The Incidence of *Gremmeniella abietina* in Relation to Topography in Southern Finland

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Field data of the 8th National Forest Inventory (NFI) from southern Finland and digital elevation models (DEMs) were used in this study. Damage due to *Gremmeniella abietina* increased slightly with an increase in absolute elevation in mineral soils. Severe damage increased almost linearly with an increase in elevation in mineral soil plots. The mean elevation in the tract area (the 7 km×8 km area surrounding the plot) was more strongly correlated with the disease than the elevation of individual plots. The relative altitude of the plot was important: the disease was most severe in the plots situated lower than the mean elevation of the tract area, especially in the peatland plots. In this group, the damage increased linearly with an increase in absolute elevation.

According to detailed DEMs in the most diseased areas, steepness of the slope was negatively correlated with the disease. The aspect of the slope had a weak influence. On mineral soils, the disease was most common in south-facing slopes. The microtopography was not as important for the disease occurrence as the relative elevation of the plot.

The disease frequencies were very similarly related to the three most common types of surface features (channels, ridges and planar regions) within the 50-m scale. At the cell size of 100 metres, the disease was more common in channels than in ridges, except in mineral soil plots.

Topographic variables only partly explained the regional patterns in the occurrence of this disease. The disease was frequent on upland areas, but, on the other hand, it was also common on lowland areas. The most diseased areas studied in detail differed very much from each other with respect to topography and the disease incidence.

Keywords *Gremmeniella abietina, Pinus sylvestris*, forest inventory, topography, digital elevation models
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1 Introduction

Scleroderris canker of conifers caused by the ascomycete fungus *Gremmeniella abietina* (Lagerb.) Morelet has been known for more than one hundred years in Europe. In southern Finland, it is the most common fungal disease in forests dominated by Scots pine *(Pinus sylvestris* L.). According to the 8th National Forest Inventory (NFI), disease symptoms were recorded in 10.5% of Scots pine stands, on more than 690000 hectares during 1986–1992 in southern Finland. The disease was clearly spatially clustered. It was almost twice as common on peatlands than on mineral soils (Nevalainen 1999).

An epidemic of this disease requires that the host trees, here Scots pines, are predisposed. If the trees are of local origin, meteorological factors and site conditions determine the degree of predisposition. Epidemics are common after cold and rainy growing seasons (Aalto-Kallonen and Kurkela 1985, Uotila 1988). Frost damage is an important cause for the differences in susceptibility (Dietrichson 1968). The susceptibility of pines is increased in shaded or dense stands (Read 1968, Niemelä et al. 1992, Nevalainen 1999). It has even been proposed that air pollution can be one of the factors that promote the disease (Bragg and Manion 1984).

The topography of a site, i.e. the configuration of a surface including its relief and the position of its natural and manmade features, is one of the factors that can promote infections by *Gremmeniella abietina*. Most of the disease studies have been conducted in one or a few stands in disease centres. The small-scaled studies have regularly shown that typical sites for the disease are river valleys, shaded, north-facing slopes, kettle holes in ridges, or other local depressions, stand edges and so on. These are places where the humidity is higher than in the surroundings, and cold air tends to concentrate because of the topography or the structure of forest cover, i.e. the microclimate is favourable for the infection and dissemination of the pathogen and for the predisposition of the host (Read 1966, Dorworth 1972, 1973, Aalto-Kallonen and Kurkela 1985, Kaitera and Jalkanen 1995). There are very few, if any, large-scaled, representative studies, except the field study by Sairanen (1990) in Middle Finland. The most serious damage in her study area occurred in the depressions and valley bottoms.

While the local studies usually show a negative correlation with disease intensity and local elevation, in some regional studies the disease has been recorded as severe in upland areas, e.g. in Norway (Kohh 1964).

Scots pine (Lähde 1974) and lodgepole pine (*Pinus contorta* Dougl ex Loud.) (Witzell and Karlman 2000) are predisposed in fine-textured soils, which may have been formerly spruce stands. Soil texture is often related to topography, because, e.g. in southern Finland the finest soil material has accumulated on the lowest parts of the terrain due to glaciations. Only supra-aquatic hilltops still contain large proportions of fine fractions, and this, with the more extreme microclimate, may be one of the factors affecting the susceptibility of these sites.

Terrain-related variations in temperature, precipitation, and solar insolation affect forest composition and structure (Waring and Schlesinger 1985). The surface geometry is a fundamental feature when describing the topographic character of a point on a land surface. A digital elevation model (DEM) is a digital file of terrain elevations for ground positions at regularly spaced horizontal intervals. For the calculation of the terrain parameters, a mathematical function $z = f(x, y)$ is fitted to the surface. A local surface interpolation is made using usually a 3×3 submatrix of the DEM with the point of interest in the centre (Zevenberg and Thorn 1987). The gradient at a specified point, and therefore its slope and aspect, results from the solving of the first derivative of the function at this point. The curvature is gained by the second derivative and can be divided into its directional parts. Curvature of the slope can be convex, flat, or concave. Profile curvature is the down-slope curvature of the slope, and thus, it describes the pathways of, e.g. water and depositional material. Plan or tangential curvature is the curvature transverse to the slope.

Slope and aspect have frequently been used also in forested vegetation classifications (e.g. Vogelmann et al. 1998). Different primary indexes have also been developed based on the first and second derivatives. For example, McNab (1989) used a terrain shape index (a convexity/concavity index) to relate tree height to land surface shape. Secondary attributes, or compound attributes, result from combinations of primary attributes and quantify the context of points or describe the variability of processes. Soil water content has been most commonly described by the secondary terrain attribute, the wetness index. For a review of the many applications of these methods, see Moore et al. 1991. There is a multitude of methods to extract (identify) morphometric features, or landscape forms, from continuous surfaces. Elevation, slope, aspect, profile and plan curvature are the most often used parameters. In addition, longitudinal curvature (intersecting with the plane of the slope normal and aspect direction), cross-sectional curvature (intersecting with the plane of the slope normal and perpendicular aspect direction), maximum curvature and minimum curvature (in any plane) have been used (Young 1978, Evans 1980, Douglas 1986, Li and De Dapper 1996). Wood (1996) has developed a system for surface feature classification. His program parameterises DEMs using first and second derivatives of quadratic surfaces. It then combines morphometric parameters (slope, longitudinal curvature, cross-sectional curvature, maximum and minimum curvature) to yield six categories of surface features (peaks, ridges, passes, plane surfaces, channels and pits). It is assumed that all locations that have a non-zero slope must be either planar, form part of a channel or form part of a ridge. Pits/peaks and passes are only assumed to occur where the slope is zero. Wood's classification system can be used at multiple scales.

