VEGETATION AS A TOOL IN THE CHARACTERISATION OF GEOMORPHOLOGICAL FORMS AND PROCESSES: AN EXAMPLE FROM THE ABISKO MOUNTAINS

BY
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ABSTRACT. This study addresses the relationships between landforms and vegetation in the sub-Arctic zone around Abisko, and the possibilities for using vegetation in the characterisation of geomorphological forms and processes. It examines the extent to which repeatable linkages can be identified between landforms and geomorphological features of the vegetation as a preliminary step in the development of phytoindicators of geomorphological forms and processes. Sixty sites representative of different landforms were studied in three mountain areas in the alpine belt on both calcareous and crystalline substrates. A series of features characterising the abiotic environment and vegetation was defined. Plant communities were distinguished in line with the 'Scandinavian-school' typology. Links were investigated between vegetation and geomorphological processes (deflation, frost sorting, solifluction and nivation) and landforms (thufurs, solifluction lobes, sorted stripes and nival niches). A clear association between vegetation and landforms was noted, though a precise description of the links encountered a number of difficulties, mainly reflecting the indirect nature of the interrelationships between landforms and vegetation (i.e. the fact that they are intermediated by other abiotic factors). A combination of indicative vegetational features capable of characterising the geomorphological processes was established, although those require further, more detailed analysis. Schematic representations of the links between the different types of landforms and the vegetation growing on them were also developed. There are limits to the applicability of phytoindication in the high-alpine belt and extending into the nival belt, reflecting the unfavourable conditions there for plant growth.

Key words: sub-Arctic, vegetation, geomorphological processes and forms

Introduction
The interdependencies between relief and the vegetation growing over it have long been of interest to both geomorphologists and geobotanists. However, the interest has tended to be both limited and imprecise. Thus, a more precise description from the point of view of one of the specialisations has usually been associated with a very superficial description from the point of view of the other. Geomorphologists have generally confined their interest to a description of the degree of closure of vegetation cover as an important factor governing the stability of particular forms of relief (e.g. Kotarba 1976; Jahn 1979; Rapp 1983). In turn, geobotanists have used a very imprecise diagnosis of landforms that are covered by the vegetation they are studying (e.g. Géhu 1986).

The need to engage in joint research results from a conceptualisation of the natural environment as a complex system of spatial units (geocomplexes) in which the components of parent rock and relief, water, soil, vegetation and animals play a part. These geocomponents may be organised hierarchically according to the relationships between them. The parent rock and the relief, together with the micro-climate, condition the other components. In turn, the vegetation is subordinate to all of the abiotic components. It is directly dependent on most of them, with only the geological substrate and the relief impacting on the vegetation in an indirect manner, via other components. However, the vegetation exerts a significant modifying influence on the state of other components and the processes that affect them.

The discovery of repeatable dependent relationships between components offers a possibility of using indicative methods. The main advantages of indicative methods are: easy application even during the most difficult and extreme field work; im-
mediate results; and low cost. According to Kostrowicki (1976), the biosphere – and within it the vegetation – shows the greatest capacity to indicate the state and dynamics of other components. It is for this reason that the use of phytointication has become so popular in agriculture, forestry, nature management as well as in exploratory geology and dynamic geomorphology.

Phytointicative methods are based on a familiarity with the requirements of plant species and the abiotic factors upon which they depend. The approach taken to phytointication depends on the model adopted for the differentiation of vegetation cover. Where a continuum of vegetation cover is assumed, phytointication is based on the links between components at appropriately selected measurement points. The relationships involved are mostly unifactorial, involving a plant species and a factor or agent acting upon it. Conversely, where a discontinuum is assumed, phytointication is based on repeatable relationships between vegetation and abiotic factors within spatial units (ecosystems, geocomplexes). Where relief with a complex network of linkages is involved, along with a need to indicate multifactorial links of an indirect nature, the ecosystem conceptualisation works best. Research into the co-occurrence of two geocomponents within spatial units may serve as a basis for a system of phytointicators for geomorphological forms and processes.

