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Conference Proceedings

Editors
Angeliki Tsorlini
Chrysoula Boutoura

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Editors: Angeliki Tsorlini, Chrysoula Boutoura
Thessaloniki: AUTH CartoGeoLab



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Preface

Historical maps are invaluable sources of knowledge about past societies, landscapes, and worldviews. Beyond their geographical content, they preserve evidence of historical processes, cultural developments, scientific advances, and artistic traditions. Exploring innovative ways to preserve, interpret, and make this information accessible for research and public engagement is a central objective of the International Cartographic Association (ICA) Commission on Cartographic Heritage into the Digital and the Map & Geoinformation Curators Group (MAGIC).

This volume brings together the papers presented at the 20th Conference on Digital Approaches to Cartographic Heritage (ICA DACH). The contributions demonstrate the richness and diversity of hi-storical map collections and highlight their potential for research across a wide range of scientific and artistic disciplines. They also illustrate how digital technologies create new opportunities for studying, interpreting, and disseminating cartographic heritage.

This year's conference features 43 papers from 16 countries, representing 41 institutions, including universities, libraries, archives, museums, research institutes, and organisations from the public and private geospatial sectors. Organised into eight working sessions, the programme addresses key topics within the remits of the ICA Commission and MAGIC, including research and development in cartographic heritage, interdisciplinary cooperation, public engagement, map collection development strategies, metadata and data-exchange standards, preservation and access, innovative visualisation and virtual exhibitions, and the intersections of cartographic heritage with the digital humanities.

The diversity of contributions reflects the evolving nature of the field, bringing together researchers, curators, librarians, archivists, and other professionals to exchange knowledge and explore new approaches to the study and preservation of historical cartographic materials.

We hope this volume will provide valuable insights and inspiration for all those working in cartographic heritage and map librarianship, encouraging further collaboration and research in this dynamic field.

Mátyás Gede
chair, ICA Commission on Cartographic Heritage into the Digital

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chair, Map & Geoinformation Curators Group-MAGIC
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Amanuel S. Mekonen*[1], Muhammad Umair[1], Gabor Timàr[2], Matteo Balistrocchi[1], Roberto Ranzi[1]

Detection of land-cover changes between the 19th and 21st centuries in the Adige River basin through a CORINE-based reclassification of the Second Military Survey

Keywords: Second Military Survey; Historical land-cover mapping; CORINE land cover; Land-cover change detection; Adige River basin.

Summary: The assessment of long-term land-cover changes provides valuable insights into landscape evolution, including cultural, environmental, hydrological, and energy-management perspectives, and shows how humans, nature, and climate have interacted over time. In this study, the value of cartographic heritage as a source of historical environmental information for reconstructing historical land cover and assessing long-term landscape changes is demonstrated by integrating the Second Military Survey of the Habsburg Empire (1816–1821) with the current CORINE Land Cover dataset. Building on refined georeferencing of these map tiles and the manual vectorization of land-cover classes, the land cover of the mountain part of the Adige River Basin in the Italian Alps during the early nineteenth century was reconstructed. Fifteen land-cover classes were identified and harmonized with the CORINE Land Cover 2018 classification. The comparative analysis indicated that forest cover increased from 56.83% to 58.58% of the total study area, revealing a moderate but significant afforestation trend over the last two centuries. The most notable reductions were observed in glaciers, grassland and pastures, which declined by 72.62% and 16.84%, respectively. A transition matrix was developed to quantify land-cover changes between the two periods. The main transition pathways occurred from grassland and pastures to forest and vice versa, from bare rocks and transitional woodland to forest, and from glaciers to bare rocks.

Introduction

Land-cover change detection using historical maps provides essential information for supporting a wide range of environmental and socioeconomic studies. In recent decades, historical maps have increasingly been exploited as spatial sources for reconstructing past landscapes and investigating long-term environmental and anthropogenic transformations. There are numerous detailed historical maps available with open accessibility (Brovelli & Minghini, 2012; Podobnikar, 2010; Zlinszky & Timár, 2013), allowing investigations of landscape dynamics to be extended back to the 18th century. This period represents a turning point in European cartography, when the first systematic cadastral and military maps were produced. These maps, usually at medium scales ranging from 1:28,800 to 1:75,000, provide a reliable and topographically consistent representation of past landscapes, making them highly valuable for historical land-cover reconstruction and spatial analysis. In contrast, earlier maps developed in the 16th and 17th centuries can offer some insights, but their limited accuracy and coverage often restrict their use to partial interpretations (Konkoly-Gyuró et al., 2017).
Satellite imagery, remote sensing, and GIS have greatly advanced the analysis of contemporary landscapes and land-cover dynamics. However, their limited temporal coverage restricts