The aim of this study is to investigate the possible effects of topography on the regional occurrence of *Gremmeniella abietina*, based on a large representative field sample, and to describe the topographical and geographical characteristics of the diseased areas.

2 Material and Methods

The present study is based on the 8th National Forest Inventory (NFI). The 8th NFI (1986–1994) was a systematic field sampling of the forest resources covering the entire area of Finland. Field plots were arranged in detached 21-plot clusters, called tracts, the plots forming a half-square. In southern Finland the distance between the tracts was 8 km × 7 km (south-north × west-east directions) and the distance between the plots was 200 metres. All the field plots were temporary angle gauge plots, Bitterlich plots. The relascope factor was 2. Altogether 24 544 pine-dominated stands on forest land, from the years 1986–1992, in southern Finland were included in this study. By definition, *forest land* has the potential capacity to produce a mean annual increment of at least 1 m^3/ha stemwood, over bark, given an optimum tree species mixture, growing stock volume and prescribed rotations.

Almost 100 variables were assessed or measured in the 8th NFI at the stand, tally tree or sample tree levels. The field inventory also contained data on forest injuries, e.g. damage symptoms, their causes and apparent severities (degrees of damage). Only standwise damage data was used in this study. Codes for registering damage symptoms, degrees of damage and causal agents of damage are presented in Table 1. In the statistical analyses, the original degree of damage (Table 1) was recorded into three classes: 0 = no *Gremmeniella* infection 1 = slight infection 2 = at least moderate infection. This transformed degree of damage is cited as 'disease degree' in the text. The disease percentages cited below indicate the percentage of all Scots pine stands that were diseased. In the calculations, the variable 'main site class', which divides forest, scrub and waste land into mineral soil and three main peatland classes (spruce/ hardwoods peatland, pine peatland, open bog) was recoded into the variable PEATL, the codes being 1 = mineral soil 2 = peatland. Elevation of the stand in which the centre point of the plot was situated (referred to as the centre point stand) was coded to the nearest 10 m in the field inventory (variable PLOT_ELEV in this study). A more detailed description of the inventory system and of the most important variables can be found in Nevalainen (1999).

A nationwide elevation data set, provided by the National Land Survey of Finland, was partly used to study the effects of elevation. The detailed digital elevation model (DEM) is calculated from the contour lines of the basic map by triangulation network interpolation into a grid model where the grid cell size is 25 m × 25 m, and the eleva-

Table 1. 8th National Forest Inventory of Finland 1986–1992. Description of the variables and codes used for assessing forest damage.

Variable	Description	Codes
Damage symptom	Visual symptoms of injury (stand and sample tree levels)	0) no damage 1) dead standing tree 2) fallen tree or standing stem broken below the crown 3) decay 4) stem or root damage within 1 m from the stem 5) broken or dry top (in the upper half of the crown) 6) other crown malformations 7) defoliation 8) discoloration of the needles or leaves. Letters A–F are used for symptoms 1–6 if the injury is older than five years
Causal agent of damage	Primary cause of injury (stand and sample tree levels)	0) unknown 1) wind 2) snow 3) other meteorological or soil factors 4) competition between plants 5) harvesting scars 6) other human activity 7) voles 8) moose 9) *Tomicus* sp. 10) Other insects 11) *Cronartium* sp. 12) *Gremmeniella abietina* 13) Other fungi
Degree of damage	Importance of the damage (stand level)	0) slight damage, symptoms observed, but the damage does not reduce the silvicultural quality of the stand 1) moderate, the silvicultural quality of the stand is reduced by one class 2) severe, the stand quality is reduced by more than one class 3) complete, artificial regeneration is required
Silvicultural quality of the stand	The division is based on species composition, density and technical quality of the dominant tree storey	1) good 2) satisfactory 3) adequate 4) under-productive: the yield is so low that the stand should be regenerated before maturity

tion is expressed as decimetres. It is the most accurate nationwide material on elevations. This model was used on the eight most diseased areas (the size of each area was 80 km × 80 km at maximum) (Fig. 1). The field data in these areas consisted of 7136 plots.

The variables computed for the plots in the most diseased areas were as follows:

– SLOPE
– ASPECT
– SLOPE and ASPECT were combined into a joint variable WARM (Kuusipalo 1985). This variable describes the microclimatic conditions of the site, and has its minimum values (0) on steep north-east slopes, maximum values (5) on steep south-west slopes and intermediate values in the various combinations of steepness and aspect lying between the two extremes
– REL_ELEV_S, relative elevation of the plot compared with its immediate surroundings, i.e. the elevation of the plot pixel minus the mean elevation of the eight surrounding pixels (the diameter of the area being 75 metres, describing local relative elevation. This variable is, in essence, very similar to McNab's (1989) terrain shape index
– REL_ELEV_150, relative elevation of the plot compared with the mean elevation of an area with a 150-metre diameter around the plot
– REL_ELEV_300, the same as REL_ELEV_150, but the diameter was 300 metres
– REL_ELEV_600, the same as REL_ELEV_150, but the diameter was 600 metres
– MIN_ELEV, minimum elevation within 180 m of the plot
– MINE_DIST, the distance of the minimum elevation pixel from the plot
– surface morphology features were identified with the methods proposed by Wood (1996), with his