There are many publications of an autecological or synecological nature regarding the Scandinavian mountains. They allow for assessments of the duration of snow cover, the soil humidity and the trophic status of the substrate (Bringer 1961a, b; Persson 1961, 1962, 1965; Gjærevell and Bringer 1965; Wijk 1986; Eurola and Virtanen 1991; Karlsson and Callaghan 1996; Påhlsson 1998). These are factors upon which the plants depend directly. On this basis it is easy to find indicative species or plant communities for these factors. It is much more difficult to apply phytointicators to geomorphological forms and processes, because – as noted above – vegetation depends only indirectly upon landforms. To date, no integrated system of plant indicators capable of indicating geomorphological forms and processes has been devised.

Since geocomponents come together at certain points in geographical space, and are within landscape units (geocomplexes) of different size and rank, the scale of research plays an important role as regards the observed co-occurrence of landforms and vegetation. This aspect of the landform – vegetation relationship has been the subject of preliminary investigation (Kozłowska and Rączkowska 1996). The most promising results seemed to be at the detailed scale, i.e. within particular landforms. The work in question was carried out in the Tatra Mountains (Rączkowska and Kozłowska 1994; Kozłowska and Rączkowska 1996; Kozłowska et al. 1999), as well as in the Pyrenees (Somson 1983). Schematic representations of the relationships between plant communities and types of nival niche have in turn been presented for the mountains of Scandinavia (Sandberg 1958; Påhlsson 1998). A role of plant life strategy and microscale diversity of plant habitats in spatial structure of the tundra vegetation was elaborated by Matveeva (1988).

In the Tatras the links between vegetation and landforms were presented in the form of quantitative data assigned values. The index of strength of linkages was calculated based on overlaying of digital maps of both components. The index has a value between 0 and 1. When limits of vegetation and morphodynamic unit fit together entirely the index value is 1. The index value diminishes to zero when particular units do not occur together. A series of indicator communities was established. In the case of slopes modelled by solifluction, an indicative role is played by Oreorchloo distichae – Juncetum trifidi with Sphagnum, or mossy forms of the sward’s typical sub-association. Slopes intensively modelled, mainly by slopewash and cryogenic processes, are indicated by initial communities of cryptogamic plant or by the pioneer, sparse form of Luzuletum spadiceae. Indicative of the nival niche is Luzuletum spadiceae. Stabilised slopes are characterised by the presence of the number of plant communities. Among these, the Vaccinium myrtillus community stands out clearly, growing on stabilised slopes with block cover or stabilised debris flow leveés.

Thus, the aim of the present study – as an example of close co-operation between a geomorphologist and a geobotanist – is to demonstrate the opportunities for using vegetation in the characterisation of geomorphological forms and processes, as well as to attempt to find phytointicators. This work in the mountains near Abisko represents a continuation of earlier work in the Tatras. It further constitutes an expanded understanding of the links between vegetation and landforms in the mountains of the sub-Arctic zone. Specifically, the research addressed questions concerning:
1. the existence of any repeatable, quantifiable or qualitatively definable links between landforms and vegetation in mountains of the sub-Arctic zone;
2. the features of vegetation cover best reflecting the diversity of geomorphological processes and forms;
3. the possibilities for designating plant indicators for geomorphological processes or forms;
4. the limits to the applicability of phytoindication in describing landforms.

Study area and methods

The work was done in the mountains of Scandina-
via near Abisko, within the areas of Mounts Njulla, Jiebrenčohkka and Läktätjakka (Fig. 1). These areas differ in lithology and geological structure (Lindström 1955; Kulling 1964). Mt. Jiebrenčohkka comprises calcareous rocks, mainly dolomites; Mt. Läktätjakka, crystalline rocks; and Mt. Njulla, rocks of both types. Sixty sites (landforms or fragments of slope modelled by defined processes) were selected for study. All of the sites were situated above the upper limits of the zone of scrub with downy birch, Betula pubescens ssp. czerepanovii, which is to say in three altitudinal belts: the low alpine belt (at 600–900 m a.s.l.), the intermediate alpine belt (at 900–1200 m a.s.l.) and the high alpine belt (above 1200 m a.s.l.). The boundaries of these altitudinal belts are defined in Påhlson (1998). Account was taken of slopes located at varying altitudes and with varying lithologies and exposures. The size of the research plots varied according to the features examined.