[1] Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM), Università di Brescia, Brescia, Italy [a.mekonen@studenti.unibs.it, m.umair@unibs.it, matteo.balistrocchi@unibs.it; roberto.ranzi@unibs.it]

[2] Department of Geophysics and Space Sciences, Eötvös Loránd University, Budapest, Hungary [timar.gabor@ttk.elte.hu]

* Corresponding author

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investigations of earlier periods. Historical maps therefore represent one of the main sources for extending landscape analyses beyond the temporal limits of modern Earth observation datasets (Affek, 2013; Cajthaml, 2011). Recent developments in digitization, georeferencing, and spatial analysis have further enhanced the potential of historical cartographic documents, allowing their integration into modern geospatial workflows and quantitative analyses. Consequently, historical cartography has become an important component of historical GIS and long-term landscape change studies.

Recent studies have demonstrated the potential of integrating historical maps with modern geospatial techniques for environmental and landscape research. Levin et al. (2025), for instance, employed supervised classification on a two-and-a-half-century map series to track vegetation changes on Norfolk Island, demonstrating the potential of historical cartography for long-term landscape reconstruction. In Southern Italy, Cervelli & Pindozzi (2022) combined digitized cadastral maps from 1817, 1907, 1960, and 2009 (with scales ranging from 1:250,000 to 1:50,000) to investigate peri-urban land-use transformations around Vesuvius, highlighting the contribution of historical maps to the understanding of urban–rural dynamics. Moreover, Manniello et al. (2022) showed how historical maps integrated within GIS environments can quantify changes in agricultural land use and assess their impact on landscape carbon balance. Beyond environmental applications, historical cartographic information also supports research in fields such as hydrology, urban development, architectural planning, archaeology, cultural landscape evolution, and demography (Brovelli & Minghini, 2012; Prokop, 2017; Zlinszky & Timár, 2013).

The increasing availability of digitized historical maps has stimulated the development of automated approaches for extracting spatial information from cartographic documents. Although recent advances in machine learning and deep learning have improved the efficiency of automated digitization and georeferencing, manual methods remain essential because of the complexity and variability of historical maps. Automated techniques typically require high-resolution, color-rich scans, standardized symbols, and clearly readable toponyms (Cervelli & Pindozzi, 2022). In addition, deep learning approaches depend on large annotated datasets, expertise in artificial intelligence, and high-performance computing (Manniello et al., 2022). These requirements are often difficult to meet for centuries-old military or cadastral maps, where symbols are inconsistent, text is handwritten or degraded, and spatial reference systems are unavailable. Although labor-intensive, manual digitization and georeferencing provide the flexibility needed to interpret historical features that automated methods may overlook or misclassify. However, the quality of visual interpretation depends on the condition of the maps, the availability of legends, and the interpreter's expertise, making appropriate validation essential for scientific applications (Groom et al., 2020).

In order to perform quantitative spatial analyses more effectively, vector spatial datasets are more suitable. In contrast, historical maps, even when digitized and georeferenced, are often available only as raster images, which cannot be readily incorporated into automated spatial analyses, thereby strongly limiting the use of these valuable datasets. A further challenge is the integration of historical cartographic information with modern standardized classification systems. Establishing a correspondence between historical land-cover categories and contemporary datasets enables consistent analyses of landscape transformations over long time periods.