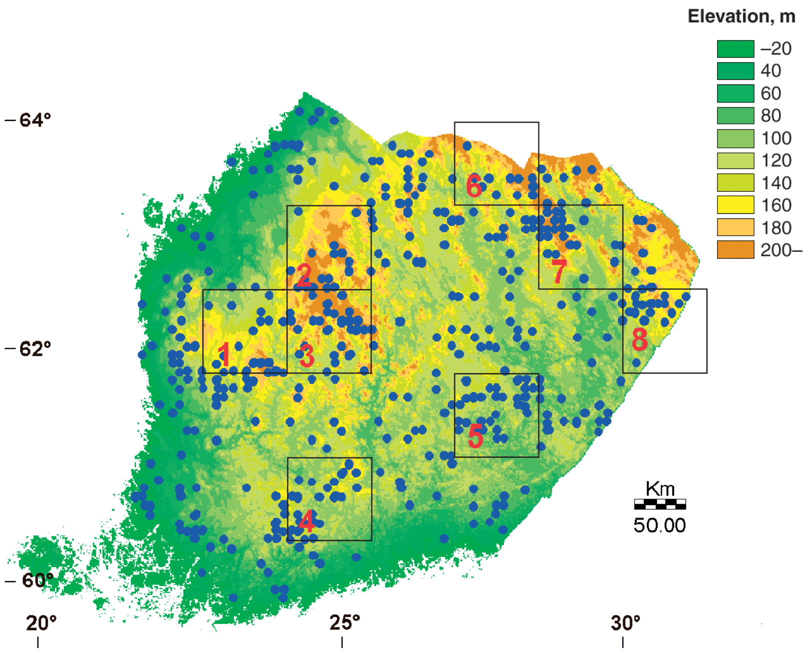

Fig. 1. The elevation classes in the 1 km × 1 km DEM in the study area. The plots where the disease was severe enough to reduce the silvicultural quality of the stand are marked with black dots. The eight most diseased areas, where a detailed 25 m × 25 m DEM was analysed, are also shown.

Landserf program. Instead of the normal 25 m × 25 m pixels, two different scales, 50 m × 50 m and 100 m × 100 m pixels were used in these calculations. The actual scale used in calculations varied from 50 m to 150 m at the smaller pixel size. Only the three most common surface features (ridges, planes and channels) were analysed in this study, because the summed frequencies of the other three types (pits, peaks and passes) were only about 0.2%. The most common features are described as follows:

Ridge: a point with no convexity/concavity

Plane: a point that does not lie on any surface with concavity or convexity

Channel: a point that lies in a local concavity that is orthogonal to a line with no concavity/convexity

– the variable LAPLAC was calculated with the Surfer-software (version 7, Golden Software, Inc., Colorado, USA). The Laplacian operator provides a measure of discharge or recharge on a surface. In grid files generated with the Laplacian operator, recharge cells (net flow into the cells) are positive, and discharge cells (net flow out of the cell) are negative. E.g. groundwater is a physical quantity whose local flow rate is proportional to the local gradient. The Laplacian operator is a good approximation of the profile curvature (Li and De Dapper 1996)

– the variable LAPPOS was the value of the nearest positive (recharge) cell, computed the same way as for the variable LAPLAC, but for the 50 m × 50 m pixel size

– the variable LAPDIST depicted the distance of the nearest LAPPOS cell from the target cell. LAPDIST was computed for the pixel size of 50 m × 50 m.

An example of the plot layout and some of the topographic variables are presented in Fig. 2.

In addition, a coarser DEM with 1 km × 1 km pixel size and the elevation coded to the nearest

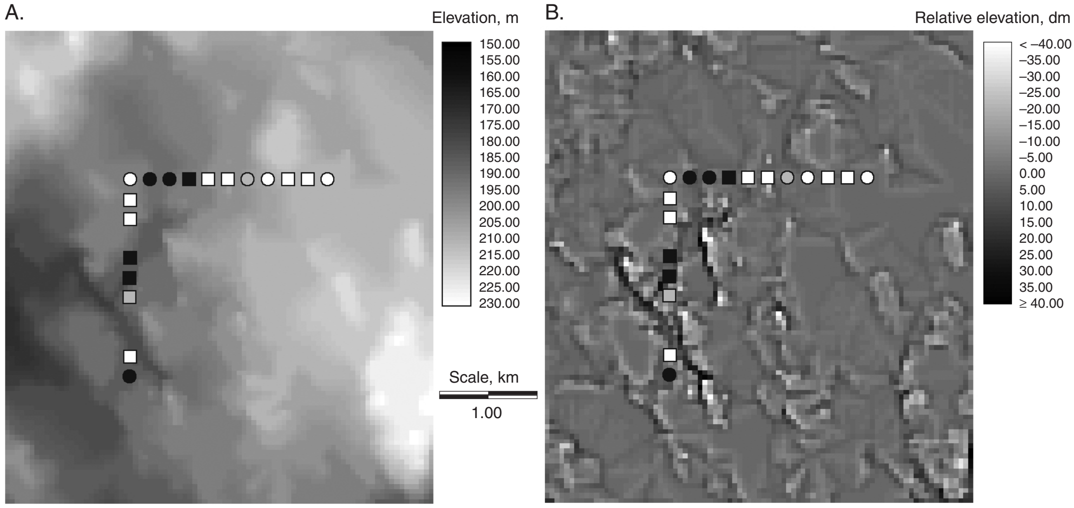

Fig. 2. Example of the location of one field tract in Multia, middle Finland and the disease degree in Scots pine stands, in main site classes. Plot symbols: Squares = mineral soil plots, circles = peatland plots, white = no infection, grey = slight infection, black = severe to complete infection.
a) The disease degree draped on the 25 m × 25 m DEM
b) The disease degree draped on the image of the relative elevation of the pixel compared the mean elevation of eight surrounding pixels (McNab's terrain shape index). In the pixels with a negative value the elevation is less than in the eight surrounding pixels.
c) The disease degree draped on the image of surface features extracted with the Landserf program.

metre was obtained from the National Land Survey of Finland for the whole study area. This data consisted of 10 011 cells, 1 km × 1 km each, with at least one Scots pine- dominated plot on forest land. The following variables were computed for this coarser grid:

– the variable TRACT_ELEV, the mean elevation of the tract area (an area of 8 km × 7 km each)
– the variable REL_ELEV_T, depicting the relative elevation of the plot compared with the elevation of the tract area, was calculated by subtracting TRACT_ELEV from the original elevation record of the plot (variable PLOT_ELEV)
– the variable REGREL_ELEV, regional relative elevation, was computed by filtering the DEM with a mean filter (kernel size 11 × 11 cells) and by subtracting the filtered value from the original DEM pixel. This variable was computed to reveal the possible influence of regional water divides on the occurrence of the disease.

Unless stated otherwise, all the GIS-based operations were performed with the IDRISI32-software package (Clark Labs, Clark University, Worchester, USA). The SPSS for Windows-package, version 9 (SPSS Inc., Chigaco, USA) was used in the statistical analysis. Non-parametric multiple comparisons after the normally used Kruskal-Wallis test were computed according to Conover (1980).

