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MODELING OF FOREST LANDSCAPE EVOLUTION AT REGIONAL LEVEL: A FOSS4G APPROACH

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ABSTRACT:

In the last decades the Alpine landscape has dramatically changed due to social and economic factors. The most visible impact has been the reduction of the population for mid and high altitude villages and the shrinking of the part of the land used for agriculture and grazing, with a progressive reduction of pastures and meadows and the expansion of the forested areas. For these reasons, a dataset describing the forest, meadows and pasture coverage for the Trentino region, in the eastern Italian Alps, has been created. A set of heterogeneous sources has been selected so that maps and images cover the longest possible time span on the whole Trentino region with comparable quality, creating a Land Use/Land Cover (LULC) map based on historical maps from 1859 to 1936 and aerial images from 1954 to 2015. The achieved accuracy ranges from 98% for historical maps to 94% for aereal imagery. The analysis of selected landscape metrics provided preliminary results about the forest distribution and patterns of recolonization during the last 155 years. It has been possible to create future scenarios for the forest evolution for the next 85 years. Given the large number of maps involved, the great flexibility provided by FOSS for spatial analysis, such as GRASS, R, QGIS and GAMA and the possibility of scripting all the operations have played a pivotal role in the success both in the creation of the dataset and in the extraction and modeling of land use changes.

1. INTRODUCTION

Social and economic factors have caused a drastic change in the European mountain landscape, and in particular in the Alpine landscape (Tattoni et al., 2017). The reduction of the population in higher areas and the abandonment of low yielding fields has resulted is a progressive decrement of pastures and meadows with the corresponding increase of the forested areas (Garbarino et al., 2020). Forest plots become also more compact, with the loss of ecotones. Landscape change is also affecting landscape perception by tourists (Pastorella et al., 2017) and different ecosystem services (Tattoni et al., 2021).
The study of this phenomenon is important not only to assess its current impact on the ecological functionality of forest ecosystems, including biodiversity conservation (Sitzia et al., 2017) and protection against natural hazards (Sitzia et al., 2019), but also to build future scenarios, taking into account also climate change issues (Tappeiner et al., 2008). The limit of the mountain treeline is gradually shifting upwards and the monitoring and modeling of these changes will be crucial to plan future interventions and the implementation of effective adpatation measures (Cantiani et al., 2016).
For these reasons, a dataset describing the forest, meadows and pasture coverage for the Trentino region, in the eastern Italian Alps, has been created.

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2. MATERIALS AND METHODS

2.1 Forest datasets for the Trentino region

To encompass the longest possible time span on the whole Trentino region, a set of heterogeneous sources has been selected so that maps and images cover the whole region with roughly the same quality and they provide information that can be used to create a Land Use/Land Cover (LULC) map at least for the forest, meadows and pasture classes. The dataset covers a time span of 155 years, from the 1859 Austrian Cadastral map to the 2015 "Volo AGEA" high resolution aereal imagery.

2.2 Historical maps

The first set of maps includes historical maps from 1859 to 1936, with an additional map from 1992 which was not available in digital format and has been digitized for this project. Historical maps have been digitized with the aim to extract the coverage of the forest, meadows and pasture classes.
The oldest map is the Historical Cadaster Map for the Province of Trento, based on the Second Military Survey of the Habsburg Empire (Timár, 2009) and carried out between 1855 and 1859 (Buffoni et al., 2016). The map does not only describe property boundaries, but also contains a representation of natural boundaries and LULC, with differentiation between agricultural uses. The 13,297 map sheets, approximately 52.68 $\times$ 65.85 cm wide, each covering roughly 288 ha, have been digitized at 230 DPI, 24 bit color depth, with a ground resolution around 0.32 m. They have been georeferenced in

the ETRS89/UTM 32 N (EPSG 25832) datum, achieving an accuracy of 5–10 m. The maps are available as JPEG images (Servizio Catasto della Provincia Autonoma di Trento, 2019), supplemented by JGW word files, with file sizes between 5 and 8 MB, under the Creative Commons Attribution 4.0 license (OPENdata Trentino, 2019).

The second map has been published in 1915 by the Istituto Geografico De Agostini in Novara, Italy, as an appendix of the book "Il Trentino. Cenni geografici, storici, economici. Con un'appendice sull'Alto Adige" by Cesare Battisti. The original book consists in 62 text pages and 19 color maps, included as separate (folded) sheets (Proto, 2015): the "Boschi" (Woodland) map has been used for this study. The scale of the original maps is 1:500,000, with a pre-Rome40 datum and unprojected lat/long coordinates. It has been transformed into a ETRS89 UTM32N (EPSG 25832) datum. The scanning resolution is 72 DPI, resulting in a ground resolution of 54.48 m in the east and 79.47 m in the north direction (Zatelli et al., 2022).