In this study, as firstly suggested by Ranzi et al. (2021), the land cover of the Adige River Basin in the early 19th century was reconstructed by manually vectorizing spatial datastes provided by the Second Military Survey (SMS) maps of the Hapsburg Empire (1816–1821). The Adige River

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basin is hydrologically interesting because long-term hydrological time series of streamflow, precipitation, and temperature are available (Mallucci et al., 2019). By reclassifying the digitized SMS land-cover information according to the CORINE Land Cover (CLC) 2018 classification scheme, this study establishes a comparable framework between nineteenth and twenty first century landscape patterns. This approach makes it possible to identify major trends such as deforestation-afforestation, urbanization, or agricultural intensification, changes often driven by political, economic, and technological shifts. A land-cover transition matrix, summarizing the transitions among different land-cover classes (Asenso Barnieh et al., 2020; Wijayasari et al., 2023), was thus obtained. This matrix was used to quantify the overall land-cover changes and to identify the main transition pathways that occurred within the Adige River basin.

Study Area

The study area is located in northern Italy, as shown in inset a of Figure 1. It covers most of the Adige River basin upstream of Trento section and lies approximately between 46.0°–47.1° N latitude and 10.4°–12.2° E longitude. The basin extends across the Italian autonomous region of Trentino-Alto Adige/Südtirol and a small portion of the Swiss Canton of Grisons. The total catchment area of the Adige River basin is approximately 12,100 km^2 (Chiogna et al., 2016), of which 9,578 km^2 were digitized (about 79%). This area does not correspond to the total basin upstream of Trento since, for the small part located in Switzerland (134.1 km^2), no SMS maps are available (main panel of Figure 1). The Adige River is the second-longest river in Italy, rising near Resia/Reschen in the Alps and flowing toward the Adriatic Sea. The basin is characterized by a pronounced altitudinal gradient, with elevations ranging from approximately 65 m a.s.l. to more than 3,900 m a.s.l., resulting in predominantly steep terrain. Higher elevations are mostly covered by forests, bare rock, and glaciers, whereas valley bottoms are characterized by extensive urban settlements and intensive agricultural areas concentrated along the main valley floors.

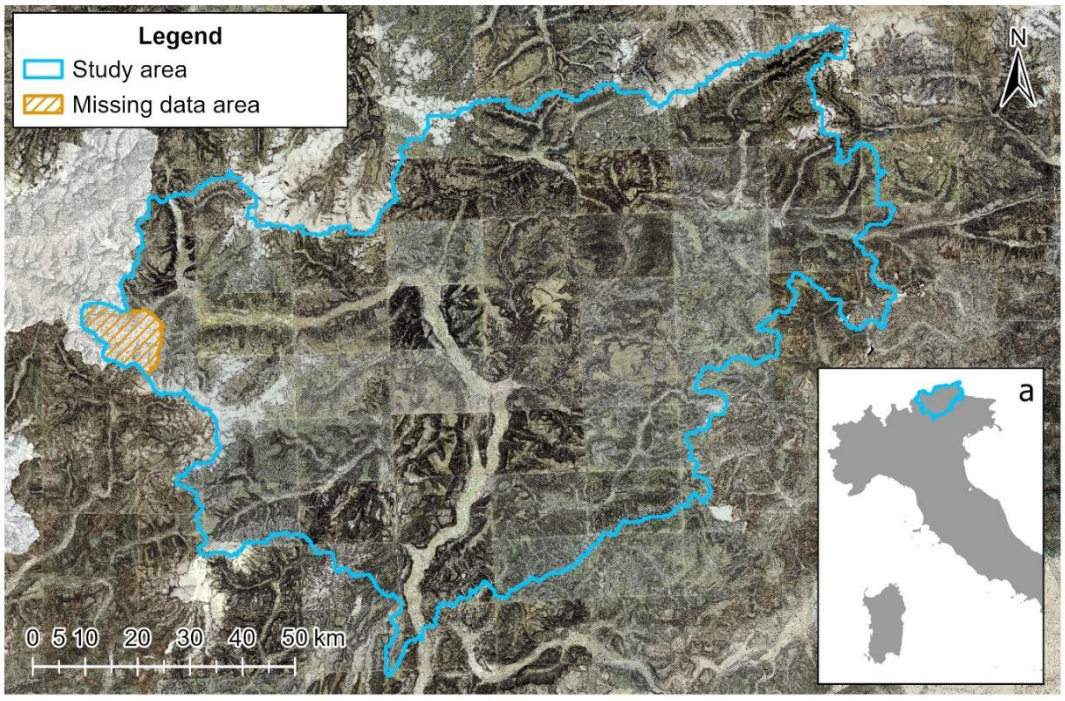


Figure 1: Adige River basin upstream of Trento section mapped over the mosaic of the Second Military Survey map tiles (inset a: location of the study area in Italy).