3 Results

According to the original plot elevation records in the whole material, *Gremmeniella abietina* damage increased slightly with an increase of the elevation of the plot in mineral soils. Damage that was severe enough to reduce the silvicultural quality of the stand (degrees 1–3, moderate to complete damage) increased almost linearly with an increase of the elevation of the plot in mineral soils. In peatland plots there was no clear trend in this respect. In these plots the disease was common in the lowest (0–20 m) elevation class. For both main site classes the disease was also quite common in the intermediate elevation classes (the 100-m and 120-m classes) (Fig. 3). The frequencies of damage degrees 0–2 (see above) in the 20-m elevation classes were statistically different on mineral soils and peatlands ($H = 60.070$ and 50.196, $p = 0.000$, $N = 18\,078$ and 6466, respectively). The Spearman correlation coefficients between the absolute elevation and the degree of *Gremmeniella* damage were positively significant for all the plots and mineral soil plots, but not for peatland plots. It should be noted however, that the mean elevation in the tract area (TRACT_ELEV) was more strongly correlated with the disease degree than the elevation of the plots (Tables 2–3).

For the whole data set, the relative altitude compared with the elevation of the tract area (the variable REL_ELEV_T) was most strongly correlated with the disease degree. This phenomenon was most conspicuous in the peatland plots (Tables 2–3). The correlation was negative, i.e. the disease was more frequent in plots which were situated lower than the mean tract area altitude (i.e. variable REL_ELEV_T had a negative value of more than one metre) as compared with the plots which were situated higher (the value of REL_ELEV_T was more than plus one metre).

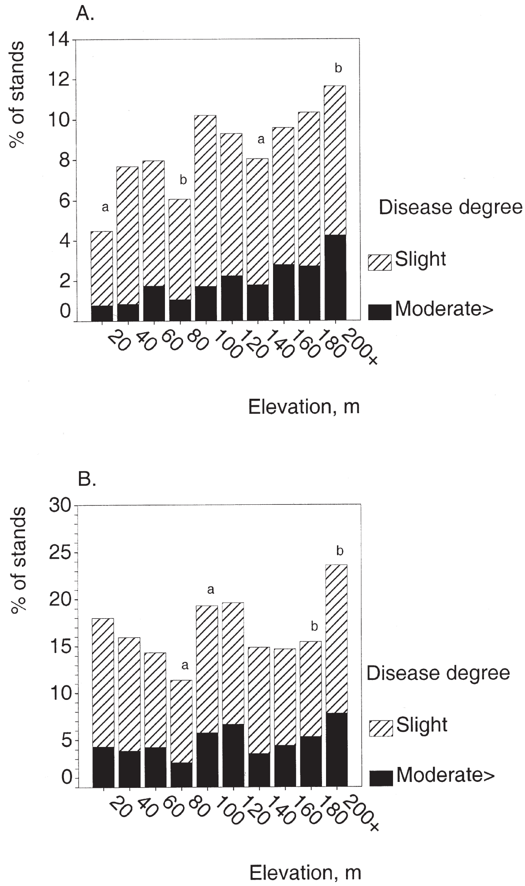

Fig. 3. The frequency of *Gremmeniella abietina* damage in Scots pine stands related to elevation classes recorded in the field inventory. a. Mineral soil plots b. Peatland plots. To exemplify the statistical significange in the occurrence of the disease degrees in elevation classes, some bars are marked with letters ‘a’ or ‘b’. The bars marked with the same letter show statistically significant differences according to Conover’s (1980) non-parametric multiple comparison test.

The disease frequency in plots situated lower was 13.8% as compared with 8.2% in plots situated higher. The occurrence of the disease degrees was very significantly different in these two groups. The Kruskal-Wallis H’s for all the plots, mineral soil plots and peatland plots were 186.691, 91.042 and 23.826, respectively. This phenomenon also displayed interaction with the absolute elevation:

Table 2. Spearman correlation coefficients and their significance between degrees of *Gremmeniella abietina* damage and some topographical variables. Significant (p ≤ 0.05) coefficients are printed in bold. Data: mineral soil and peatland plots combined.

Variable	Whole dataset			The eight most diseased areas in Fig. 1.		
	Coefficient	Significance	Number of plots	Coefficient	Significance	Number of plots
PLOT_ELEV	**0.022**	0.000	24544	–0.005	0.673	7136
TRACT_ELEV	**0.055**	0.000	24478	**0.036**	0.003	7120
REL_ELEV_T	**–0.097**	0.000	24284	**–0.099**	0.000	7070
REL_ELEV_S				**–0.028**	0.018	7086
REL_ELEV_150				**–0.051**	0.000	7086
REL_ELEV_300				**–0.035**	0.003	7080
REL_ELEV_600				**–0.035**	0.003	7076
MIN_ELEV				0.004	0.743	7086
MINE_DIST				**–0.028**	0.018	7086
SLOPE				**–0.036**	0.002	7086
LAPLAC				**0.052**	0.000	6962
LAPPOS				–0.016	0.191	6999
LAPDIST				**–0.034**	0.004	6999

in the plots situated lower than the mean tract area elevation, the disease frequency increased with an increase in absolute elevation, while in the plots situated higher, the disease percentage reached its maximum in the elevation class 100–120 metres (Fig. 4).

The detailed DEMs were analysed in the most diseased areas. The steepness of the slope (expressed in degrees) was negatively correlated with the disease degree. The correlation coefficient was very small in the mineral soil plots, but, despite this, the correlation became significant in the whole dataset (Tables 2–3).

The aspect of the slope only had a weak effect of the disease occurrence. On mineral soils, the disease was most common in south-facing slopes, whereas planar regions and west-facing slopes were the most vulnerable among the peatland plots. However, the differences between different aspects and undetermined aspects (planar regions) were not significant (Table 4).

There were no differences in the occurrence of the disease degrees between the classes of the joint variable WARM (H = 4.650, p = 0.589) in the most diseased areas, although in peatland the disease was most common on plots with WARM = 1 (representing a northern aspect and a slope between five and ten degrees). Unfortu-

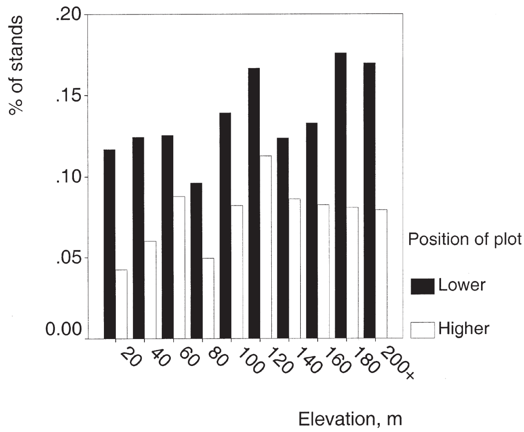

Fig. 4. The frequency of *Gremmeniella abietina* damage in Scots pine stands related to absolute elevation classes and to the relative position of the plot (i.e. the elevation of the plot minus the elevation of the mean height of an 7 km × 8 km area around the pixel). Lower = the difference is less than –1 metres, higher = the difference is more than +1 metres.