For each site the following were defined: the geomorphological process and form of relief, the slope dynamics, the altitude a.s.l., the inclination and exposure of the slope, the altitudinal belt, the geological substrate, the dominant vegetation formation, the extent of the vegetation cover and the extent of bare ground, the homogeneity and complexity of the vegetation, the dominant plant species, and the name of the plant community and its code according to Nordic Council of Ministers (1998). This unified, hierarchical conceptualisation of vegetation types allowed the use of typological units of differing rank, characterised by numerical codes.

For most of the sites there were several vegetation units. Only in a few cases was just one type of vegetation ascribed to a given site. Over the whole study area of c. 5 km², some 14 types of landform and 10 types of geomorphological process were found, along with 30 types of vegetation. Further analysis was, however, confined to those geomorphological processes and forms characterised by the greatest frequency of occurrence. The analysis was therefore restricted to the best documented processes of deflation, nivation, solifluction and frost-sorting, as well as the most frequently occurring forms, namely: thufurs, sorted stripes, poly-
gons, nival niches and solifluction lobes. These provide the basis for the conclusions presented below regarding the interrelationships between vegetation and relief.

Results and discussion

Vegetation and geomorphological processes

The results of the analysis of the dependence between geomorphological processes and vegetation are presented in Table 1. The areas modelled by different geomorphological processes are characterised by a combination of the following vegetational features:

- the type of vegetation coded after Nordic Council of Ministers (1998);
- the dominant plant life forms;
- the cover of the surface by vegetation.

None of these features applied singly was capable of offering a good, unambiguous and distinct characterisation of processes, because particular features of vegetation are the same for many geomorphological processes. The same type of vegetation may occur in areas modelled by different processes. Thus, for example, vegetation type 1.3 (snowfield vegetation) occurs in areas modelled both by frost sorting processes (polygons) and solifluction. The feature of the vegetation distinguishing a surface modelled by these processes is the degree of cover. A further complicating factor is that the process of frost sorting can produce – in relation to environmental factors such as the mechanical composition of the weathering cover, its humidity and slope inclination – a range of different geomorphological forms and hence different habitat conditions. For this reason, the plant cover on the surface of different slopes modelled by frost sorting may also differ (Table 1).

The features of the vegetation growing in an area modelled by a given process also vary fundamentally in relation to the altitudinal belt. Changes linked with this sometimes involve only one feature of the vegetation, with others remaining unchanged. This relationship is especially visible in the vegetation of areas modelled by frost sorting, but also by solifluction or nivation. Only some processes like deflation (Fig. 2) or soil creep have the same plant characteristics irrespective of altitudinal belt.

A further obstacle to the precise characterisation of geomorphological processes with the aid of vegetation is the fact that more than one type of vegetation frequently occurs in areas of slope modelled by a given geomorphological process. This is especially true of processes widespread in a given area, like solifluction in the mountains of Abisko (Fig. 3).

Table 1. Geomorphological processes and vegetation.

<table>
<thead>
<tr>
<th>Geomorphological process</th>
<th>Number of observations</th>
<th>Altitudinal belt</th>
<th>Vegetation type code</th>
<th>Name</th>
<th>Dominant life-form</th>
<th>Cover*</th>
</tr>
</thead>
<tbody>
<tr>
<td>deflation</td>
<td>7</td>
<td>low alpine, intermediate alpine</td>
<td>1.1</td>
<td>snowfree exposed mountain heath</td>
<td>dwarf shrubs, mosses</td>
<td>XX</td>
</tr>
<tr>
<td>nivation</td>
<td>18</td>
<td>low alpine, intermediate alpine, high alpine</td>
<td>1.3, 1.2</td>
<td>snowfield vegetation, snowcovered vegetation</td>
<td>mosses, dwarf shrubs, grasses</td>
<td>XX</td>
</tr>
<tr>
<td>solifluction</td>
<td>45</td>
<td>low alpine, intermediate alpine</td>
<td>1.2, 1.3, (1.1)</td>
<td>snowcovered vegetation, snowfield vegetation</td>
<td>dwarf shrubs, grasses, mosses</td>
<td>XXX</td>
</tr>
<tr>
<td>frost sorting (sorted stripes)</td>
<td>9</td>
<td>intermediate alpine</td>
<td>1.1</td>
<td>snowfree exposed mountain heath</td>
<td>dwarf shrubs, mosses</td>
<td>XX</td>
</tr>
<tr>
<td>frost sorting (sorted stripes)</td>
<td>5</td>
<td>high alpine</td>
<td>1.3.1</td>
<td>snowfield vegetation</td>
<td>grasses, herbs, mosses</td>
<td>X</td>
</tr>
<tr>
<td>frost sorting (polygons)</td>
<td>11</td>
<td>intermediate alpine</td>
<td>1.1, 1.3</td>
<td>snowfree exposed mountain heath, snowfield vegetation</td>
<td>dwarf shrubs, mosses</td>
<td>XX</td>
</tr>
<tr>
<td>frost action (thufurs)</td>
<td>9</td>
<td>low alpine, intermediate alpine</td>
<td>1.2</td>
<td>snowcovered vegetation</td>
<td>grasses, herbs, mosses</td>
<td>XXX</td>
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</table>