The 1936 Italian Kingdom Forest Map (IKFM, "Carta Forestale della Milizia Forestale del Regno d'Italia del 1936") represents the forest extent and main species composition in the whole Italian territory and parts of some surrounding countries in 1936 (Ferretti et al., 2018). It is composed of 276 sheets hand-drawn on a printed 1:100,000 scale map. The base map is the Italian official map of the time, developed by the Istituto Geografico Militare Italiano (IGMI, Italian Military Geografic Institute). The original sheets have been scanned with a resolution of 400 DPI with a ground pixels size of around 6.5 m, resulting in 6650×5900 pixels images saved as TIFF files, approximately 112 MB each. The map has been geo-referenced in the Italian national Rome 40 datum with Gauss-Boaga projection, in the east or west zone (EPSG 3003 and 3004) depending on the location of the map sheet, with an estimated accuracy of around 30 m, (Ferretti et al., 2018). The map, both in raster and vector format, is available on a dedicated web site (Ferretti et al., 2018), under the Creative commons Attribution—Version 3.0 license.

The "Map of the potential limit of the forest in Trentino" (MPLFT, "Carta del limite potenziale del bosco in Trentino") (Piussi, 1992), published in 1992 by the local government (Provincia Autonoma di Trento) in Trentino, is based on ground surveys carried out between 1987 and 1990. It represents forest areas as colored polygons printed with transparency on the 1:50,000 IGMI color map (Gobbi et al., 2019b). The original map is divided into 98 small 23×23 cm sheets printed in colors using halftones. The map sheets have been digitized with 600 DPI resolution and saved as TIFF files, approximately 60 MB each. The images have been geo-referenced in their original ED50/UTM32N datum (EPSG 23032) with ground pixel size of 2.12 m and an accuracy of the coordinates of 0.6 m. The map contains four classes: forest area, real potential [forest] area, excluded potential [forest] area and area beyond the upper [forest] limit.

The main features of the historical maps datasets are reported in Table 1.

Map	Year	Scale	Res. [m]	EPSG	Files
Cadaster	1859	1:1,440	0.3	25832	13297
Battisti	1915	1:500,000	80	25832	1
IKMF	1936	1:100,000	157	3003	6
MPLFT	1992	1:50,000	2.1	23032	98

Table 1. Historical maps main features. The "Res." column refers to ground resolution.

2.3 Orthophotos

The second dataset consists of sets of aerial images, covering the time span from 1954 to 2015. The four sets differ for mean scale, number of bands, resolution and datum.

The oldest imagery set belongs to the "Volo GAI" (Gruppo Areonautico Italiano, Italian Aeronautical Group) of 1954. The aereal images are available as 23×23 cm prints and have been digitized at 600dpi after tests have shown that higher resolutions do not carry any significative advantage (Gobbi et al., 2019a). The flight covers the whole Italy and the ortho-rectified images were not available for the Trentino region, but for a few small areas. Therefore a set of 130 B/W images, with mean scale of 1:35,000 and ground resolution of 2m, have been ortho-rectified in the Italian national Rome40 datum using GRASS GIS (Gobbi et al., 2019a).

The second imagery set comes from the "Volo Italia" of 1994, with 230 B/W images, already available as ortho-photos at a nominal scale of 1:10,000 and 1m ground resolution, in the Rome40 datum with Gauss-Boaga. west zone, projection (EPSG 3003).

The third set is part of the "Volo TerraItaly" of 2006, where the Trentino region is covered by 250 RGB+IR ortho-photos with 1:5,000 scale and 0.5m ground resolution, in the Rome40 datum, with Gauss-Boaga. west zone, projection (EPSG 3003).

The final set is composed of 850 RGB+IR ortho-photos of the 2015 "Volo AGEAT", with 1:5,000 scale and 0.5m ground resolution, in the ETRS89/UTM32 (EPSG 25832) datum.

The main features of the ortho-photos dataset are reported in Table 2.