Table 3. Spearman correlation coefficients and their significance between degrees of *Gremmeniella abietina* damage and some topographical variables. Significant (p ≤ 0.05) coefficients are printed in bold. Data: mineral soil and peatland plots separated.

Variable	Whole dataset			The eight most diseased areas in Fig. 1.		
	Coefficient	Significance	Number of plots	Coefficient	Significance	Number of plots
Mineral soil plots						
PLOT_ELEV	**0.026**	0.000	18078	–0.004	0.790	4905
TRACT_ELEV	**0.050**	0.000	18022	0.024	0.091	4892
REGREL_ELEV	**–0.054**	0.000	18065	**–0.061**	0.000	4860
REL_ELEV_S				–0.017	0.229	4860
REL_ELEV_150				**–0.036**	0.012	4860
REL_ELEV_300				–0.014	0.317	4859
REL_ELEV_600				0.014	0.322	4859
MIN_ELEV				0.000	0.994	4860
MINE_DIST				–0.007	0.607	4860
SLOPE				–0.003	0.808	4860
LAPLAC				0.027	0.058	4768
LAPPOS				–0.000	0.191	4794
LAPDIST				**–0.030**	0.040	4794
Peatland plots						
PLOT_ELEV	–0.016	0.192	6466	–0.026	0.224	2231
TRACT_ELEV	0.015	0.219	6456	0.026	0.225	2228
REGREL_ELEV	**–0.049**	0.000	6466	**–0.052**	0.014	2226
REL_ELEV_S				–0.023	0.284	2226
REL_ELEV_150				–0.038	0.072	2226
REL_ELEV_300				**–0.104**	0.000	2221
REL_ELEV_600				**–0.103**	0.000	2217
MIN_ELEV				–0.024	0.261	2226
MINE_DIST				–0.036	0.093	2226
SLOPE				–0.027	0.206	2226
LAPLAC				**0.051**	0.017	2194
LAPPOS				–0.034	0.115	2205
LAPDIST				–0.030	0.164	2205

nately, 2198 of the 2226 peatland plots in the most diseased areas had a WARM value of 2.5 (i.e. the slope was less than 5 degrees).

The local relative elevation (REL_ELEV_S) in the most diseased areas (i.e. the difference between the elevation of the plot and the mean elevation of the eight surrounding 25 m×25 m pixels) was not as important for the disease occurrence as the relative regional elevation (REGREL_ELEV) or the relative elevation compared with the elevation of the tract area (REL_ELEV_T) mentioned earlier. The correlations between REL_ELEV_S and the disease degree were all negative, i.e. the disease degrees were the higher the lower the plots were situated with regard to their immediate surroundings, but the correlation was significant in mineral soil plots only. The correlations with the disease degree and the variables REL_ELEV_150, REL_ELEV_300 and REL_ELEV_600 were also negative. These correlations also revealed the importance of scale: the correlation with REL_ELEV_150 and the disease degree was not statistically significant in peatland plots, whereas in mineral soil plots only this correlation was important.

The local minimum elevation (the minimum

Table 4. Proportion of diseased plots according to slope directions. Data: The plots in the eight most diseased areas (Fig. 1).

Slope direction	Mineral soil plots [a)]		Peatland plots [b)]	
	% of plots	N	% of plots	N
Undetermined	10.4	796	21.6	744
North	12.6	787	14.2	323
East	13.2	1173	18.8	431
South	14.4	1034	19.2	370
West	11.6	1070	20.7	358
All	12.6	4860	19.5	2226

a) Kruskal-Wallis-test: Chi-square = 8.016 p = 0.091

b) Kruskal-Wallis-test: Chi-square = 7.950 p = 0.093

within 180 m of the plot, variable MIN_ELEV) did not correlate with the disease degree. The distance of this local minimum (the variable MINE_DIST) was more strongly correlated, and the correlation was always negative (Tables 2–3).

The correlations between the Laplacian operator (the variable LAPLAC) and disease degree were positive, suggesting more disease in the pixels, which would be 'recharged' (i.e. which, e.g. surface water would flow into). This effect was more pronounced in the peatland plot data. The variables LAPPOS and LAPDIST behaved similarly as the variables MIN_ELEV and MINE_DIST: the absolute value of the nearest positive Laplacian cell was not significant, while the distance of this cell from the target cell (LAPDIST) was negatively correlated with the disease degree, indicating more disease if the target cell was situated near a 'recharged' cell (Tables 2–3).

The disease frequencies were very similarly related to the three most common types of surface features (channels, ridges and planar regions) within the 50-m scale, except in mineral soil plots, where the disease was most common in plots located in channels. The frequencies of the disease degrees were not, however, statistically, significantly different, even in mineral soil plots (Kruskal-Wallis test: chi-sq = 5.258, $p = 0.072$). At the 100-m scale, the occurrence of disease degrees was statistically significantly different in these three surface feature types for all the plots (chi-sq = 9.858, $p = 0.007$) and peatland plots (chi-sq = 5.241, $p = 0.073$). The non-parametric multiple comparisons showed that the disease was more common in channels than in ridges for all the plots and peatland plots (test values 9.210, $p < 0.01$ and 5.991, $p < 0.05$, respectively) at this scale.

