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3.4.10. Biogeomorphology: sampling and analysis of proglacial and supraglacial vegetation

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ABSTRACT: Herbaceous and arboreal vegetation are useful tools in the study of the landscape transformations affecting glacial areas. In glacier forelands, the study of vegetation succession enables the identification of the age of the deglaciated terrain and contributes to investigation of the distribution of the main geomorphological processes occurring in the area, such as gravitative and glaciofluvial processes. On the surface of debris-covered glaciers, the analysis of the distribution and characteristics of vegetation provides information on the glacier dynamics, such as glacier velocity and the stability of the supraglacial debris. In this chapter, two methodologies for the study of the distribution and characteristics of vegetation in glacial environments are proposed. The first enables a rapid and preliminary investigation of the study area (both in the glacier foreland and at the surface of a debris-covered glacier) through remote sensing analysis, by performing a supervised classification on colour orthophotos. The second method involves detailed field surveys to describe species composition and, when applied to recently deglaciated areas, enables the estimation of terrain age. On the other hand, on debris-covered glaciers the analysis of vegetation, in particular arboreal species, allows the investigation of the past and current glacier dynamics.

KEYWORDS: glacier retreat, vegetation succession, supraglacial vegetation, debris-covered glacier, glacier foreland

Introduction

Glacier retreat and the increase in the number of debris-covered glaciers are amongst the main consequences of the ongoing climate change in high mountain environments. Geomorphic processes affecting recently deglaciated areas, including stream activity, frost action, debris fall and mass movement, cause rapid variation of the glacier foreland (Ballantyne, 2002). On the other hand, the supraglacial debris coverage is characterized by frequent changes, due to ice flow, differential ablation rate and surface velocity, causing continuous downvalley debris displacement (Pelfini *et al.*, 2012).

Even though these landscape transformations create unstable surfaces, glacier forelands and the surface of debris-covered glaciers represent new habitats for biological forms, such as bacteria, animals and plants (e.g. Cannone *et al.*, 2008; Nakatsubo *et al.*, 2010; Zumsteg *et al.*, 2012; Franzetti *et al.*, 2013; Arroniz-Crespo *et al.*, 2014). The characteristics of vegetation in particular, including both herbaceous (herbs, characterized by no woody stem above ground) and arboreal (trees) species, can provide detailed data about the terrain age of glacier forelands. Moreover, vegetation is not homogeneously distributed in these areas, since its growth is negatively influenced by the occurrence of gravitative and glaciofluvial processes affecting the area after deglaciation. For this reason, the analysis of the distribution and age of vegetation represents a contribution to the identification and mapping of past and current processes occurring in the area. The arboreal vegetation colonizing the supraglacial environment of a debris-covered glacier can provide information about the glacier dynamics, in particular its velocity, debris stability and debris thickness (Caccianiga *et al.*, 2011; Leonelli and Pelfini, 2013). In fact, vegetation establishment and growth in such areas are related to several climatic and environmental parameters, as well as to glacier dynamics and the frequency and intensity of geomorphological processes. Thus making vegetation a valuable tool for the study of changing glacial environments (Gentili *et al.*, 2015).

In recently deglaciated terrains vegetation establishment follows a specific trend, related to a gradual shift in the dominant processes leading to vegetation establishment; from abiotic to biotic. Colonization begins with pioneer species, that are adapted to dominant abiotic processes (sediment properties, hydrology, slope, exposure, moisture) and grow where there is no, or low, competition for resources. Then, biotic parameters (competition with other species, tolerance, inhibition) gradually become more important in the establishment of vegetation. This variation in process dominance, from abiotic to biotic, results in a gradient in species composition and vegetation cover with increasing terrain age (for more details see Matthews, 1992; Rossi *et al.*, 2014; Suvanto *et al.*, 2014). Vegetation succession is influenced not only by climatic conditions, but also by geomorphic processes. In particular, paraglacial processes are dominant in the preliminary phases of colonization. When the ecosystem is at a more developed stage (when late successional vegetation such as arboreal species occur), then vegetation has a stabilizing effect on the deglaciated terrain (Eichel *et al.*, 2013; Figure1).

