Exploration of beta diversity across altitude gradients in an Alpine region in Trentino using FOSS4G and a historical floristic archive

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Abstract

In the changing alpine mountain environment, beta diversity plays a crucial role in understanding ecosystem dynamics and guiding conservation efforts. This study wants to demonstrate the FOSS4G capabilities presenting a preliminary exploration of species turnover across environmental gradients in the Province of Trento, a highly biodiverse region in the northeastern Italian Alps, using a large database of vegetation surveys from the 1970s that was digitized and organized into a geodatabase using FOSS4G in the FORCING project. GRASS, QGIS, PostGIS, and R were used to process data from 517 linear transects, encompassing 190,761 species records. Beta diversity was assessed in relation to environmental factors such as altitude and slope, with statistical tests performed using Pearson correlations and Sørensen's similarity coefficient. Variance partitioning was conducted via redundancy analysis (RDA) in R's Vegan package. Results indicate that species richness and beta diversity increase with greater altitude and slope variation along transects, confirming that more heterogeneous environments support higher species turnover. Sørensen's coefficient revealed that species similarity declines with altitude separation, particularly beyond 1,500 meters. Variance partitioning identified altitude range as the most influential factor, with combined effects from slope and elevation contributing significantly to beta diversity. This study demonstrates the effectiveness of FOSS4G software for spatial statistical analyses in biodiversity research, highlighting its capability to integrate numerical and geostatistical approaches. Future research will compare historical and contemporary floristic data, apply alternative statistical methods, and incorporate remote sensing for enhanced biodiversity assessments.

1. Introduction

Biodiversity evaluation is one of the most important open issues in ecological research, and its assessment is one of the most fascinating and difficult field of study for naturalist and ecologist (Chiarucci et al., 2008, Imran et al., 2024). Often, when scientists try to communicate the concept of biodiversity to the general public, the term "biodiversity" is described as species richness, the number of species in a certain area (Naughton-Treves at al., 2005) Species richness is the simplest of many ways to measure biodiversity, the concept is more complex and relative abundance of the species is taken into account to develop different indexes. Traditionally, biodiversity can be divided into three main components: i) alpha or local diversity (α), ii) beta diversity or differentiation (β) and iii) gamma or regional diversity (γ) (Koeleff et al., 2003). While alpha diversity and gamma diversity can be defined as the number or diversity of species within community samples or within the entire study region, beta diversity represents a measure of the rate of change of species presence (Whittaker, 1972). So, beta diversity is the spatial turnover in the identities of species and is a measure of the difference in species composition either between two or more local assemblages or between local and regional assemblages (Jost, 2007, Malanson et al., 2022). In other words, the analysis of beta diversity can stress the presence of patterns in biodiversity along gradients or within a study area. This aspect is particularly important due to the direct implications in nature conservation and in planning of nature protection areas (Bonari et al., 2025).
For example, Jankowski et al. (2009) assert that high beta diversity along environmental gradients reflects habitat specialization by the constituent species, and quantifying beta diversity along such gradients can contribute to set up strategies to protect the biological diversity of a landscape. Or, again, spatial variation in species composition is important for planning because it quantifies the area that is necessary to protect species of a habitat type (Tattoni et al., 2019).

Several scientific studies underlined that beta diversity is a key concept for understanding the functioning of ecosystems as well as for the conservation of biodiversity (Legendre et al., 2005, Socolar et al., 2016). The difference in terms of beta diversity can be due to the degree of environmental change between different areas but can also be related to the spatial or temporal distance between samples (McGlinn and Palmer, 2011).

The results of several research that compare the species turnover across environmental gradients on large-scale study areas, show that altitude, latitude, and geographical distance are the main drivers of beta diversity. (Beck and Khen, 2007, Jankowski et al., 2009, Ricotta et al., 2019). These studies, although fascinating and fundamental to understand the global trend in biodiversity and species composition, can hardly be applied to a local scale, for example pursuing the purpose of obtaining information in a local conservation planning point of view.

In this context, it is essential to conduct biodiversity analysis at finer scales investigating the species turnover across environmental gradients within a defined territory, i.e. local administrative areas, to provide information that support the management of protected areas or to develop conservation planning strategies (Andrew, 2011, Rickert et al., 2012).

