests (category C) at a rate determined by the geomorphic conditions of the site, which were in turn determined by soil moisture levels. On convex slopes in areas with granitic soils, where the soil is usually dry and weakly developed, pine forests enriched the soils and improved the soil moisture environment. Subsequently, deciduous broadleaved trees invaded these sites more easily to produce IDC and GDC patterns. Unforested areas classified into categories I and G in 1954 on north-facing, concave-up slopes with relatively good soil moisture conditions recovered to deciduous broadleaved forest (category C) before the pines were planted in the early 1950s. In other cases, pines planted in the early 1950s quickly succeeded to category C before aerial photographs were taken in 1964.

Conclusions

The "Kaisho-no-mori" and "Hirokute-no-mori" forests in the southeastern part of Seto City, Aichi Prefecture, were chosen as typical suburban forests of Japan. Analysis of the relationships between geomorphic conditions and vegetation change were performed using a high-resolution 5-m-mesh DTM and a GIS.

This analysis confirmed that a geographical gradient of soil moisture conditions, which are determined by slope gradient, slope aspect, and profile curvature, influenced the speed of succession from planted Japanese red pine forest to deciduous broadleaved forest and the distribution of different patterns of vegetation change. That is, soil moisture conditions control the transition to deciduous broadleaved forest. It was already known as a result of previous ecological and geoecological studies that Japanese red pines were a major component of the forests in dry areas (Yoshioka, 1959). In the present study, we confirmed the previous results by re-examining the geographical statistics and conducting the analysis with high-resolution data and GIS methods, which proved to be an effective means of conducting geoecological studies at this scale. These results suggest that this form of analysis will be suitable for analyzing other areas using aerial photographs.

To describe the scale of the landforms handled in the present study, a high-resolution DTM is needed. The former 50-m-mesh DTM had insufficient resolution to reveal differences between the geomorphic conditions that affect soil moisture over large areas, but a high-resolution (5-m-mesh) DTM let us analyze natural environmental factors of the suburban forests in detail; these factors included slope gradient, slope aspect, profile curvature, and the distance from the nearest body of water. The intermediate factors responsible for the change in vegetation communities originated from these geomorphic conditions and their impac could be estimated. This means that large-scal geoecosystems can be analyzed by high resolution DTM. This method is thus an important tool for predicting vegetation distribution and patterns of succession. The method als simplifies and broadens the scope of using GI in future studies of the relationships betwee vegetation change and landforms.

In the future, we plan to perform a multivariate analysis with many different natural environmental variables, such as landform, soil, and climate, as well as with human-social variables such as accessibility to villages, so as to bette quantify the relative contribution of each factor.

Acknowledgments

Our special thanks are due to Mr. T. Nomura, Mr. M Nakajima, Mr. M. Yuhara, and Mr. M. Hirose (Taman Consultants Co., Ltd.) for creating the database used in our study. We also thank Prof. N. Handa (Aichi Prefectural Univ.), Dr. T. Oguchi (Univ. of Tokyo), Dr Y. Onda (Tsukuba Univ.), Dr. K. Yamamoto (Nagoya Univ.), Dr. T. Kumamoto (Okayama Univ.), Mr. H Sugimori (Soken Co., Ltd.), and Mr. N. Masaoka (Hiroshima-Gakuin High School) for their helpful suggestions during the REGIS meeting. The manuscrip was improved by the critical comments of anonymous reviewers. The research described in this paper was supported in part by grants from the Aichi Prefectural Government and Grants-in-Aid for Scientific Research from Japan's Ministry of Education, Culture, Science, Sports, and Technology (Grant No 11794031).

(Received 13 May 2004)
(Accepted 1 December 2004)

Notes

1. The vegetation data were obtained from monochrome aerial photographs of about 1 : 14 000 scale taken in 1949 by the U.S. military, color photographs of about 1 : 10 000 scale taken in 1965 and 1977 by the Geographical Survey Institute in Japan, and color photographs of about 1 : 8000 scale taken in 1995 by the Seto City Government.
2. "High deciduous broadleaved forest" and "middle or low deciduous broadleaved forest" appear as the same kind of forest, so we merged them into "deciduous broadleaved forest" (category C). "Old afforested Cedar and Cypress" and "young afforested Cedar and Cypress"

were merged into "afforested Cedar and Cypress" as category F. "Wasteland, and weed community," "landslide," and "bare ground" were merged to "unforested ground" as category G, because these were places where the vegetation is not formed by natural processes, and it is possible for change to occur later. "Residential land" and "artificial ponds" were merged to "residuals and artificial ponds" as category H. Finally, "cultivated field" and "cleared section" were merged to "cultivated field and cleared section" as category I because they are nonforested areas formed by human impacts.

3. The geomorphic attributes (position coordinates, slope gradient, slope aspect, profile curvature, and distance from a body of water) were calculated as follows: The gradient (G) and the aspect (A) of the slope at each point were calculated using the algorithms provided by the commercial GIS software *Surfer 7* (Golden Software Inc.). The profile curvature (PC) was also calculated using *Surfer 7*. If the altitude of a point (x, y) is h, the following equations describe G, A, and PC at that point:

$$G=\arctan\sqrt{f_x^2+f_y^2}$$

$$A=\arctan\left(\frac{f_y}{f_x}\right)$$

$$PC=\frac{f_{xx}f_x^2+2f_{xy}f_xf_y+f_{yy}f_y^2}{(f_x^2+f_y^2)(1+f_x^2+f_y^2)^{3/2}}$$

where,

$$f_x=\frac{\partial h}{\partial x},\ f_y=\frac{\partial h}{\partial y},\ f_{xx}=\frac{\partial^2 h}{\partial x^2},$$

$$f_{xy}=\frac{\partial^2 h}{\partial x\partial y},\ f_{yy}=\frac{\partial^2 h}{\partial y^2}$$

PC determines the rate of change of slope along the slope's prevailing direction at that point. Negative values represent slopes that are convex upward, and indicate an accelerated flow of water over the surface. Positive values represent slopes that are concave upward, and indicate a reduced flow of water over the surface (Golden Software Inc. 1999). Position coordinates represent a vector quantity for the slope, transformed from G and A (which are scalar values). This value is used to compare the slope direction with the direction of insolation. Distances from the nearest body of water were calculated using the algorithms provided by the commercial GIS software *ArcView* 3.2a (ESRI Inc.) as follows. First, a channel network was generated from the DTM using the "Hydrologic Modeling v1.1" extension with a minimum cell number of 100 (=2500 m^2 per cell). Next, the distance between the streams generated by this approach and each point was calculated using 10-m-interval buffers.

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