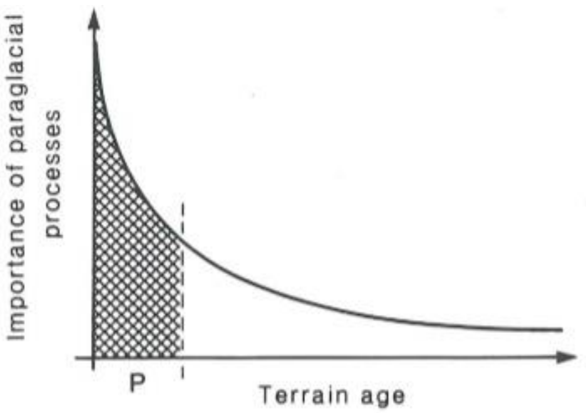

Figure 1: Decline of the importance of paraglacial processes with increasing distance and time from the retreating glacier. The darker area represents the phase characterized by dominance of paraglacial processes (from Matthews, 1992).

Several factors influence the colonization of vegetation and, in particular, arboreal vegetation on the surface of debris-covered glaciers. The distance between the closest proglacial forested area and the glacier itself is certainly important, but other glacier parameters play a role in the establishment of arboreal vegetation, such as glacier surface velocity, slope, debris thickness and grain size of the substrate (Leonelli and Pelfini, 2013). Therefore, investigating the distribution and characteristics of supraglacial arboreal species contributes to the study of debris-covered glaciers and can be investigated using dendrochronological techniques.

Dendrochronology is a dating method based on the analysis of tree rings (Fritts, 1976). Tree-ring width and characteristics are influenced by several factors including climate and environmental disturbances. For this reason, a dendrochronological study performed on supraglacial vegetation enables the reconstruction of the evolution of debris-covered glaciers in the recent past. In fact, growth disturbances and compression wood are produced as a response to a dynamic glacier surface (Pelfini *et al.*, 2007; Garavaglia *et al.*, 2010), thus making dendrochronology a valid approach to determine the years characterized by high surface instability and to reconstruct past glacier dynamics.

An approach for analyzing the dynamics of glacial environments through the investigation of vegetation is outlined in the remainder of this chapter.

Vegetation distribution using remote sensing

Remote sensing techniques enable the identification of herbaceous and arboreal vegetation in glacier forelands and on debris-covered glaciers. There are only a limited number of studies using remote sensing techniques in these environments, for example Klaar *et al.* (2014) successfully applied it in the study of vegetation succession in glacier forelands in Alaska (USA), with the aim of analyzing the interactions between physical and biological processes in recently deglaciated terrains. Until now, only Vezzola *et al.* (submitted) mapped the distribution of vegetation on the surface of a debris-covered glacier, using colour images to investigate the largest debris-covered glacier in the Italian Alps, the Miage Glacier (Aosta Valley, Western Italian Alps). Both these studies found that remote sensing is certainly a useful approach in an initial mapping of vegetation in these areas, however full understanding can only be gained by complementing it with field surveys to obtain detailed information about vegetation distribution. By using remote sensing, it is possible to cover wide areas and collect distributed data, as well as enabling repeat analysis over different years. However, the small canopy, reduced height and discontinuous distribution of the vegetation growing in these areas cannot be easily identified by remote sensing techniques, since it will not be visible in the image as a consistent green patch. For this reason, using solely remote sensing for this research would result in an underestimation of vegetation coverage.

High resolution is an essential requirement to detect vegetation in glacial environments. Images featuring a pixel size of at least 0.5 m x 0.5 m are appropriate for the investigation of herbaceous and arboreal species; resolutions any lower make it impractical to distinguish the vegetation (see the example in Figure 2).