Volo	Year	Scale	Res. [m]	EPSG	Files
GAI	1954	1:35,000	2	3003	130
Italia	1994	1:10,000	1	3003	230
TerraItaly	2006	1:5,000	0.5	3003	250
AGEAT	2015	1:5,000	0.2	25832	850

Table 2. Ortho-photos datasets main features. The "Res." column refers to ground resolution.

2.4 Methods

A new procedure has been developed to automatically extract LULC classes from these maps, combining GRASS (GRASS Development Team, 2017) and R (R Core Team, 2022) for the segmentation, classification and filtering with the Object Based Image Analysis (OBIA) approach, which achieves higher accuracy than other classification methods (Zatelli et al., 2019b).

With respect to the classification of aereal or satellite imagery, the classification of maps introduces some challenges: i) labels, symbols and boundary lines must be removed; ii) colors are not uniform in hand written/painted maps; iii) some maps have hatching (Battisti's, Figure 1) or halftones (MPLFT, Figure 2).

Figure 1. Hatching example from the 1915 Battist's map.

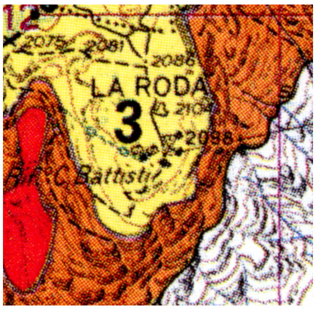

Figure 2. Halftones example from the 1992 MPLFT map.

For this reason a new filtering technique has been devised, which allows the removal of specific map categories, substituting their values with the values of the surrounding pixels. Two new GRASS GIS (GRASS Development Team, 2017) modules used in this procedure have been created and made available as add-ons on the official repository (Gobbi et al., 2019). The first GRASS GIS module, *r.fill.category* (Gobbi, S. and Zatelli, P., 2019), substitutes the category of their pixels with the category of the surrounding pixels. A second GRASS GIS module, *r.object.thickness* (Zatelli, P., 2019), has been created to estimate the smallest filter size needed to entirely remove text, symbols and lines on a map, using *r.fill.category*. Both modules are available as a GRASS add-on in the standard repository under the GNU General Public License (Gobbi, S. and Zatelli, P., 2019) (Zatelli, P., 2019).
The classification of areas containing hatching has been carried out by using additional bands, such as texture maps and an high pass filter map on a specific band (Zatelli et al., 2022). Given the large number of maps which have been processed, all the procedures have been scripted, mostly in python. Details of the OBIA classification and of the filtering procedures can be found in (Gobbi et al., 2019b) and (Zatelli et al., 2022).
The "Volo GAI" imagery set has been ortho-rectified using GRASS GIS, while images in the other sets were already ortho photos. A subset of 90 images out of 130 has been selected for the orthorectification, since some were already available as orthophotos and some lower quality images, overlapping better images, have been discarded.
The ortho-rectification process consists in three steps: internal orientation (to evaluate the position of the image with respect to the camera frame), external orientation (to evaluate the position of the camera with respect to an external reference system) and orthorectification (to re-project the image). The first step requires information about the focal length of the lens, the coordinates of the principal point of autocollimation and the number and coordinates of the fiducial marks on the camera frame. Since no calibration certificate for the camera is available, these parameters have been assessed by the markings on the images and their geometry. Sixteen Ground Control Points (GCPs) have been identified on each image for the external orientation, using maps or more recent orthophotos as reference. Since most of the area is covered by mountains and identifiable objects (building, roads, etc.) exists only on a small part of the area, the distribution of the GCPs is not uniform for some images, causing distortions in some higher areas (Gobbi et al., 2018).

The classification of all maps have been carried out using Object-based Image Analysis (OBIA), which requires two steps: the identification of homogeneous areas (called "segments") on the images and their classification.

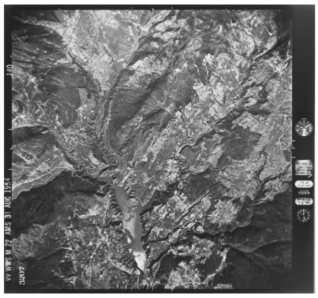

Figure 3. Original 1954 image.

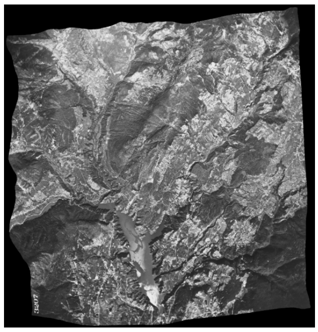

Figure 4. Ortho-photo from the 1954 image.