The Edmund Mach Foundation, in collaboration with the University of Trento, Department of Civil, Environmental and Mechanical Engineering, recovered a huge database of vegetation surveys, originally build in the 1970s to represent the "Schmid's vegetation belts" in the forests of Province of Trento (Geri et al., 2016). Trentino is one of the most forested regions in Italy, it harbours a huge biodiversity both for alpine and mediterranean flora and fauna (Marini et al., 2009, Prosser et al., 2019) and is experiencing a continuous trend of forest cover expansion that is dramatically changing forest landscape quality and quantity (Ciolli et al., 2012, Gobbi et al., 2019).

The identification of the forest Schmid's belts had a specific forest management meaning because they were supposed to become a permanent component of the forest assessment planning process.

Although for a series of different reasons, their management meaning was replaced by other instruments, such as forest types (Tattoni et al., 2019), all the information contained in the belts archive still maintains its meaning. In the frame of the scientific project FORCING (Geri et al., 2016) the surveys and the cartographic materials were digitized and organized in a geographic database, allowing users to explore the data using GIS tools and software (Zatelli et al., 2019). The data set is useful to detect vegetation changes occurred over the last 20-40 years. It could also help to identify the effects of potential climate change and human impacts on the Trentino's forests. Trentino region was divided into 16 homogeneous zones, each corresponding to a morphological sub-basin system, and, at the same time, divided into 5 altitude belts. Within each belt, linear segments that encompass the mountain sides in perpendicular way to the contour lines, called "series" were individuated.

A team of at least two field workers walked through the series, stopped every 50 meters of altitude step, and set the sampling area on the terrain, i.e. a transect with a length of 10 meters and 1 meter width. Within the transect all floristic species were identified and information about their abundance as well as about the morphological/geological conditions of the sampling site was collected.

This sampling design is perfectly suited to being analysed from a beta diversity perspective, permitting to compare several environmental gradients in terms of species turnover and species richness.

The aim of this paper is to perform an explorative analysis of the species turnover in a relatively small area using FOSS4G, to underline patterns and driving forces and stimulate further research questions.

2. Materials and methods

2.1 Study area

The study area is the Province of Trento in the northeastern Italian Alps, a mountain region of about 6.212 km² (Fig. 1). The territory is characterized by strong variability in forest species composition due to the presence of different geomorphological conditions and elevations (Prosser et al., 2019). The forest varies from Mediterranean vegetation where forests of *Quercus ilex* can be found, up to Alpine areas where *Pinus mugo* and alpine shrub and herbaceous vegetation are the main coverage. The importance of the region for biodiversity is underlined by the fact that it is the only area in the Italian Alps where the presence of brown bear has been constant (Tattoni et al., 2017).

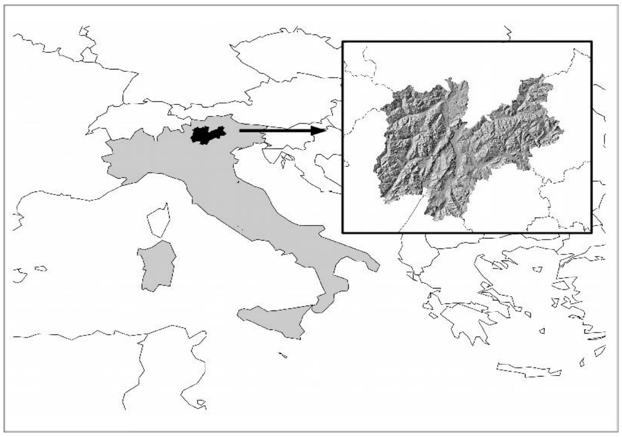

Figure 1. Study area, Trentino Province, Italy.

2.2 Data collection

The data coming from the original sampling project were digitized using Qgis software, saved in the Spatialite geographic database format and georeferenced in the WGS84 UTM 32 N reference system (srid: 32632). The linear transects, originally drawn on the paper map used for the field work were digitized manually. Each single point corresponding to the center of the transect was automatically associated with a pair of coordinates using a python script that by comparing a series of topographical parameters such as altitude, slope aspect, belonging zone can extract the corresponding record in the database.

The number of linear transect is equal to 517 for a total amount of 7,059 sampling points distributed uniformly. The total number of species detected was 1,285, for a total of 190,761 records. The estimated distance covered by the entire sampling team was equal to 65,536 meters. Figure 2 shows an overview of the study area with the sampling points plotted in red, overlayed to the transects of the original map, where it is possible to appreciate the series manually drawn that are represented by the green lines.