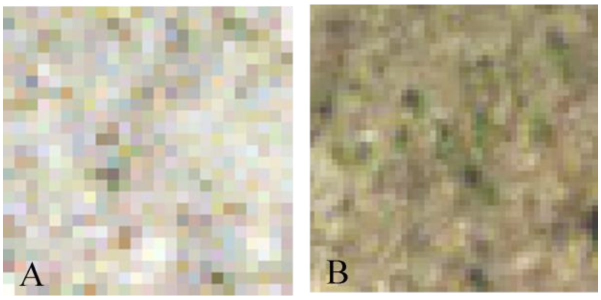

Figure 2. The same 25 m^2 area on the surface of the debris-covered Miage Glacier in the Italian Alps in a colour orthophoto acquired in (A) 1999 with pixel size 1m x 1m, and (B) 2010 with pixel size 0.5m x 0.5m. Green pixels represent vegetated areas. As can be seen, a pixel size of 0.5m x 0.5m allows more accurate analysis, compared to the image featuring pixel size of 1m x 1m.

Colour orthophotos are aerial photographs that have been geometrically corrected, so that the scale in the image is uniform and they are authentic representations of the surface of the planet. Colour orthophotos acquired in the last 10 years generally have sufficient resolution to be suitable for the analysis of vegetation in glacial environments. For research purposes, colour orthophotos are often available for free or at discounted prices from the local and regional administrative offices or mapping agencies. For instance, in Italy colour orthophotos may be found on the website of the Geoportale Nazionale, while in the United Kingdom the Ordnance Survey can be contacted.

Both in the case of recently deglaciated areas and debris-covered glaciers, a semi-automatic approach can be employed, by performing a supervised classification using Maximum Likelihood algorithm. The study area must be extracted from the orthophotos and using a GIS software such as ENVI ("ENvironment for Visualizing Images", a software commonly used for image analysis; for more information and purchasing see the website), the classifier must be trained to discriminate between classes through selection of appropriate Regions Of Interest (ROIs). These can be either polygons or individual pixels, and must include at least one ROI corresponding to vegetation. To do this in ENVI, after uploading the image, the "Roi Tool" must be selected (Basic Tools > Region of Interest > Roi Tool), and the pixels in the "Zoom window" manually selected where vegetation is present (Figure 3). The ROIs must then be saved on the computer.

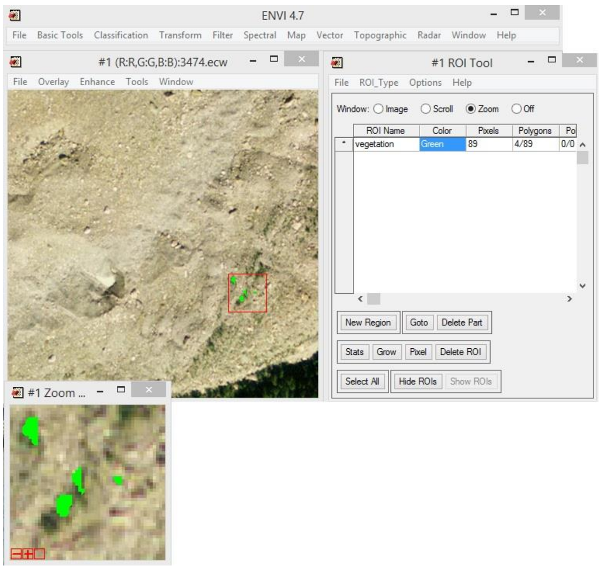

Figure 3. The selection of appropriate pixels for the ROI in ENVI called "vegetation" in a colour orthophotos representing a debris-covered glacier.