*Cover: X, sparsely covered; XX, moderately covered; XXX, entirely covered
Dominant types are indicated by bold typefaces.
and creep in the Tatras. Only in the case of certain processes like frost sorting – which gives rise to sorted stripes, and then within a confined altitudinal range – did it prove possible to define the type of vegetation more precisely.

With altitude, the number of types of vegetation declines on account of the difficult conditions for the existence of plants. For this reason, irrespective of whether a given fragment of slope is modelled by frost sorting processes giving rise to polygons or sorted stripes (Fig. 4A), or by solifluction (Fig. 4B), the highest parts of the mountains support a numerically limited set of plant communities. This is a further restriction on the use of phytointegration in characterising geomorphological processes.

Fig. 2. Vegetation on slope modelled by deflation. Vegetation cover consists of two types: 1.1.1.1 Loiseleuria procumbens–Arctostaphylos alpina–Empetrum hermaphroditum type (on the dome) and Empetrum hermaphroditum type 1.1.1.2 (at the bottom of the slope); Jiebrenčohkka 800 m a.s.l.

Fig. 3. Vegetation on slopes modelled by solifluction, northern slopes of Jiebrenčohkka, 800 m a.s.l. Vegetation cover consists of two types: 1.1.3.2 (Dryas octopetala type) and 1.2.2.2 (Salix reticulata–Poa alpina type).

These preliminary results demonstrate the limitations of using vegetation in characterising geomorphological processes. This probably reflects the fact that different geomorphological processes give rise to similar habitat conditions, which in turn determine the development of similar types of vegetation. Moreover, the intensity of process, dependent on altitude or exposure, may have an influence on the degree of development of vegetation, thereby posing a further obstacle in characterising relief using vegetation. If dependent relationships are to be defined more precisely, a greater number of cases will need to be studied by statistical and cartographic methods.
Another means by which to analyse relief–vegetation relationships is by establishing a scheme for the distribution of plant communities on different landforms. The differentiation of vegetation according to landforms is readily observed in the field. Landforms may be described by reference to a sequence (zonation) of plant communities, or else a mosaic-like configuration of plant communities. A full listing of the plant communities actually recorded within selected landforms is presented in Table 2. A series of schematic representations of plant communities and landforms was generated from the field observations. In constructing these models, however, it is important to bear in mind that a degree of generalisation is involved and that other factors also influence vegetation. For example factors such as lithology or the location within an altitudinal belt exert a stronger impact on the spatial configuration of plant communities than does the form of relief alone, thereby necessitating modification or multiple modelling in the depiction of forms. The type of vegetation is above all dependent on whether or not the substrate has crystalline or carbonate rocks. The properties of the rocks can influence the vegetation directly or indirectly, however. For example, on the western slopes of Njulla – from the summit down to an altitude of c. 900 m a.s.l. – calcicolous vegetation occurs, in spite of there being no outcrops of calcareous rocks. According to Lindström (1955) and Kulling (1964), Njulla is formed from layers of crystalline schists and a layer of marble that slope down towards the west. The calcicolous vegetation may thus be related to groundwater flow from the carbonate rocks.

The following are examples of the typical system of vegetation on selected geomorphological forms.
Thufurs. The characteristic vegetation of thufurs is presented in Fig. 5. The thufurs on crystalline substrates in the low-alpine and intermediate-alpine belts (Fig. 5A) have a vegetation complex including types 1.2.3 (short-herb meadow on poor soil) on the crests of thufurs, as well as 1.3.1 (snowfield vegetation on poor soil) in the intervening parts. In turn, those in the low-alpine belt on a dolomitic substrate (Fig. 5B) have a vegetation comprising types of heath vegetation on poor soils (1.2.1), or else meadow vegetation (1.2.4). These differences are evident in the field (Fig. 6).