A Digital Elevation Model (DEM) of the province of Trento, with a spatial resolution of 10 m, was acquired from the cartographic portal of the Province of Trento, and used to derive

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environmental variables such as elevation, slope, and aspect. These 3 derived maps were overlaid with the vector line transect data and for each line were extracted a series of basic statistical parameters, specifically, mean, range, variance for slope and altitude, while only the average aspect was recorded.

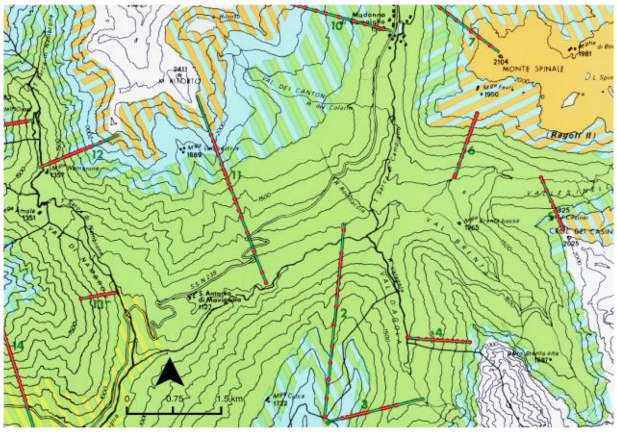

Figure 2. A particular of line transect (the green line) and the sampling site across the line, overlaid to the original paper map used during the field work.

2.3 Data analysis

Assuming that each linear transect represents a single ecological community, the beta diversity was calculated using site as simple point. The following formula was used to calculate this (Tuomisto, 2010):

$$\beta = \frac{S}{\overline{\alpha}} - 1 \qquad (1)$$

where S is the total number of species detected in the entire linear transect and $\overline{\alpha}$ is the average species richness per one site, due to the direct relation existing between S and the number of sites of the same community. Thus, we were able to evaluate the degree of species turnover across the environmental gradient that is created along the transect.

The basic statistical properties extracted for each linear transect were put in relation with the beta diversity index and (for a further comparison) with the corresponding values of species richness, producing a series of graphs that shows the various trends. The significance of the linear relations was tested using the Pearson correlation coefficient.

Deepening the relationship between altitude gradient and species turnover, the DEM of Province of Trento was reclassified in altitude belts of 300 meters of range, from a minimum of 0 meters to a maximum of 2,100 meters, obtaining 7 altitude belts. Each belt was compared in terms of species composition using the Sørensen's coefficient of similarity:

$$S = 2\,\frac{j_N}{(a_N + b_N)} \qquad (2)$$

where a_N and b_N are the total species abundances of zones a and b and j_N is the sum of the minimum abundance for each species between zones a and b. This index, which is equivalent to one minus the Bray–Curtis or the Steinhaus dissimilarity coefficient (Legendre & Legendre, 1998), has been shown to be one of the most suitable in numerous comparative studies of similarity indices (Magurran, 2004).

The Sørensen's index of similarity was applied in two ways: i) with increasing altitudinal separation from the lower belt ii) in pairwise mode, between adjacent altitude belts. Finally, the behaviour of the beta diversity and species richness were explored in terms of variance partitioning.

In particular, the technique of variation partitioning is used when two or more complementary sets of hypotheses can be invoked to explain the variation of an ecological response variable. The presence of significant relationships between the species and environmental variables would strongly support the hypothesis of environmental control (Legendre et al., 2005, Legendre, 2008).

In this case it was tested the variance explained by the four variables: mean altitude, mean slope, range of altitude and range of slope against beta diversity and species richness. The analysis should stress the role of the variable in single or in multiple way to drive the species turnover.

The variance partitioning analysis were processed using the Vegan package of the R cran statistical software (R Core Team, 2025) and, in particular the module "varpart". This function partitions the variation of response data table with respect to two, three, or four explanatory tables, using redundancy analysis ordination (RDA). To simplify the results interpretation the variance partitioning in combinations of group of three variables was applied.

Both altitude and slope data and both beta diversity and species richness data were transformed with a log transformation to obtain a normal distribution of data.