To accurately classify the images it is best to select a similar number of pixels for each ROI. The number of selected pixels is related to the size and resolution of the image and it can vary greatly. As a general rule, for images featuring pixel size of 0.5 m x 0.5 m, at least 2000 pixels should be selected for each ROI. The number of ROIs can also vary, in some studies the selection of only one ROI, corresponding to vegetation can be enough; all the other features will be automatically classified as belonging to another ROI. The final result, in this case, will be a two-colour image, defining the distribution of vegetation and of all the other features that are classified as "different from vegetation". However, more ROIs can also be selected, to describe other features in the image. In this latter case, the probability of classifying some pixels incorrectly is reduced.

After defining the ROIs, an automatic classification of the image must be performed, using the Maximum Likelihood algorithm. In ENVI, the option "Maximum Likelihood" must be selected (Classification > Supervised > Maximum Likelihood). A new window will appear, in which the saved ROIs must be selected and the Probability Threshold must be chosen (for this study I suggest a value of 0.9, that usually enables a correct classification of the image pixels). This will lead to an automatic classification of every pixel of the image (Figure 4).

After this step, visual comparison of the resulting masks against the colour orthophotos is highly recommended to validate the results: in fact. Manual correction of the image is often necessary, since the automated approach in some cases misses areas of vegetation or detects vegetation in areas where there is no vegetation (due, for instance, to shadows or debris that sometimes feature a colour that is similar to some species of vegetation). After performing this procedure, the area occupied by vegetation (both herbaceous and arboreal species) can be easily calculated, by multiplying the number of pixels featuring vegetation by the area of each pixel.

Overall, this method provides an initial approach to quickly identify the more stable areas on debris-covered glaciers, characterized by the presence of abundant vegetation. It also enables the identification of areas characterized by geomorphic activity affecting the distribution of vegetation in recently deglaciated areas; no or low vegetation is present where glaciofluvial and gravitative processes are active.

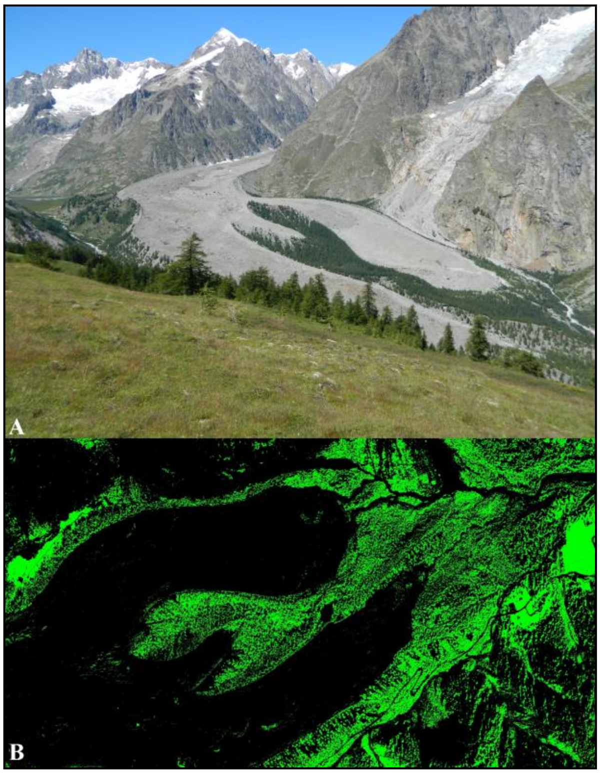

Figure 4: (A) The snout part of the Miage debris-covered glacier (Mont Blanc Massif, Western Italian Alps) (photo: D. Zannetti, August 2011), (B) classified using a semi-automatic approach by choosing two ROIs. The green colour indicates the vegetation, the black colour corresponds to "other features". Vegetation is also detected on the supraglacial debris.