When the results were examined individually at each of the most diseased regions shown in Fig. 1, the figure becomes more complicated. The regions in Fig.1 were quite different in relation to their topography and disease frequency. The order of the regions from the most to the less diseased was 5 > 3 > 4 > 8 > 7 > 2 > 1 > 6, the disease percentages being 20.6, 19.9, 15.9, 13.7, 12.8, 12.7 and 9.6%, respectively. However, the two most diseased regions were different in that the mean plot and tract area elevations (variables PLOT_ELEV and TRACT_ELEV, respectively) were lowest in region 5 and highest in region 3, while the local relative elevation (RELEV_S) was the highest in region 5 but the value was among the lowest in region 3. Region 5 is, thus, characterised as a 'low land area', with small knolls, a high mean value of slope angle, and, also, a low proportion of peatland plots. Region 3 is best described as an 'uphill area', with relative small local differences, but with an intermediate proportion of peatland plots. On the other hand, the least diseased region, 6, is characterised by rather high values of plot and tract area elevations, but low mean values of slope, local relative elevation and regional relative elevation (RELEV_R). In addition, the proportion of peatland plots was the highest in this region.

4 Discussion

The National Forest Inventory, although exact when forest resources are concerned, has several disadvantages and limitations regarding the monitoring of specific epidemic forest diseases, like the Scleroderris canker caused by *Gremmeniella abietina* (see Nevalainen 1999).

The digital elevation models exploited in this study may exhibit many types of errors and artifacts. Fundamental factors affecting the accuracy of the DEM are the sampling method of the contours, contour density, quality of the numerical data and the computing method in generating the DEM. The errors can include flattening of the terrain, e.g. overgeneralization of ridges and valleys. The DEM can be also be planimetrically offset– then the error appears in slope direction and steepness. Coastal and flat areas may appear as terraces, resulting from rounding elevation values to integers, e.g. metres (Wood 1996). Two DEMs used in this study showed an artifact called 'interpolation terracing'. They sometimes appeared to have regular terraces over the surface, flatter regions alternating with narrow bands of steeper slopes. The reason may be that the DEM was interpolated from contour data by an interpolation method that failed to interpret the contour data correctly. However, a plot of the frequency histograms of the modulus to the base of the suspected contour interval (the so-called Hammock plots) did not reveal this artifact to be general in the data. According to the National Land Survey of Finland, the mean error of the elevation is 1.76 metres in the 25 m×25 m DEMs in the whole country. In this study, the mean error was mostly less than 5 metres (Korkeusmalli 25:n… 1997). The plots were quite correctly positioned on the digital elevation maps, because the elevation obtained using the digital elevation model in the most diseased areas was well correlated with the original elevation record of the NFI (Pearson correlation 0.982, $p=0.000$, $N=7086$). In 97.8% of the cases, the difference between the original plot elevation record and the elevation in the detailed DEMs was less than 10 m. The 153 erratic values were situated either at the borders of the DEM, e.g. near the country border, or at very steep slopes. These errors were judged to be negligible for the main results of this study. Unfortunately, the accuracy of the original elevation record in the field survey was 10 m.

The precision with which the DEM models the true surface will depend on surface roughness and DEM resolution. Even at the 3×3 kernel size, a quadratic function cannot precisely model the 9 values used in its construction. The work of Wood (1996) suggests that there will always be detail at a finer scale than that measured by the DEM resolution. As discussed later, even small differences in elevation may be important for the predisposition of trees to *Gremmeniella abietina*.

The scale of the DEM is often arbitrarily defined and not necessarily related to the scale of characterisation required, and the derived results may not always be appropriate. Also, the pattern of local curvature varies considerably with scale. Surface parameters should, thus, be expressed at a variety of sizes. At the finest scale (50 m×50 m pixel size in his study), a rather fragmented network of ridges and channels was revealed. Smaller, well dissected upland valley systems were relatively well defined, while the major valleys were not delineated (see Wood 1996). The results suggest that the disease frequency in relation to surface features also changes with scale.

Many single variables were used to describe the topographical position of the plots. Most of them described only the position of a single pixel. A more suitable method would have been to generate a system of larger 'valleys' or 'ridges'. This is, however, quite difficult to achieve mathematically. The method for identification of the surface features used in this study is only one of the many possibilities available. Many methods were tested (e.g. the toposhape module of the Idrisi32 package) and visually inspected against normal topographic maps (1:20 000) in this study. Different programs produced slightly different results. So far few attempts have been made to study in detail the accuracy of the algorithms used by these software. The Landserf program may be the most advanced, but nevertheless, the results obtained with it were not fully satisfactory in visual inspections. Therefore, the results should be considered as approximate only. Although tools for geomorphometrical analysis have been developed in the study of Wood (1996) they have not yet been used to provide a comprehensive geomorphological assessment of landscapes.

Gremmeniella abietina infestations were present all over southern Finland in this study. However, a clear clustered pattern had been earlier reported, using the same material as in this study (Nevalainen 1999). Topography is related to many factors, for instance the geological origin of the soil, soil properties and microclimate. In this material, the occurrence of the disease was clearly different for the main site classes, mineral soil plots and peatland plots. This distinction was also clearly reflected in many topographical variables. Topographic variables did not entirely explain the regional patterns in the occurrence of this disease. The disease was frequent on upland areas (like areas 3 and 7 of Fig. 1), but, on the other hand, it was also common on low-land areas, like area 5. Even in the highest areas, the most severely infected plots were not situated at the very top of the hills. Outside the areas studied in detail, the disease was quite common in south-western Finland, in a very low land area (in areas with a mean elevation around 40 metres). The most diseased areas studied in detail differed so much from each other that finding common topographical factors that depicted the disease susceptibility of the plots was difficult. In visual examination of the diseased plots against base maps, it could also be seen that the disease was concentrated near or in river valleys or in or near 'bays' of peatland (narrow peatland stripes surrounded by mineral land). This phenomenon was evident only on upland areas, like areas 3 or 7 of Fig. 1. The diseased plots were also often within the joint area of a rocky hill and a river valley or a 'bay' of peatland.

As a generalisation, the disease was most common on two different geographical and geological area types:

1) Large water divides, like Multia and its surroundings; North-Savo, (dividing waters running to the Gulf of Bothia or the Gulf of Finland); in eastern Finland between the pool of Lake Pielinen and Saimaa lake system; surroundings of Mikkeli (between Lake Päijänne and Saimaa). The remnant mountain area in south Bothia acts as a local water divide, as well as the upland area of Tammela in south-eastern Häme.
2) Low-lying plateaus, like the south-western coast, coastal areas of Bothia, and the areas south of the Salpausselkä ridge. These areas have been sub-aquatic after the glaciations, and the finest soil fractions have accumulated in the valleys during the different phases of the Baltic Sea (Suomen Kartasto 1990).