QGIS 3.34 (QGIS Development Team, 2025) was used to import data and standardize the data set, as well as to process data and produce maps useful to perform or assist R statistical analysis. GRASS 8.5 (GRASS Development Team, 2025) was used to perform data integrity check fixing data errors, recombine data from diverse sources and convert data from vector to raster or vice versa when necessary.

Different environmental covariates were collected from the PAT service while others (e.g. contours and slope) were created from the Digital Terrain Model (DTM). The cartographic raster and vector data was collected from PAT WebGis and ViabGis (see the Appendix section for all the addresses).

3. Results

In this section, the main preliminary results are reported, with the aim to start giving an idea of the main potential of FOSS4G software to analyse these data, as well as to start understanding original FORCING database limitations, possibly due to sampling methods as well as other intrinsic features that we may have not considered.

In table 1, the Pearson correlation coefficient is reported. Pearson indices demonstrates that all the variables are significant with the exception of the slope variance for both beta diversity and species richness and the mean altitude only for species richness.

Environmental variable	Beta diversity		Species richness	
	Value	p-value	Value	p-value
Mean altitude	0.2169	0.0000	0.0812	0.0814*
Variance altitude	0.4321	0.0000	0.2425	0.000
Range altitude	0.4569	0.0000	0.2588	0.0000
Mean slope	0.2638	0.0000	0.2689	0.0000
Variance slope	0.0522	0.2643*	0.0899	0.0539*
Range slope	0.2199	0.0000	0.1746	0.0002

Table 1. Results of Pearson correlation coefficient. (*not significative for a P < 0.05).

The scatterplot (Figures 3 and 4) shows the relationship between the beta diversity or species richness and the environmental variables.

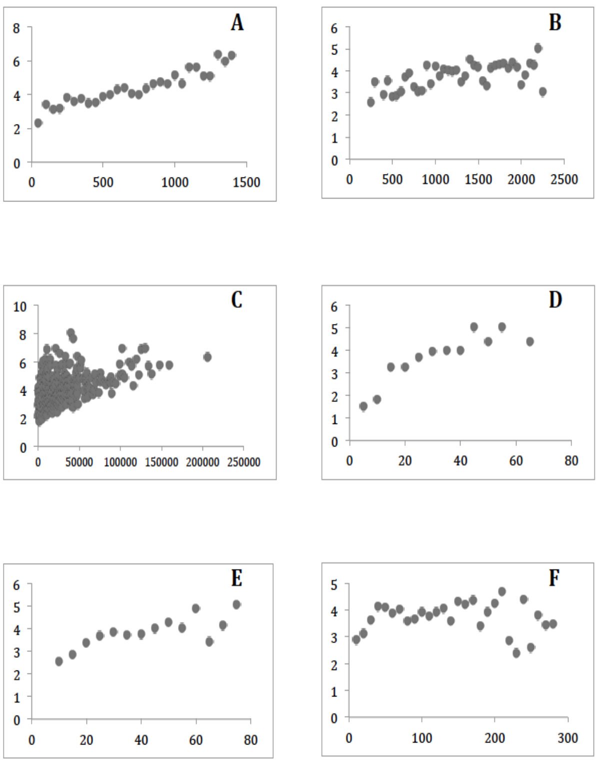

Figure 3. Relationship between beta diversity versus: A) altitude range; B) altitude mean; C) altitude variance; D) slope mean; E) slope range; F) slope variance.