Image segmentation recognizes objects on the maps using their radiometric and geometric features. The calibration of the segmentation parameters, similarity threshold and minimum number of pixels in a segment, have been carried out applying an Unsupervised Segmentation Parameter Optimization (USPO) in GRASS GIS and manually modifying the resulting values after tests on a subset of each mapset.
A supervised classification has been carried out using Machine Learning in R through GRASS *v.class.mlR* module for all the datasets. A procedure has been scripted to create training segments from a set of training points, which are manually selected. This procedure has the advantages of being quicker than the selection of segments and of being independent from the segment configuration, thus different segmentation and classification tests are possible with the same set of training points. Four different classifiers have been used for the classification: Support Vector Machine With a Radial Kernel (SVMradial), Random Forest (RF) and Recursive Partitioning (Rpart), and K-Nearest-Neighbor Classifier (K-NN). Their results have been combined using four different voting systems, Simple Majority Vote (SMV), Simple Weighted Vote (SWV), Best Worst Weighted Vote (BWWV), and Quadratic Best Worst Weighted Vote (QBWWV).
The evaluation of the results has been carried out using a proportional stratified random sampling approach, with the creation of 750 sampling points for each map, distributed on each LULC class according to the ratio of its area with respect to the total area of the region (Figure 5). The procedure has been scripted in GRASS GIS using Python.

The evolution of the forest and meadows coverage has been analyzed by evaluating a series of landscape metrics, namely the number of patches, the largest patch index, the patch density and the edge density. During this analysis the need for a comparison between available software for landscape metrics evaluation has been necessary, since different choices in the cell

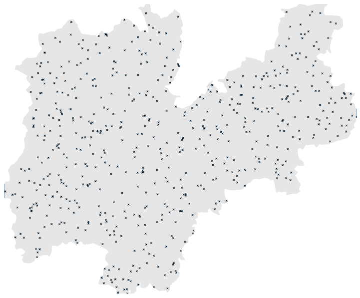

Figure 5. Sampling points distribution.

neighborhood configuration lead to very different results for some non-ratio metrics (Zatelli et al., 2019a). Based on this study, a procedure has been scripted in R to run the *landscapemetrics* module and automatically create charts displaying the modification of the landscape features in time.
Finally, the time series describing the forest evolution in the last 155 years has been used to create future scenarios using Markov Chains and Agent Based Modeling (Wallentin, 2017).

3. RESULTS

All the processing stages have been subject to independent evaluation, to make sure that the final forest maps provide an accuracy suitable for further processing.

3.1 Orthorectification

The orthorectification process of the imagery set for year 1954 achieved a mean overall RMS error of about 1.28 m, slightly over half the pixel resolution, but with a mean point displacement, evaluated by using independent control points of 10m, with values of more of 20 m on very steep slopes (Gobbi et al., 2018). This usually happens in high rise areas where vegetation does not grow in any of the years of the analyzed time frame, therefore the impact on the assessment of the forest evolution is negligible. The ortho-photos have been patched in the mosaic shown in Figure 6.

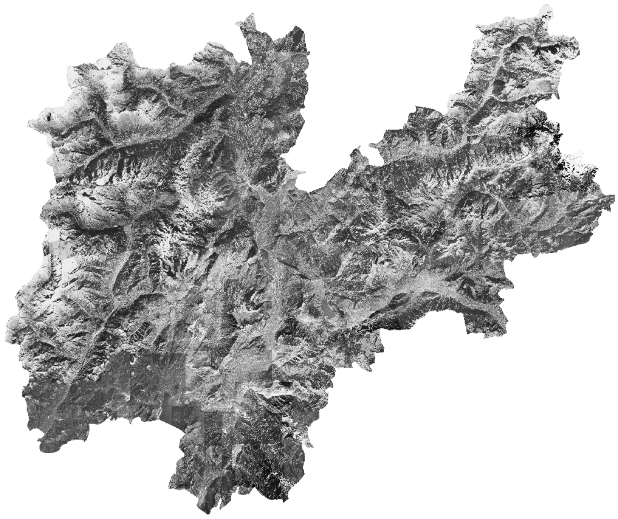

Figure 6. Mosaic of the 1954 ortho-photos.

3.2 Segmentation

The classification of the historical maps have been carried out by calibrating the segmentation parameters on each dataset. For the historical map, optimal values for the similarity threshold range from 0.03 to 0,25, while the minimum segment size vary from 10 to 60 (Table 3). This high variability is expected because of the heterogeneity of the historical maps, which have very different scales, types of objects and graphical layout.