Solifluction lobes. Solifluction processes are frequent and active in the study area, hence the frequency of occurrence of solifluction lobes or tongues which may be overgrown to differing extents. Figure 7 presents an example longitudinal profile of a lobe with a relatively complex spatial system of plant communities on the surface, mainly comprising complexes formed from the communities of types 1.2 (snowcovered vegetation — early thaw on firm ground) and 1.3 (snowfield vegetation). In contrast, small terraces or thufurs formed on the surface of the lobe mainly have vegetation type 1.1 (snowfree exposed mountain heath). The schematic representation in Fig. 7 is typical for the solifluction lobes in the intermediate- and low-alpine belts, on crystalline substrates, in which the spectrum of plant communities included growing

<table>
<thead>
<tr>
<th>Geomorphological form</th>
<th>thufurs</th>
<th>solifluction lobes</th>
<th>sorted strips</th>
<th>nival niches</th>
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<tr>
<td>Lithology</td>
<td>dolemes</td>
<td>crystalline rocks</td>
<td>dolemes</td>
<td>dolemes</td>
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<td>Altitudinal belt*</td>
<td>l.a.</td>
<td>l.a.</td>
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<td>Vegetation type</td>
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<tr>
<td>1.1.1.1 Loiseleuria procumbens–Arctostaphylos alpinus</td>
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<td>1.1.2 Empetrum hermaphroditum type</td>
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<td>1.1.3 Juncus trifidus type</td>
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<td>1.1.3.1 Kobresia myosuroides–Dryas octopetala type</td>
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<td>1.1.2.2 Dryas octopetala type</td>
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<td>1.2.1.1 Vaccinium myrtillus–Phylloce caerulea type</td>
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<td>1.2.1.3 Carex bigelovii–C. lachenali type</td>
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<td>1.2.1.4 Deschampsia flexuosa–Anthoxanthum odoratum–Alchemilla alpina type</td>
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<td>1.2.1.5 Juncus trifidus–Salix herbacea type</td>
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<td>1.2.2.1 Cassiope tetragona type</td>
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<td>1.2.2.2 Salix reticulata–Cassiope capillaceum type</td>
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<tr>
<td>1.2.3.1 Vaccinium myrtillus–Phylloce caerulea type</td>
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<td>1.2.3.2 Saxifraga stellaris–Oxysta digyna type</td>
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<td>1.2.4.1 Potentilla crantzii–Bistorta vivipara type</td>
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<td>1.2.5.1 Athyrium distichum type</td>
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<td>1.2.6.3 Trollius europaeus type</td>
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<td>1.3.1.1 Cassiope hypnoides–Salix herbacea type</td>
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<td>1.3.2.1 Distichium capillaceum variant</td>
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<td>1.3.2.3 Carex bigelovii–Sphagnum compactum variant</td>
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* l.a., low alpine belt, 600–900 m a.s.l.; i.a., intermediate alpine belt, 900–1200 m a.s.l.; h.a., high alpine belt, above 1200 m a.s.l.
on the lobe is very broad. In contrast, in the high alpine belt, the surface of solifluction lobes is either entirely bare of vegetation or else characterised by practically all of the types that can grow at this level, which is to say 1.3 (snowfield vegetation) and 1.1 (snowfree exposed mountain heath). The solifluction lobes studied on dolomites are poorly represented and came only within the low-alpine belt, where the vegetation growing on them is mainly of type 1.2 (meadow).

**Sorted stripes.** A very characteristic spatial configuration of vegetation was recorded on sorted stripes (Fig. 8). This usually grows on the edges of the stripes, while the flat parts are formed from different fractions of rock debris. Irrespective of altitude or exposure, the vegetation of the stripes comprises plant communities within type 1.1.1 (exposed mountain heath on poor soil, i.e. communities tolerating sites exposed to wind action and thus lacking in snow during winter). The flat parts of the stripes usually have procumbent and less compact dwarf shrubs, while the steep edges have taller and more compact dwarf shrubs of type 1.1.1.2, with heights up to 10 cm.