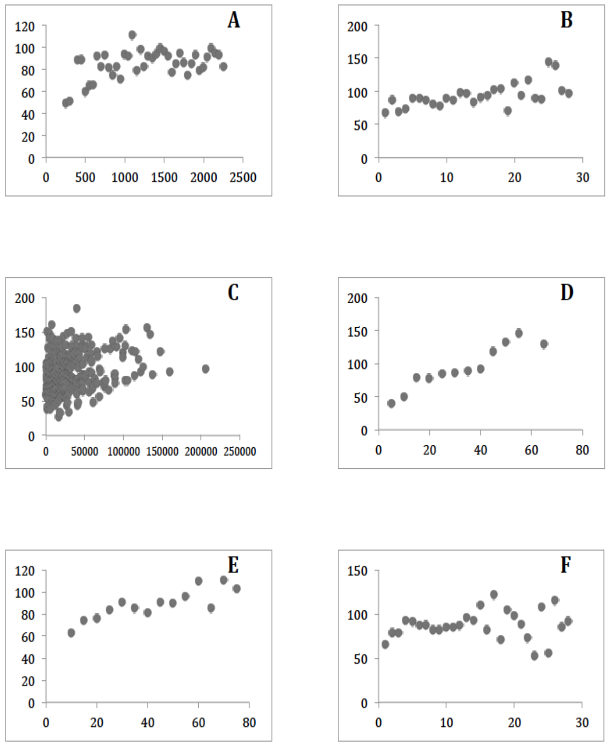

Figure 4. Relationship between species richness versus: A) altitude range; B) altitude mean; C) altitude variance; D) slope mean; E) slope range; F) slope variance.

Both species richness and beta diversity show a similar trend: they increased with altitudinal range, slope range and slope mean, while variance does not show a definite trend considering the species richness.

Examining the result of the Sorensen statistic (Figure 5) the black line shows how the similarity decreases when the altitude separation from the lower level increases, while the red line shows the pairwise comparison between altitude adjacent belts. The latter statistic shows how the similarity presents a different behaviour with the altitude increase, rising very fast in the first step (between 0-300 meters and 300-600 meters) then it levels off and finally decreases in correspondence to the last two steps, between 1,500 and 2,100 meters.

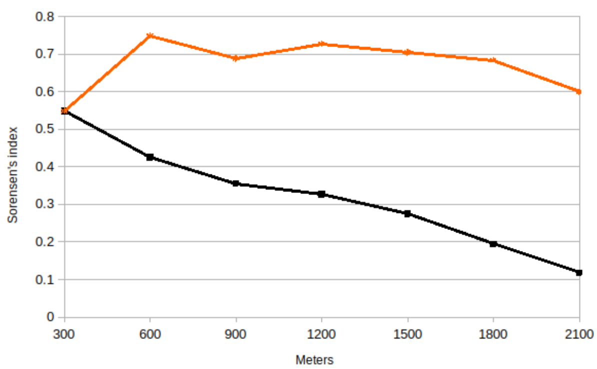

Figure 5. Sorensen similarity trend with altitude. The black line shows how the similarity decreases with increasing the altitude from the low level. The red line shows the results of the Sorensen statistic similarity processed in pairwise mode.

The relative contribution to total diversity by each altitudinal belt is shown in Figure 6 expressed in overall values and in Figure 7 where values are standardized per area.

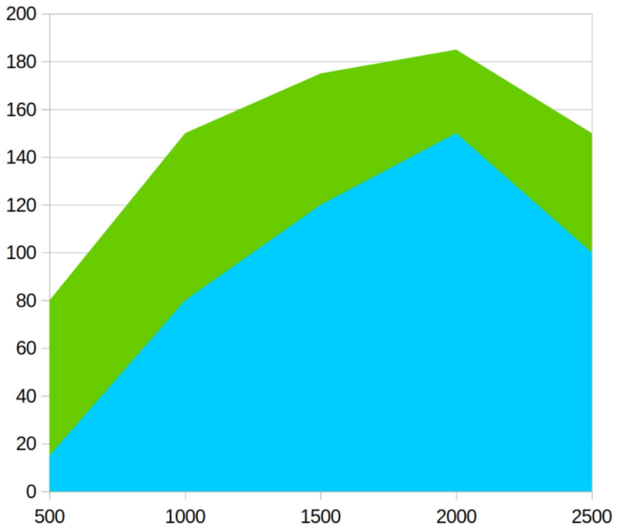

Figure 6. Relative contribution to total diversity by each altitudinal belt (overall values). The colors indicate: green, beta diversity; blue, alpha diversity.