Volo	Year	Threshold	Min. size [pixel]
Cadaster	1859	0.06	25
Battisti	1915	0.25	10
IKMF	1936	0.03	20
Piussi	1992	0.03	60

Table 3. Optimal segmentation parameters for historical maps datasets.

Optimal parameters values for the ortho-photo datasets are more uniform, with the exception of the 1994 ”Volo Italia”, for which slightly higher values have been obtained, even for images with very different features in terms of number of bands and ground resolution. This is mainly due to the fact that the minimum size of recognizable objects is inversely proportional to the resolution moving from B/W images to RGB+IR ones.

Volo	Year	Threshold	Min. size [pixel]
GAI	1954	0.04	100
Italia	1994	0.06	125
TerraItaly	2006	0.04	100
AGEAT	2015	0.04	100

Table 4. Optimal segmentation parameters for ortho-photos datasets.

3.3 Classification

The classification of the historical maps achieved an accuracy for the forest class ranging from 96% to 98% (Table 5).

Mapset	Year	Accuracy [%]
Cadaster	1859	98
Battisti	1915	98
IKMF	1936	93
Piussi	1992	96

Table 5. Accuracy of the classification of the forest coverage class for the different historical maps.

For historical maps the filtering stage, which eliminates text, symbols and boundary lines, proved to be fundamental. The number and types of LULC classes reported on the historical maps are different for each map, but they have been reclassify to identify the classes for forest and meadows.
The accuracy of the classification of the otho-photo dataset is generally lower (Table 6). The classification of the 1954 and 1994 ortho-photos is less accurate, as expected because the images are single band and some images presents some blurry areas.

Given the heterogeneity of dataset, even for the orthophotos the number and types of LULC classes depends on the image, but they have always been reclassified into forest and meadows classes.

3.4 Forest coverage evolution

The forest class from the LULC maps has been analyzed to identify trends. The “Battisti” map for year 1915 reports forest density for each district (Figure 7) and not forest coverage (Zatelli et al., 2022), therefore it is not directly comparable with the other maps.

Volo	Year	Accuracy [%]
GAI	1954	93
Italia	1994	93
TerraItaly	2006	95
AGEAT	2015	94

Table 6. Accuracy of the classification of the forest coverage class for the different aereal images.

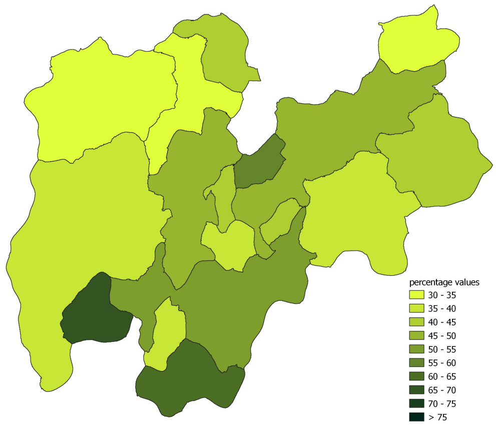

Figure 7. Forest density in the Trentino region according to the "Battisti" map for year 1915.

The MPLFT map has been created to evaluate the potential forest area and it has not been directly used in the analysis.
The resulting forest coverage maps for years 1859, 1954 and 2015 are reported in Figures 8 to 13.

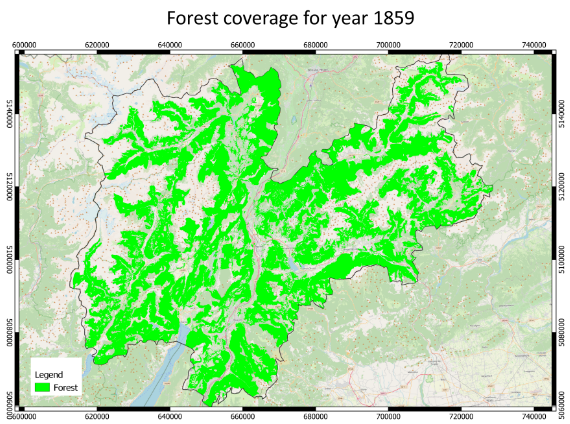

Figure 8. Forest coverage in the Trentino region in 1859.

The overall forest coverage for each year is reported in Table 7 and Figure 14.

A trend is clearly observable, with a minimum forest coverage in 1936 and a fast growth in the period after the second world war. The trend is still the same in the last decades, but the expansion has slowed due to the saturation of most of the potential forest area.