Fine soil fractions have also remained on supra-aquatic hilltops. Owing to land uplift, the highest shore level, in different levels in different parts of the study area, reaches from 90 metres at the south-eastern corner, up to 200 metres in the coast of Gulf of Bothia. The evolutionary stages of the Baltic Sea and local ice-lakes with their regressions and transregressions have caused additional variation in the ancient shore level (Suomen Kartasto 1990). For these reasons, defining the supra-aquatic areas accurately was impossible. The hilltops in one of the disease centres in this study, Multia, are partly supra-aquatic (Sairanen 1990). However, it should be noted, that the disease intensity correlated neither with the proportion of fine fractions nor with the elevation level in Sairanen's (1990) study.

The disease has been most severe in topographic depressions in several small-scaled studies (e.g. Dorwort 1973). Although the disease was more common in topographic depressions also in this study, the microtopography of the site, here the plot's surroundings at 75-m or 150-m distances, was important for mineral soil plots only. The correlations with the variables depicting relative elevation within various distances around the plots indicate that in mineral soils smaller topographic depressions can play a role in disease susceptibility than in peatlands. The disease was not more common on north-facing slopes. Aspect and slope together, as depicted by the joint variable WARM, and reflecting the microclimatic conditions, had no influence on the severity of the disease. These results are somewhat contradictory to some earlier findings. According to Read (1966, 1968), Corsican pine (*Pinus nigra* var. *calabrica* (Loud.) Schn.) stands were more diseased in north-facing slopes and artificial shading increased the infection rate. Uotila (1988) found that in a steep kettle hole in North Finland, the seedlings were most susceptible to the disease in the north-facing slopes and in the bottom of the hole. Karlman et al. (1994) also report that slopes having northern aspect were more severely diseased than those with a southern aspect.

In the whole data set of southern Finland, the disease degrees correlated most strongly with the relative elevation of the plot compared with the elevation in the tract area. The results support the findings of the previous, mostly local, studies. The disease was more common in areas with high elevation, and in those plots that were at the same time situated lower than the surrounding area. The relative regional elevation and the mean elevation of the tract area were also more important than the absolute elevation of individual plots, except on peatlands. In the most diseased areas studied in detail, the Laplacian operator was also strongly correlated with the disease, and especially on peatland plots. Places situated lower than their surroundings can be thought to be places where fine soil material has also accumulated. Unfortunately, the NFI field system does not contain detailed information on soil types or soil fractions. Sites like this may also be easily paludificated, as they collect water. Stands on paludified mineral soil sites show more disease than those on well-drained sites (Nevalainen 1999).

In Lapland, it has been found that *Gremmeniella* infection has been most severe in valleys near a pond or a river or in small local depressions in upland areas. The relative altitude of the site, in relation to the nearest lake or river, was more important than the absolute site elevation. The treewise damage degree correlated negatively with the absolute elevation (Kaitera and Jalkanen 1995, Jalkanen and Kaitera 1995). Karlman et al. (1994) report a similar situation for lodgepole plantations in northern Sweden: although the disease was severe in stands growing in a high elevation area, it initially had spread out from topographic depressions. They also found that the disease was more common in depressions and in plane areas than on hillsides, slopes or on undulating terrain. To my knowledge, their study is the only report, in which different landscape forms have been compared in relation to *Gremmeniella* infection. Aalto-Kallonen and Kurkela (1985) report that the disease was more severe at the lowest elevations, if the downward flow of cold air was blocked, e.g. by a forest edge. Sairanen (1990) found that the disease intensity was negatively correlated with the elevation from the bottom of the nearest cold air drainage basin. The most severely damaged stands were found in the river valleys. The severely damaged stands were mostly at a height of less than 10 metres above the bottom of the main cold air drainage basin. Stands growing in small depressions in the elevated area between the two major valleys were not severely damaged. Although she did not study absolute elevation, the most diseased stands were in rather high areas (170–180 metres a.sl.). (Sairanen 1990).

One disadvantage of the present study was that the distance of each plot, e.g. from the nearest lake/river or peatland could not be computed, since the digital masks in question, although available in Finland, were unattainable for this study. Several methods were tested to isolate drainage networks from the DEMs (e.g. the module runoff of the Idrisi32 package), but, despite the results at first seemed to be promising, they were not used in further analyses after careful visual inspection.

In Canada, in the Lake Superior region, *Gremmeniella abietina* had killed red pine (*Pinus resinosa* Ait.) plantations in the pleistogene drainage troughs. These troughs were so shallow (a few metres) that they were indistinguishable in standard topographic maps. These glaciofluvial depressions probably functioned as a cold air drainage system, perhaps also concentrating the airborne spores of the pathogen (Dorworth 1978). It may be, that in some parts of Finland the shallow terraces formed, e.g. during the Ancylus-lake stage of the Baltic Sea, act similarly as pathways directing cold air (Haavisto 1983, p. 23). Even slight variations in topography produce quite significant differences, e.g. in frost damage of Scots pine (Raitio 1987). Laiho (1986), among others, has described sites having unfavourable microclimates (i.e. colder nights) for Scots pines because of topography. The sites had also suffered from *Gremmeniella*-infection.

The disagreement with earlier, mostly very local studies can partly be explained by the inadequate number of plots when a small area, e.g. a local depression, is examined. The large-scaled NFI-survey is not suitable for describing differences at a very local scale. On the other hand, although in many earlier studies it has been found that the disease is severe, e.g. in topographic depressions or in north-facing slopes, and these sites may act as primary disease centres (e.g. Karlman et al. 1994), during epidemic years many other kinds of sites are affected. The local studies are often made in the most diseased stands, and thus, they may overemphasize some predisposing factors. Only large-scaled, statistically sound samples make a simultaneous examination of the several predisposing variables and their relative importance conceivable. In addition to the spatial patterns, the temporal dynamics of the disease, in relation to climatic factors, also warrants detailed study.

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References

Aalto-Kallonen, T. & Kurkela, T. 1985. Gremmeniella disease and site factors affecting the condition and growth of Scots pine. Communicationes Instituti Forestalis Fenniae 126. 28 p.

Bragg, R.J. & Manion, P.D. 1984. Evaluation of possible effects of acid rain on Scleroderris canker of red pine in New York. In: Manion, P.D. (ed.). Scleroderris canker of conifers: proceedings of an International Symposium on Scleroderris Canker of Conifers, held in Syracuse, USA, June 21–24, 1983. M. Nijhoff/W. Junk Publishers. p. 130–141.