Analysis of vegetation: field surveys

As already established, remote sensing provides preliminary analysis of vegetation presence and distribution. Subsequently, detailed investigation of the characteristics of vegetation should be performed in the field to describe the species established in the area and their relationship with environmental and glacier parameters. This enables the accurate reconstruction of the recent glacial history, through the calculation of the minimum age of the moraines deposited in the glacier foreland, and of the terrain between the moraines. On debris-covered glaciers, the investigation of arboreal vegetation is of particular interest for geomorphological purposes, because tree rings may be dated and consequently used to identify the years characterized by high and low dynamicity of the glacier surface. Moreover, the characteristics of tree rings provide information about the areas affected by glacial melting water on the glacier surface or in its proximity (whenever affecting the growth of arboreal vegetation). For this reason, the analysis of arboreal vegetation represents a contribution to the assessment of the geomorphological hazards related to the dynamics and hydrology of debris-covered glaciers.

Recently deglaciated areas: chronosequences

Field surveys of vegetation in glacier forelands are performed by conducting chronosequences. These are sets of sites formed from the same substrate that differ in the time since they were formed (Walker *et al.*, 2010). When planning vegetation sampling in recently deglaciated areas, it is important to select the distribution, number and size of plots to provide a representative analysis for the whole study area.

When the study of vegetation is very detailed (that is considering both herbaceous and arboreal vegetation) the size of the plots could range between 0.5 m x 0.5 m and 5 m x 5 m. The number of plots is related to the size of the study area, however, a minimum of 10 plots homogeneously distributed should always be sampled. The plots should be delimited using quadrats or tape measures (Figure 5). The advantage of using quadrats, when available, is that they are usually characterized by the presence of a grid delimiting smaller squares that allow an easier approximation of vegetation cover.

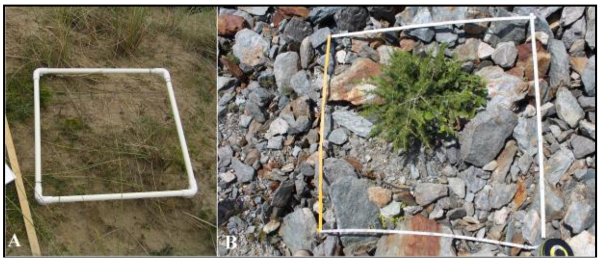

Figure 5: A plot delimited by (A) a quadrat and (B) tape measures.

The characteristics of every plot can then be collected and subsequently organized in one or more tables including the following data:

- List of species;
- Vegetation coverage;
- Age since deglaciation (years);
- Environmental information (site-specific);
- Soil analysis.

In every plot, species and coverage of vegetation must be analyzed. After identifying the species with the aid of a guide to local flora (e.g. for alpine species: Dalla Fior, 1926) both vegetation cover and the cover of every species detected can be visually estimated using percentage coverage. Usually, relative abundance (the ACFOR scale) rather than absolute is preferred (Table 1).

Table 1: The ACFOR scale for measuring relative abundance of species in every plot.

Species abundance	Letter
Abundant (30% +)	A
Common (20 to 29%)	C
Frequent (10 to 19%)	F
Occasional (5 to 9%)	O
Rare (1 to 4%)	R

Vegetation coverage can also be defined using the Braun-Blanquet scale (Braun-Blanquet, 1932; see example of its application in a glacier foreland in Caccianiga and Andreis, 2004). This associates a symbol, letter or number to each percentage defined in the plot (Table 2).

Table 2: The Braun-Blanquet scale for determining vegetation coverage.

Percentage cover	Braun-Blanquet
Single Individual	r
Sporadic	+
0-5%	1
5-25%	2
25-50%	3
50-75%	4
75-100%	5

Percentage of cover and vegetation strata are related to the terrain age. For this reason, the variation in species richness in plots located at increasing distances from the actual glacier terminus enables the calculation of the minimum age since deglaciation (see example in Figure 6).