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Materials and methods

Georeferencing refinement and vectorization of historical data

SMS maps are already available as georeferenced and mosaicked images for almost all of the Adige River basin, as shown in Figure 1. Details regarding the georeferencing of these maps are provided by Timár et al. (2006, 2011). Nevertheless, a further improvement in the georeferencing of the SMS images was found to be needed. Bearing in mind the study objectives that include the spatial comparison of historical and current land covers, high accuracy in the spatial data alignment with respect to the actual ground surface is mandatory. The historical images were thus re-georeferenced by assigning the coordinate reference system of the reference map through the identification of corresponding ground control points. Stable landmarks, including old churches, bell towers, roads, bridges, settlement features, and, where available, natural boundaries, were selected to ensure accurate alignment between the historical maps and contemporary geospatial datasets. Within the Adige River basin, churches and bell towers located close to the Adige River corridor were particularly useful as ground control points because they are clearly identifiable on historical maps and have generally remained in the same position over time. Ranzi et al. (2019) similarly used churches, buildings, and bell towers to georeference the 1847 Adige River map.

The re-georeferenced maps were manually vectorized in a GIS environment by delineating land-cover polygons. An attribute table was populated for each polygon, including metadata such as the land-cover class, polygon area, and feature description (Piškinaite & Veteikis, 2023). To ensure the spatial integrity of the digitized data, topological cleaning was carried out. This involved checking for and correcting errors such as overlapping polygons, dangling nodes, and unclosed boundaries. Topology validation tools available in GIS software were used to streamline this process (de França, 2018). Differentiation between land-cover types was achieved by interpreting the color and texture represented on the historical maps.

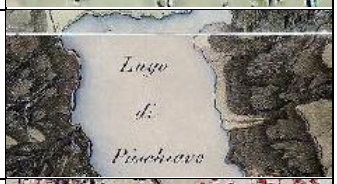
Harmonization of land-cover classifications

The CLC program was introduced by the European Commission in 1985 to provide consistent and standardized land-cover information across Europe. Its main purpose is to support environmental monitoring, land management, and spatial planning. The CLC classification system includes 49 land cover classes arranged in a three-level hierarchical structure. These classes range from general groups, such as artificial surfaces, agricultural land, forests, wetlands, and water bodies, to more specific subcategories. In contrast, the historical map did not distinguish between several land-cover types represented separately in CLC such as deciduous, coniferous, and mixed forests, which must be merged into a single forest class. Other detailed CLC classes, such as the various types of urban and rural areas or grassland and pasture meadows, bear the same issue.

Therefore, a simpler land-cover classification had to be implemented in the SMS dataset. To achieve a meaningful comparison of land-cover changes despite differences in thematic detail, the two classifications had to be harmonized. Table 1 supplies the reclassification criterion by relating the CLC classes of the third hierarchical level existing in the study area to the corresponding SMS classes proposed in this study. Sample images extracted from the SMS maps for each land-cover class are also reported. As can be seen, 30 CLC classes were detected within the study area. However, only 21 classes are associated with an area larger than 99.9% of the total study area.

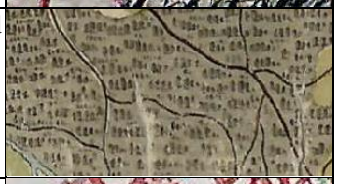
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Table 1: Harmonization of land-cover classes between CORINE and Second Military Survey.

N°	Third level CORINE classification		Reclassification	Second Military Survey sample images
	Code	Name		
1	211	Non-irrigated arable land	Arable land	
	241	Annual crops associated with permanent crops		
	331	Beaches		
2	332	Bare rocks	Bare rocks	
3	311	Broad-leaved forest	Forest	
	312	Coniferous forest		
	313	Mixed forest		
	333	Sparsely vegetated areas		
4	142	Sport and leisure facilities	Gardens within settlements	
5	335	Glaciers and perpetual snow	Glaciers	
6	231	Pastures	Grasslands and pastures	
	242	Complex cultivation patterns		
	321	Natural grasslands		
	322	Moors and heathland		
7	411	Inland marshes	Lakes	
	412	Peat bogs		
	512	Water bodies		
8	243	Land principally occupied by agriculture, with significant areas of natural vegetation	Land principally occupied by agriculture	
9	222	Fruit trees and berry plantations	Orchards	
10	511	Water courses	Rivers	

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Table 1: (follows).