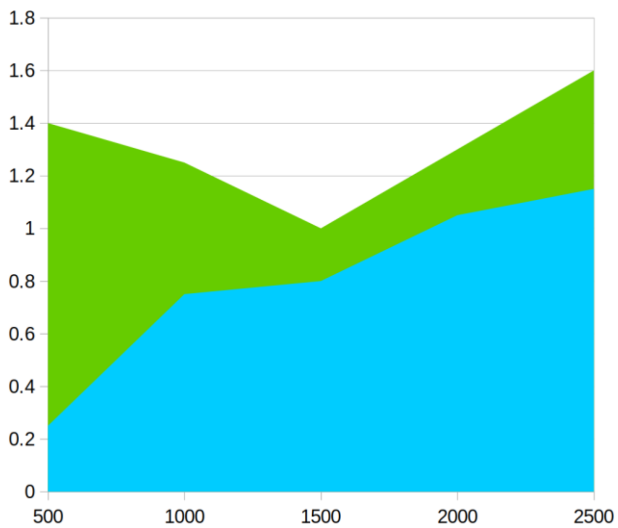

Figure 7. Relative contribution to total diversity by each altitudinal belt (values are standardized per area). The colors indicate: green, beta diversity; blue, alpha diversity.

Generally, the variable that explains the variance can be considered the altitude for both beta diversity and species richness.

Regarding beta diversity the greater joined effect is due to the combination of altitude range and mean slope while altitude range, mean slope, and slope range present a higher joined effect for three variables (Figure 3).

4. Discussion and conclusions

Although the results of this work are only preliminary, they confirm that the transects characterized by a wider range of slope and elevations show a higher rate of beta diversity. This is expected, since the larger the number of different environments the transects cross is, the more pronounced the beta diversity should be (Malanson et al., 2022).

This is also confirmed by the linear relation of the single variables highlighted both as graphical trend (Figures 3 and 4) and by the Pearson tests (Table 1) and, moreover, by the fact that the variance is explained as a joint action of variables.
Regarding the partitioning calculation, the values are very low while the residues are high especially for species richness. With beta diversity the factors considered and analysed explain about 20-25 % of variance; the main factors are always connected to elevation range and mean slope.

The Sorensen graph clearly shows that in the bottom of the valleys the species similarity is very high, while species similarity values decrease gaining elevation. It is interesting to compare this behaviour with linear relations graphs, i.e. mean altitude and species richness; that show a very flat relation, highlighting that number of species does not increase with altitude.
The relation between beta diversity and altitude, although appearing statistically significant, does not show a high R^2 value. Therefore, species turnover along the transects seems relatively constant and independent from the lower or higher elevation position of the transect, even though the species that can be found in the low altitude transects are very different from those found in the high altitude transects.

The general turnover trend can be partially explained by the fact that many forest environments in Trentino (as well as in many other parts of the Alps) are recovering from a period of former overexploitation occurred in the 19th century up to the end of the second world war (Tattoni et al., 2021) and this phenomenon may affect somehow species distribution and diversity.

The species are reconquering their place (Anselmetto et al., 2025) with a different dynamic at different altitudes and rebuilding a natural environment in a spatial distribution that interests the whole alpine regions, including the Trentino territory. It could be interesting to analyse the data considering the forest types classified in anthropic disturbance order.

Further studies may include a temporal perspective that examines beta diversity variation in the last 50 years considering shifting management practices (Koch et al., 2017, Chianucci et al., 2025, Marengo et al., 2025) as well as considering climate change effects (Lelli et al., 2023, Liberati et al., 2019, Tordoni et al., 2020). Another interesting possibility is to compare more recent data, for example those collected in the “forest types” (Tattoni et al., 2019) catalogues or recent information about invasive species distribution (Campagnaro et al., 2022), with those of the FORCING historical archive.

Although this is only a preliminary study and a more comprehensive analysis is needed to fully understand the overall ecological situation of the dataset, the main conclusion of this work is that FOSS4G has demonstrated to possess all the features to perform the entire process along the realization of this work, from storing data in a WebGIS to performing complex statistical and geostatistical analyses on floristic data, and the FORCING dataset is suitable to be used for further analysis.

Unfortunately, due to a hacker attack the FEM servers, the website https://meteogis.fmach.it/forcing/webgis.php is currently under maintenance, but we hope to restore its functionality during 2025 maintaining the same address.

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APPENDIX

Data for different features, Topography, DTM, Land Use, Urban Planning, Roads, Cadastral Data, hydrography, in Shape file and other various format can be downloaded at the following addresses:

Provincia Autonoma di Trento - Urbanistica - Cartografia PUP, http://www.urbanistica.provincia.tn.it/pianificazione/piano_urbanistico_provinciale/cartografia/pagina161.html Accessed: 7 December 2024

OPENdata Trentino - http://sdi-pat.provincia.tn.it/. Accessed: 7 December 2024.