A similar analysis has been carried out for the forest coverage distribution with altitude in Figure 15.

While the same trend is visible for every altitude, the increase for higher areas is more marked, as notable in the breakdown between areas below and above 2200 meter of altitude in Table

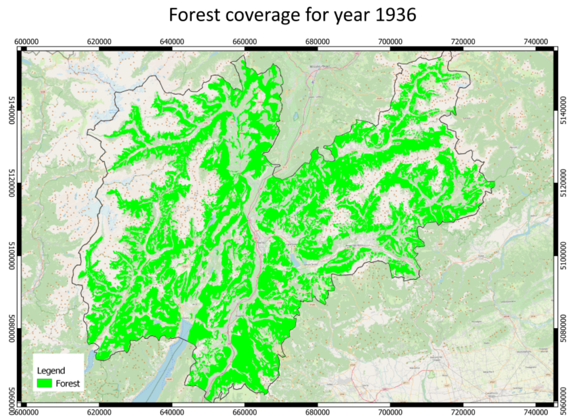

Figure 9. Forest coverage in the Trentino region in 1936.

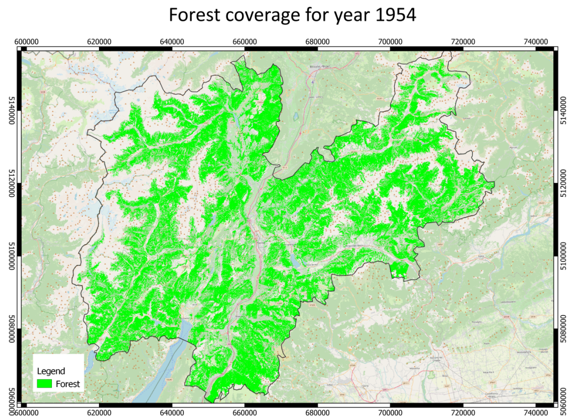

Figure 10. Forest coverage in the Trentino region in 1954.

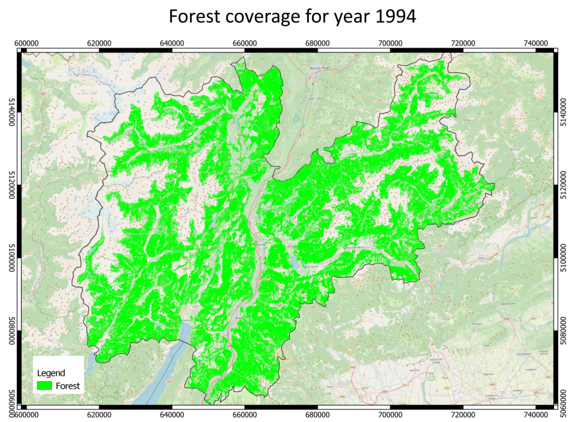

Figure 11. Forest coverage in the Trentino region in 1994.

8. This hints to an expansion of the treeline towards higher altitudes, but this effect must be further investigated.

3.5 Landscape analysis

The analysis based on landscape metrics has highlighted a general trend towards a configuration with fewer (Figure 16) and larger patches (Figure 17), with decreasing patch density (Figure 18) and nearly constant total edge density (Figure 19).
Landscape metrics for historical maps are less significative,

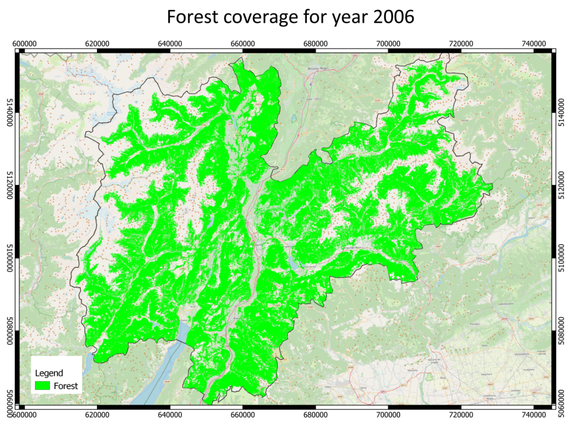

Figure 12. Forest coverage in the Trentino region in 2006.