N°	Third level CORINE classification		Reclassification	Second Military Survey sample images
	Code	Name		
11	122	Road and rail networks and associated land	Road and rail networks	
12	324	Transitional woodland-shrub	Transitional woodland	
13	111	Continuous urban fabric	Urban and rural areas	
	112	Discontinuous urban fabric		
	121	Industrial or commercial units		
	124	Airports		
	131	Mineral extraction sites		
	132	Dump sites		
	133	Construction sites		
14	221	Vineyards	Vineyards	

Transition Matrix

To quantify land-cover changes between the historical map and the CLC 2018 dataset, both layers were imported into GIS and overlaid using the intersect geoprocessing tool. The resulting polygon layer inherited the land-cover attributes from both datasets, allowing each polygon to be assigned to a unique combination of historical and contemporary land-cover classes. Polygon areas were then aggregated according to these class pairs to generate a land-cover transition matrix, in which rows represent the historical SMS classes and columns represent the corresponding CLC classes. The resulting matrix quantified the area associated with each transition and formed the basis for the subsequent analysis of long-term land-cover dynamics.

Results

Georeferencing refinement

The georeferencing refinement process for the early 19th-century Adige River Basin map revealed variations in accuracy across the map tiles. Most of them show positional errors of less than 200 m, although errors of about 350 m were observed in mountain areas. Rotational errors were also observed in some tiles, further complicating the accurate alignment of the historical map. Two examples of georeferencing inaccuracies are presented in Figure 2: panel a shows the positional and rotational displacement of a mountain peak, whereas panel b shows the positional displacement of a mountain lake. The corresponding locations were identified in the georeferenced SMS map tiles and in Google Maps satellite imagery. In both panels, the left endpoint (Location A) indicates the actual feature position in the Google Maps satellite imagery, while the right endpoint (Location B) indicates the position in the georeferenced SMS map. The red line connecting the two endpoints represents the approximate magnitude and direction of the

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positional displacement between the two datasets. In these cases, the displacements are approximately 210 m (panel a) and 335 m (panel b).

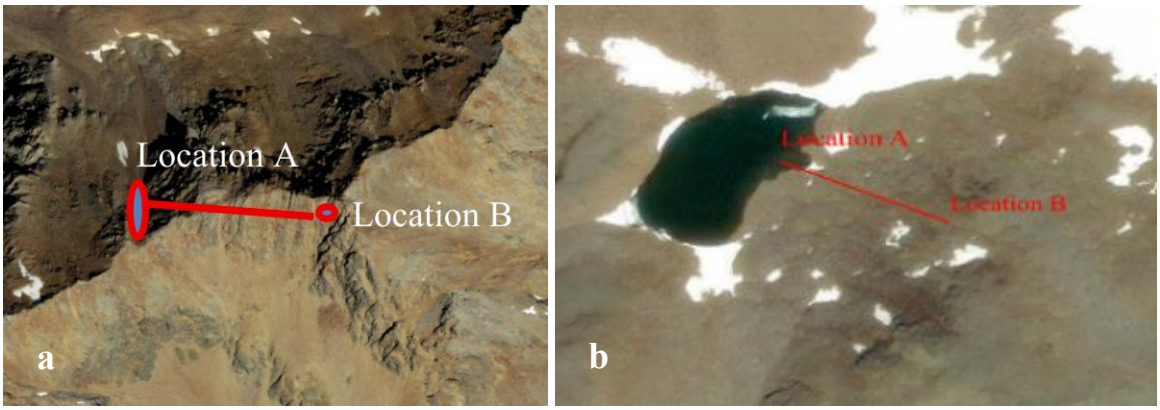


Figure 2: Examples of georeferencing positional inaccuracies: mountain peak (panel a) and mountain lake (panel b), locations detected trough the SMS compared to their actual locations detected by current Google map Satellite imagery.