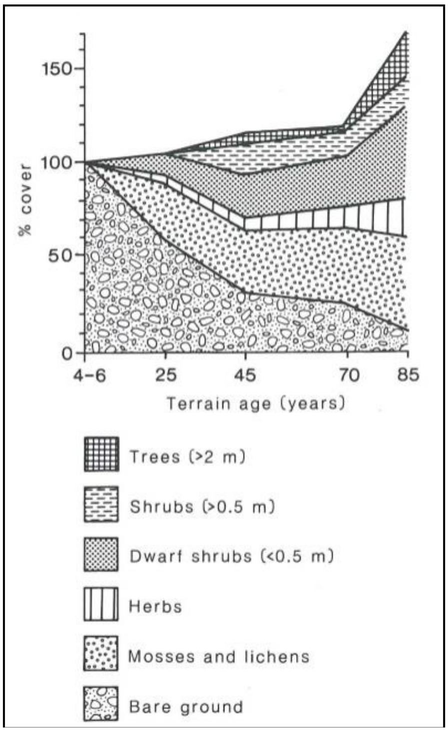

Figure 6: Variation of cover percentage and vegetation strata related to terrain age at the Grand Glacier d'Aletsch, in the Swiss Alps (from Lüdi, 1945). Values in parenthesis indicate the height of the strata.

Environmental parameters must also be evaluated for each quadrat. Slope can be measured using an inclinometer or similar, and aspect determined using a compass. Elevation may be measured using a GPS (Global Positioning System) when available, otherwise it can be calculated using contour lines on a map of the study area. The distance from the current position of the glacier terminus may also be measured using a GPS or a map. If the position of the plot is recorded, distance from the glacier tongue can be easily measured using GIS (using the "measure" and "distance" tools). Other relevant information for the specific study area should be noted during the field surveys, in particular those related to the occurrence of geomorphological processes affecting the location. The most common in glacier forelands are gravitative slope movements, stream flow, and drainage.

The representation of the position of each plot and their characteristics in a cartographic map can help in the understanding of the relationship between the position of the glacier terminus and the gradual development of the glacier foreland. In order to do that, the position of the plots can be recorded with a GPS and then reported in GIS for the subsequent creation of a detailed map of the study area.

The analysis of the physical and chemical properties of the soil (horizon identification and designations, grain size analysis, humified organic carbon) represents an additional analysis. It is performed on some homogeneously distributed plots from the study area and it may provide information about the degree of evolution of the terrain. Soil analysis is performed by first identifying the horizons present in a selected profile by digging a plot, as shown in Figure 7 (useful information for distinguishing between different horizons can be found in Chapter 3 of the free online resource "Soil Survey Manual"). Grain size and humified organic carbon can be analyzed using laboratory techniques, so it is important to get samples of soil from each horizon identified in the profiles. Further information on analysing soil properties can be found in numerous articles in Section 1 of *Geomorphological Techniques*.

Figure 7: The soil properties of profiles detected in a plot are investigated. In the image, the identification of the horizons and their depth are being performed (photos: F. Sobacchi; summer 2014).

The study of the colonization of recently deglaciated terrains can also be focused on arboreal species only. In this case, bigger plots can be considered, still homogeneously distributed in the study area (e.g. plot size 15 m x 15 m). Terrain age is the main factor controlling the colonization of arboreal vegetation, but also herb coverage and altitude (Garbarino *et al.*, 2010). The advantage in studying trees lies in the possibility to date the minimum age of the glacier-free surface, through dendrochronological investigations (see Torbenson, 2015). *Ecesis*, in particular is the lag time between surface exposure and germination of arboreal species (McCarthy and Luckman, 1993). When tree rings are dated, reconstructions of glacier retreat and dynamics can be conducted.

Figure 8: A young Norway spruce (species Picea abies Karst) in the Forni Glacier foreland (Italian Alps) during summer 2014. To determine its age, whorls branch counting was performed: in this case, three whorls can be easily identified (indicated with red lines), so the tree is three years old.