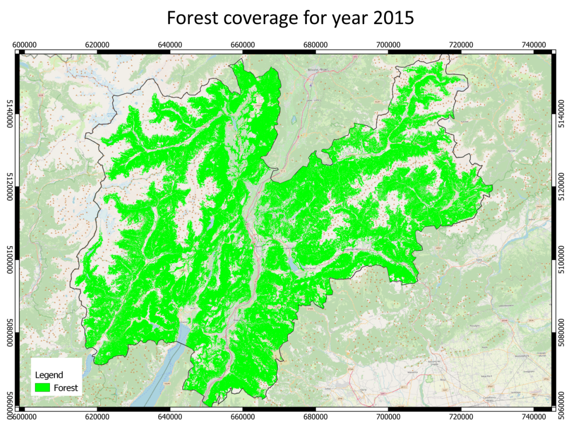

Figure 13. Forest coverage in the Trentino region in 2015.

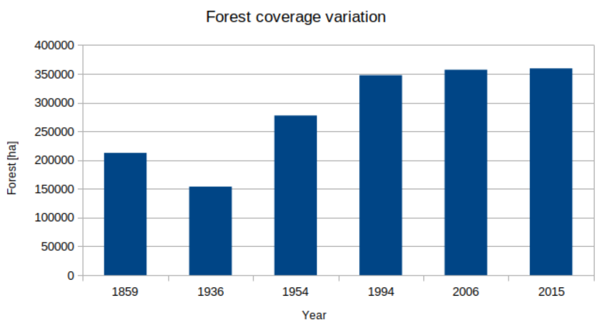

Figure 14. Forest coverage evolution in the Trentino region from 1859 to 2015.

since drawn areas are already compact and the separation between forest and open areas is visible only at a macro level. Results from the 1954 ortho-photos dataset seem to be outliers with respect to the general trend for some metrics: the reason for this is still under investigation, but the most probable cause is the lower quality of the image, which is reflected in a less accurate classification and landscape metrics evaluation.

Future scenarios, created using Markov Chains and Agent Based Modeling on a test area in the eastern part of the Trentino region, predict a further expansion of the forest coverage, with more compact patches, but the expansion is slowing as the vast majority of the suitable areas are already covered by forest.

Year	1859	1936	1954	1994	2006	2015
[sq km]	2125	1538	2774	3474	3572	3593
%	34	24	44	55	57	58

Table 7. Forest coverage evolution in the Trentino region from 1859 to 2015.

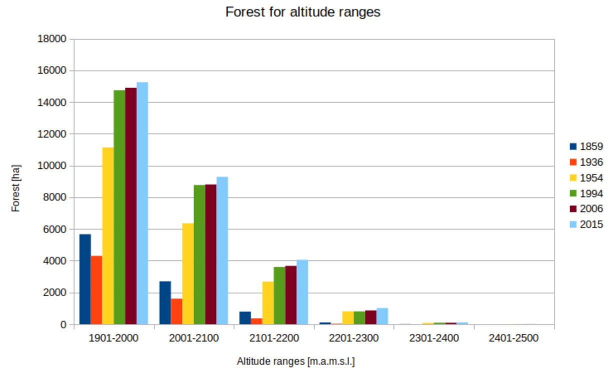

Figure 15. Forest coverage evolution distribution for different altitudes in the Trentino region from 1859 to 2015.

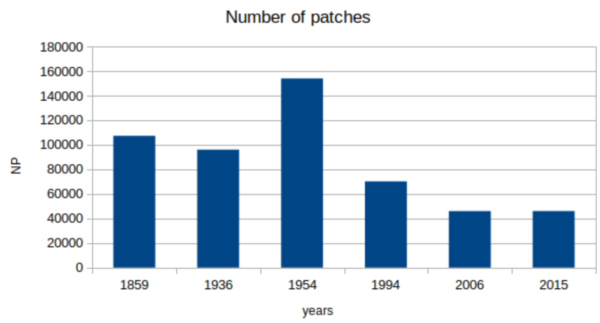

Figure 16. Number of forest patches change between 1859 and 2015.

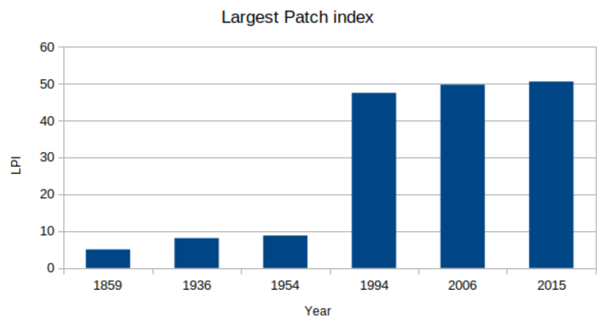

Figure 17. Largest patch index for forest class change between 1859 and 2015.