The comparison with Google Maps satellite imagery also revealed that CLC polygons can be affected by positional inaccuracies, which can lead to errors in current land-cover classification. Figure 3 shows the CLC layer superimposed on satellite imagery, highlighting a limited area where some classification inconsistencies were observed. The red circle indicates an area classified as forest in CLC where grasslands and pastures appear in satellite imagery. Similarly, the blue circle indicates an area classified as grasslands and pastures where bare rocks are visible in the satellite imagery.

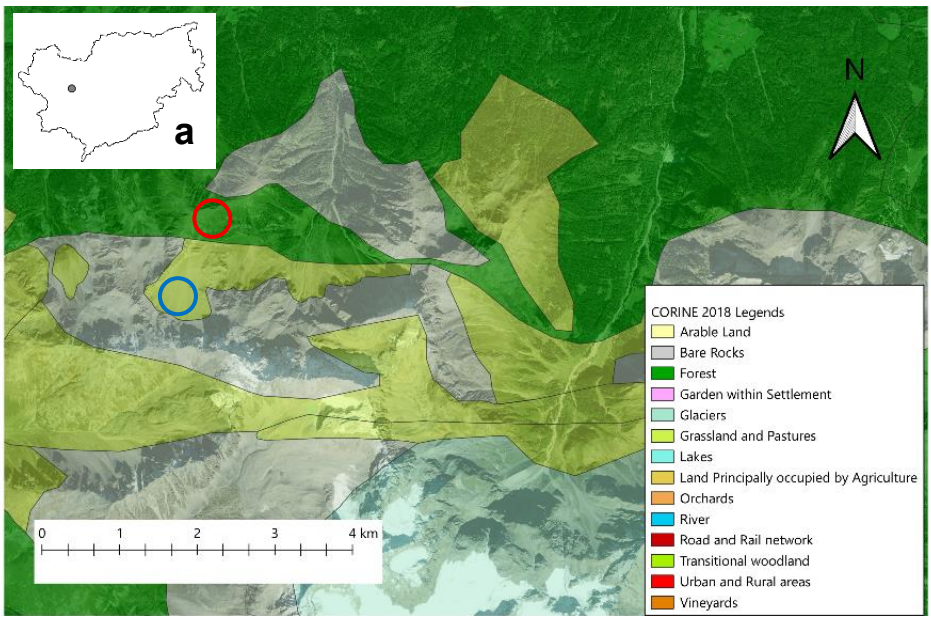


Figure 3: CORINE Land Cover 2018 superimposed on Google map Satellite imagery for a limited part of the study area (located in the Adige River basin as shown in inset a), where land-cover misclassification can be observed: red circle, grasslands and pastures in a forest polygon, blue circle bare rocks in a grasslands and pastures polygon.

Historical land-cover map (1816–1821)

Figure 4 presents the vectorized historical land-cover map of the study area according to the classification defined in Table 1. The areal distribution of the land-cover classes is summarized in

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Table 2. The dominant land-cover class is forest, which occupies 56.83% of the total study area. This class is followed by grasslands and pastures, which account for 18.16%, and bare rocks, covering 11.92%. Other significant land-cover classes include glaciers, occupying 4.25%, and transitional woodland, which accounts for 2.28%. As expected, these classes dominate the mountain slopes and higher elevations, where land cover progressively changes from forest, transitional woodland, and grasslands and pastures to bare rocks and glaciers with increasing elevation.