Tree size does not always allow the sampling of cores and, for this reason, two different approaches should be applied. For trees taller than about 1 m, standard dendrochronological techniques may be applied (see Torbenson, 2015), to correctly date each tree ring and compare this data to the distance from the glacier front. When trees are smaller than 1 m, and only when the investigated species is a conifer, the age can be determined by whorls branch counting (Figure 8). This technique consists of counting the "layers" of branches, called whorls by botanists, since for tree species producing annual branch whorls, each branch whorl represents a year of life, thus allowing a precise estimation of the age of young trees (e.g. Haire and McGarigal, 2010). In both cases, after defining the tree age, comparison with the distance from the glacier front can be performed. In this way, it is possible to determine the minimum age of the deglaciated terrain, both in recent times and in further back in time.

Debris-covered glaciers

To analyze detailed glacier dynamics in the recent past, arboreal vegetation can be studied on the supraglacial debris. Tree analysis can be performed using a dendrogeomorphological approach. After selecting one or more species to investigate, the individuals to sample must be selected. Usually, conifers are the most common tree species on the glacier surface (i.e. *Larix decidua* Mill., *Picea abies* Karst). Trees located in different sites on the glacier surface should be chosen, to analyze glacier dynamics in different areas. The distribution of trees is usually not homogeneous, due to differences in debris thickness and glacier velocity on the glacier surface that influence tree establishment and germination (Pelfini *et al.*, 2012). For this reason, it is not always possible to get samples from trees homogeneously distributed on the glacier surface. However, if it is possible to select at least ten trees on the glacier surface, the analysis of recent glacier dynamics in the sites surrounding the sampled trees can be successfully conducted.

To analyze tree-ring characteristics, only adult trees should be selected (trees at least 1-2 m high dependent on species), and two cores should be taken from each selected tree, using a Pressler's increment borer (Figure 9). By comparing the sampled cores of each tree, tree rings can be correctly dated. The years characterized by high surface instability are usually characterized by the presence of growth anomalies such as compression wood, abrupt growth changes and eccentricity in the tree rings, that can be observed under a microscope (Figure 10; for details about these specific terms see Torbenson, 2015). By collecting and analyzing samples from trees located at different sites on the glacier surface, distributed data about the glacier past dynamics may be obtained. In this way, the reconstruction of past events at an annual resolution involving changes in glacier surface stability is possible.

Figure 9: Tree sampling using a Pressler's increment borer.

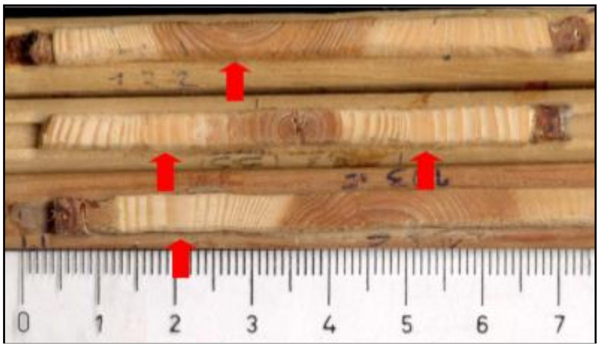

Figure 10: Three cores sampled from supraglacial trees at the Miage Glacier, presenting typical responses to the substrate movement (indicated by the arrows). The upper core shows stem eccentricity, the central core shows compression wood, the lower core shows an abrupt growth change (from Leonelli and Pelfini, 2013).

Conclusion

The investigation of vegetation in glacier forelands and on the surface of debris-covered glaciers represents a valid contribution in the reconstruction of the recent glacier history and dynamics, especially in the context of climate warming. By applying the methods described in this chapter, it is possible to undertake both analyses of vegetation distribution (using remote sensing techniques) and detailed studies of its characteristics using field surveys. In glacier forelands, the study of the distribution and characteristics of vegetation enables the estimation of the age of the deglaciated terrain and it contributes to the investigation of the geomorphological processes occurring after deglaciation, such as gravitative and glaciofluvial processes. On the surface of debris-covered glaciers, the analysis of arboreal vegetation provides information on the glacier past and current dynamics, including glacier velocity and the stability of the supraglacial debris.

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