**Nival niches.** One of the most often researched and best-known systems is the characteristic configuration of vegetation in nival niches, described by Sandberg (1958) and Påhlsson (1998) among others. Differences in vegetation cover between niches are explicable in terms of differences in geological structure, particularly the lithology and depth of the niche, which in turn condition the thickness of the snow cover. The schematic representation shows a belt-like system of vegetation in a nival niche (Fig. 9). In reality, though, this is a mosaic-like system related to the micro-relief.

The vegetation of nival niches is relatively well documented (Gjaerevoll 1956; Wijk 1986). This would seem to imply relative ease of designating indicative species, but in fact it is not straightforward. The floors of nival niches on non-calcareous substrates are often overgrown by the willow, *Salix herbacea*, which is a common species in the study area. As it is easy to observe and recognise, it might be considered an indicator species. Unfortunately, the willow is also included within the composition of type 1.1 (snowfree exposed mountain heath), among others, so cannot be regarded as particularly specific. This reflects the fact that plant species...
have wider ecological amplitudes than communities thereof, meaning that their occurrence is not confined to one narrow habitat type. This is also true of other species associated with other landforms, such as the easily recognisable *Empetrum hermaphroditum*, which may be a component of both type 1.2 (snowcovered vegetation – early thaw on firm ground) and type 1.1 (snowfree exposed mountain heath). Clearly, species of plant may only be considered indicators within one form of relief, as *Salix herbacea* is for the bottoms of nival niches.

Furthermore, account needs to be taken not only of the presence or absence of a species, but also of its frequency of occurrence.

Spatial vegetational complexes characteristic of different geomorphological forms also change in relation to the exposure of the slope on which the given form occurs. This means, for example, that although nival niches have their specific set of plant communities, it is their spatial configuration and plant cover that change in relation to the exposure of the slope on which the given niche has developed.
Conclusions

The broad links between vegetation and relief in the mountains around Abisko are clear, though our preliminary research does not yet allow a precise description of these links for all of the identified geomorphological forms and processes.

Different processes can be characterised using a combination of indicative features of the vegetation, namely the types of plant community, the prevailing habits (life forms) of the plants and the degree of cover. However, none of these alone constitutes an indicative feature. Further it is worth emphasising that plant communities are better indicators than single species, because their ecological amplitude is narrower than those of their constituent species.

Some processes and landforms can be characterised more unequivocally than others. This may reflect not only the present level of knowledge, but also the properties of the plant species or communities themselves, as these reflect a whole complex of habitat conditions, and not merely the conditions associated with relief.

The nature of the substrate and climatic conditions give rise to a very distinct differentiation of vegetation into trophic series and altitudinal belts, respectively. For this reason, consideration of the
Vegetation and geomorphological forms should be made separately for non-carbonate and carbonate series, with account also being taken of altitudinal differences.

Not all of the features of vegetation examined in this preliminary analysis have emerged as being decisive in encapsulating the relief–vegetation relationship. In particular it proved impossible to demonstrate the influence of exposure on the links between vegetation and geomorphological processes, though a different spatial configuration of communities on slopes of differing exposure may be observed.

If vegetation is to be useful in characterising geomorphological forms and processes, it will be necessary to describe phytoindicators more precisely and to develop indicative scale. The results of the present study are a first step in establishing the existence of repeatable dependent relationships.

The study in mountains of the sub-Arctic zone also allows the setting of limits to the applicability of phytoindicative methods. From the high-alpine belt onwards, the living conditions for plants are so harsh that only ever more limited forms can survive. The high diversity of geomorphological processes in these areas is thus associated with a small number of plant communities, for which the snowline is an absolute boundary of occurrence. This rule probably applies to many high-mountain areas.

The mountains of the Abisko area differ quite markedly from the Tatras as far as the vegetation is concerned, and while the geomorphological processes are similar, they differ in intensity and frequency of occurrence. In addition, research on the interrelationships between vegetation and landforms has a longer history in the Tatras, with the result that more precisely defined links have been established. Nevertheless, the character of the linkages is very similar, resulting from the fact that vegetation and landforms are not interlinked directly, but rather via other geocomponents.

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Fig. 9. Schematic representation of vegetation within the nival niches: (A) located at 780 m a.s.l. (low-alpine belt); (B) located at 1070 m a.s.l. (intermediate-alpine belt).
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