Conover, W.J. 1980. Practical nonparametric statistics. 2nd ed. Wiley, New York. 493 p.

Dietrichson, J. 1968. Provenance and resistance to Scleroderris lagerbergii Gremmen (Crumenula abietina lagerb.). The international Scots pine provenance experiment of 1938 at Matrand. Meddelser fra det Norske Skogforsöksvesen 25: 398–410.

Dorworth, C.E. 1972. Epidemiology of Scleroderris lagerbergii in Central Ontario. Canadian Journal of Botany 50(4): 751–765.

— 1973. Epiphytology of Scleroderris lagerbergii in a kettle frost pocket. European Journal of Forest Pathology 3: 232–242.

— 1978. Presence of a late pleistocene drainage system manifested through depredation of red pine by Gremmeniella abietina. Ecology 59(4): 645–648.

Douglas, D.H. 1986. Experiments to locate ridges and channels to create a new type of digital elevation model. Cartographica 23(4): 29–61.

Evans, I.S. 1980. An integrated system of terrain analysis and slope mapping. Zeitschrift für Geomorphologie, Suppl-Bd 36: 274–295.

Haavisto, M. 1983. (ed.). Maaperäkartan käyttöopas. Summary: Basic mapping of quarternary deposits in Finland. Geological Survey of Finland, Guide 10. 80 p.

Jalkanen, R. & Kaitera, J. 1995. Versosurman alueellinen vaihtelu. In: Tikkanen, E. (ed.). Kuolan saastepäästöt Lapin metsien rasitteena. Itä-Lapin metsävaurio -projektin loppuraportti. Maa- ja metsätalousministeriö & Metsäntutkimuslaitos, Jyväskylä. p. 149–151. ISBN 951-40-1407-3. (In Finnish).

Kaitera, J. & Jalkanen, R. 1995. Stand and site characteristics in the decline of Pinus sylvestris caused by Gremmeniella abietina shoot disease in a severely damaged 50-year old plantation in SE Lapland. Scandinavian Journal of Forest Research 10: 256–263.

Karlman, M., Hansson, P. & Witzell, J. 1994. Scleroderris canker on lodgepole pine introduced in northern Sweden. Canadian Journal of Forest Research 24(9): 1948–1959.

Kohh, E. 1964. Om tallens gren- och granens topptorka och dess bekämpning. Skogen 51: 200–203.

Korkeusmalli 25:n tarkkuusanalyysi. 1997. [The accuracy analysis of the elevation model 25]. (In Finnish). http://www.nls.fi/kartta/tuotteet/korktark.html.

Kuusipalo, J. 1985. An ecological study of upland forest site classification in Southern Finland. Acta Forestalia Fennica 192.

Lähde, E. 1974. The effects of grain size distribution on the condition of natural and artificial sapling stands of Scots pine. Communicationes Instituti Forestalis Fenniae 84(3). 23 p.

Laiho, O. 1986. Lämpöolojen paikallisvaihtelu ja sen merkitys metsänuudistamisessa. Metsäntutkimuslaitoksen tiedonantoja 235. p. 25–34. (In Finnish).

Li, M. & De Dapper, M. 1996. Geomorphometric variables extraction based on a grided Digital Terrain Model (DTM). In: Guan, W., Li, B., Shaw, S.L. & Zhou, Q. (eds.). GIS & Remote Sensing: Research, Development & Applications. The Proceedings of Geoinformatics ‘96. West Palm Beach, Florida, USA, April 26–28, 1996. p. 90–100.

McNab, H.W. 1989. Terrain shape index; quantifying effect of minor landforms on tree height. Forest Science 35(1): 91–104.

Moore, I.D., Grayson, R.D. & Ladson, A.R. 1991.

Digital terrain modeling: a review of hydrological, geomorphological and biological applications. Hydrological Processes 5: 3–30.

Nevalainen, S. 1999. Gremmeniella abietina in Finnish Scots pine stands 1986–1992 – a study based on National Forest Inventory. Scandinavian Journal of Forest Research 14: 111–120.

Niemelä, P., Lindgren, M. & Uotila, A. 1992. The effect of stand density on the susceptibility of Pinus sylvestris to Gremmeniella abietina. Scandinavian Journal of Forest Research 7: 129–133.

Raitio, H. 1987. Site elevation differences in frost damage to Scots pine (Pinus sylvestris). Forest Ecology and Management 20: 299–306.

Read, D.J. 1966. Dieback disease of pines with special reference to Corsican pine Pinus nigra var Calabrica Schn. I. The nature of the disease symptoms and their development in relation to the crown and aspect. Forestry 39: 151–161.

— 1968. Some aspects of the relationship between shade and fungal pathogenity in an epidemic disease of pines. New Phytologist 67: 39–48.

Sairanen, A. 1990. Site characteristics of Scots pine stands infected by Gremmeniella abietina in Central Finland. I. Mineral soil sites. Acta Forestalia Fennica. 27 p.

Suomen Kartasto 1990. Vihko 124. Maaperä. (Atlas of Finland 1990. Book 124. Surficial deposits). Maanmittaushallitus, Helsinki.

Uotila, A. 1988. Ilmastotekijöiden vaikutus männynversosyöpätuhoihin. Summary: The effect of climatic factors on the occurrence of Scleroderris canker. Folia Forestalia 721. 23 p.

Vogelmann, J.E., Sohl, T. & Howard, S.M. 1998. Regional characterization of land cover using multiple sources of data. Photogrammetric Engineering and Remote Sensing 64(1): 45–58.

Waring, R.H. & Schlesinger, W.H. 1985. Forest ecosystems, concepts and management. Academic Press. 340 p.

Witzell, J. & Karlman, M. 2000. Importance of site type and tree species on disease incidence of Gremmeniella abietina in areas with a harsh climate in northern Sweden. Scandinavian Journal of Forest Research 15(2): 202–209.

Wood, J. 1996. The geomorphological characterisation of Digital Elevation Models. PhD Thesis, University of Leicester. http://www.geog.le.ac.uk/jwo/research/dem_char/thesis

Young, M. 1978. Terrain analysis: program documentation. Statistical characterisation of altitude matrices by computer: Report 5 on grant DA-ERO-591-73-G0040. University of Durham, England.

Zevenbergen, L.W. & Thorne, C.R. 1987. Ouantitative analysis of land surface topography. Earth Surface Processes and Landforms 12: 47–56.

Total of 35 references