4. CONCLUSIONS

An uniform dataset for forest coverage has been built for the Trentino region, covering about 13,606 sq km, spanning 155 years from 1859 to 2015. This datasets allow the analysis of

Year	1859	1936	1954	1994	2006	2015
<2200 m	2124	1538	2765	3465	3562	3582
>2200 m	109	28	900	901	963	1142

Table 8. Forest evolution in the Trentino region from 1859 to 2015 for areas below and above 2200 meters. Areas are in square kilometers.

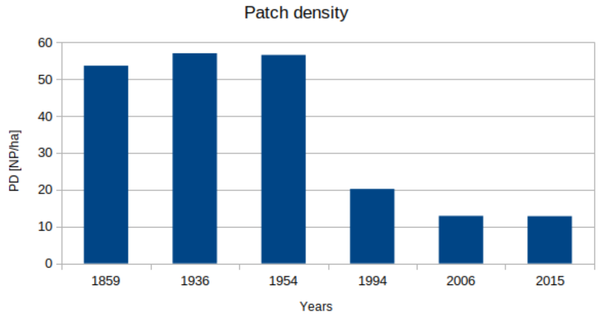

Figure 18. Patch density for forest class change between 1859 and 2015.

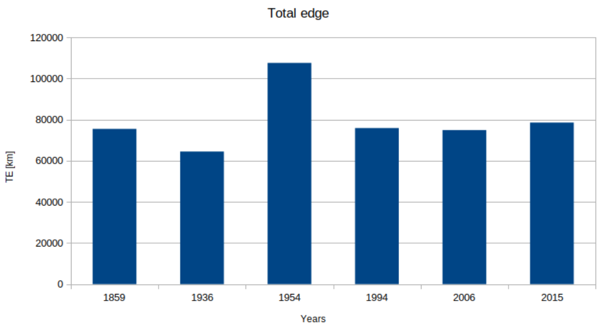

Figure 19. Total edge index for forest class change between 1859 and 2015.

evolution of the forest coverage in the area, with quantitative assessment of some known trends in the Alps, such as the expansion of the forest coverage and the creation of more compact forest patches. The analysis of selected landscape metrics provided preliminary results about the forest distribution and the pattern of recolonization during the last 155 years.
While the classification methods described in (Gobbi et al., 2019b) and (Zatelli et al., 2022) are able to achieve high accuracy (Tables 5 and 6), there is still the need for manual calibration of some parameters. This is mainly due to the heterogeneity of historical maps, both in the original maps and in the digitization process (resolution, color depth and image compression), and in the different features of the ortho-photos, especially in terms of resolution and number of bands. As expected, higher resolution images yeld better classification results when OBIA is used, as objects are more clearly identified by a larger number of pixels.
The landscape metrics analysis allows the quantification of trends in the landscape evolution. A comparison between the capabilities of FOSS4G available systems for landscape metrics was performed to evaluate the best analysis tools (Zatelli et al., 2019a). The combination of larger forest surface and a configuration with larger patches indicates the closure of clearings and the shrinkage of pastures, with the loss of ecotones. This could be the result of the combined effects of land use modifications and climate change. but further investigation is necessary. Finally, these time series of LULC coverage were used to create future scenarios for the forest evolution in a test area of Trentino in the next 85 years, using both the Markov chain and the Agent Based Modeling approaches with GAMA (Taillandier et al., 2019), which highlight a continuation of the past trend in the area.
Furthermore, the analysis of the forest landscape after the 2018 Vaia storm, whose effects have been very relevant in the region, is under way.
Free and Opens Source software has been effective in dealing with all aspects of the processing of spatial information, from education (Ciolli et al., 2017), enviroment suitability for fauna (Tattoni et al., 2019), image analysis (Gobbi et al., 2019b) and landscape metrics evaluation (Zatelli et al., 2019a) to database management (Simeoni et al., 2014).
The great flexibility provided by FOSS for spatial analysis, such as GRASS, R, QGIS and GAMA and the ease of their combined use has been critical for the management and analysis of the maps, given the huge number of heterogeneous maps and images involved. The possibility of scripting all the operations is vital for these type of procedures and this has lead to the creation of some GRASS GIS Addon modules, with the engineering of some of the scripts. The development of additional GRASS add-on modules, based on the scripts created during this study, is planned.

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