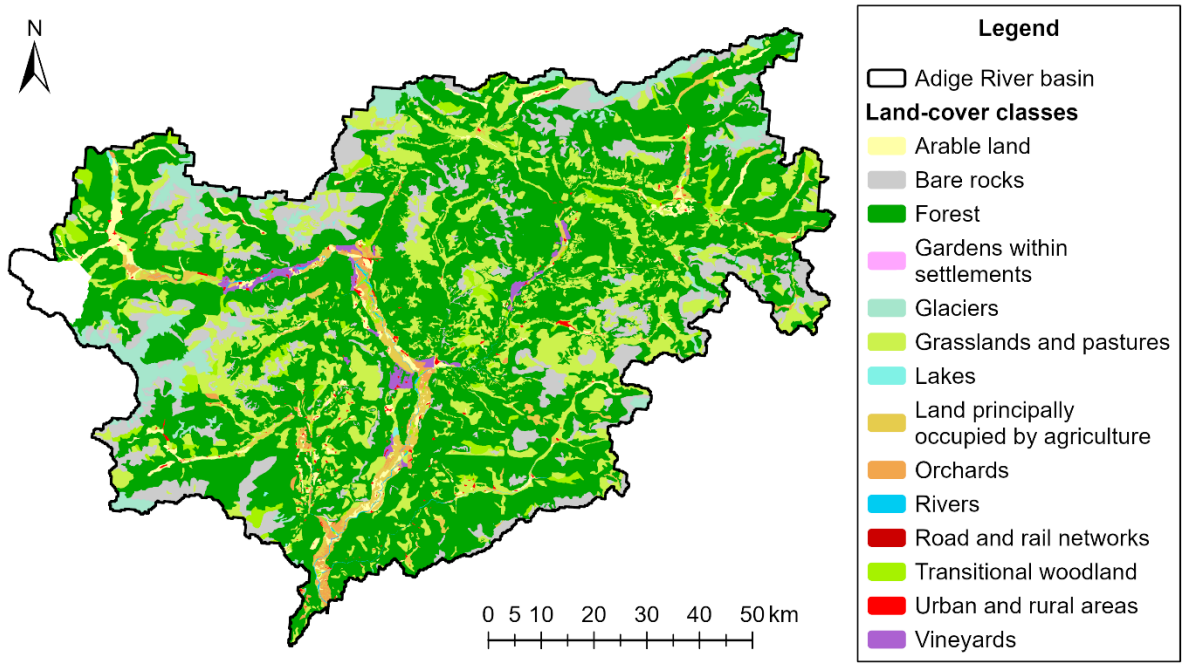


Figure 4: Reconstructed land cover of the Adige River Basin (1816–1821).

Table 2: Land-cover changes between the Second Military Survey (1816–1821) and CORINE Land Cover 2018.

Land-cover class	SMS area (km²)	CLC area (km²)	Area change	
			(km²)	(%)
Arable land	210.55	45.58	-164.97	-78.35
Bare rocks	1141.62	103.98	-107.63	-9.43
Forest	5443.10	5611.10	168.00	3.09
Gardens within settlements	0.63	0.86	0.23	36.06
Glaciers	407.22	111.51	-295.72	-72.62
Grasslands and pastures	1739.07	1446.18	-292.90	-16.84
Lakes	10.26	24.46	14.20	138.47
Land principally occupied by agriculture	178.76	184.45	5.69	3.18
Orchards	80.73	319.42	238.70	295.68
Rivers	21.96	4.70	-17.26	-78.59
Road and rail networks	0.63	2.24	1.61	254.65
Transitional Woodland	234.50	536.44	301.94	128.75
Urban and rural areas	40.40	177.68	137.27	339.75
Vineyards	68.88	79.73	10.85	15.75
Total	9578.33	9578.33	0.00	0.00

Compared with the mountain slopes, the valley floors exhibit a more heterogeneous land-cover composition, although they account for a relatively small proportion of the study area. These

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classes include arable land, which covers 2.20%; land principally occupied by agriculture, which accounts for 1.87%; orchards, which cover 0.84%; urban and rural areas, which occupy only 0.42%; and the road and railway network, which accounts for only 0.01%. Transitional woodland is also present in the valley floors, as this category includes shrublands mainly located along the Adige River, representing 6.9% of the total transitional woodland area. Rivers are also mainly confined to the valley floors, occupying 0.23% of the total study area. Vineyards, which account for 0.72%, are mainly located in the northern part of the basin on valley floors, foothills, and lower mountain slopes. Gardens within settlements represent only a marginal land-cover class.

CORINE land-cover map (2018)

Figure 5 shows the reclassified CLC 2018 land-cover map according to the classification scheme defined in Table 1. The areal distribution of the land-cover classes is summarized in Table 2 together with the overall changes in area for each class. The dominant land-cover class remains forest, which increased to 58.58% of the total study area. This class is still followed by grasslands and pastures, which account for 15.10% following an overall decrease of 292.9 km^2. Bare rocks account for 10.80% of the study area after decreasing by107.3 km^2. Another significant land-cover class that expanded is transitional woodland, which now occupies 5.60% of the total area following an increase of 318,1 km^2. Glaciers account for only 1.16% after a dramatic decrease of 295.7 km^2.

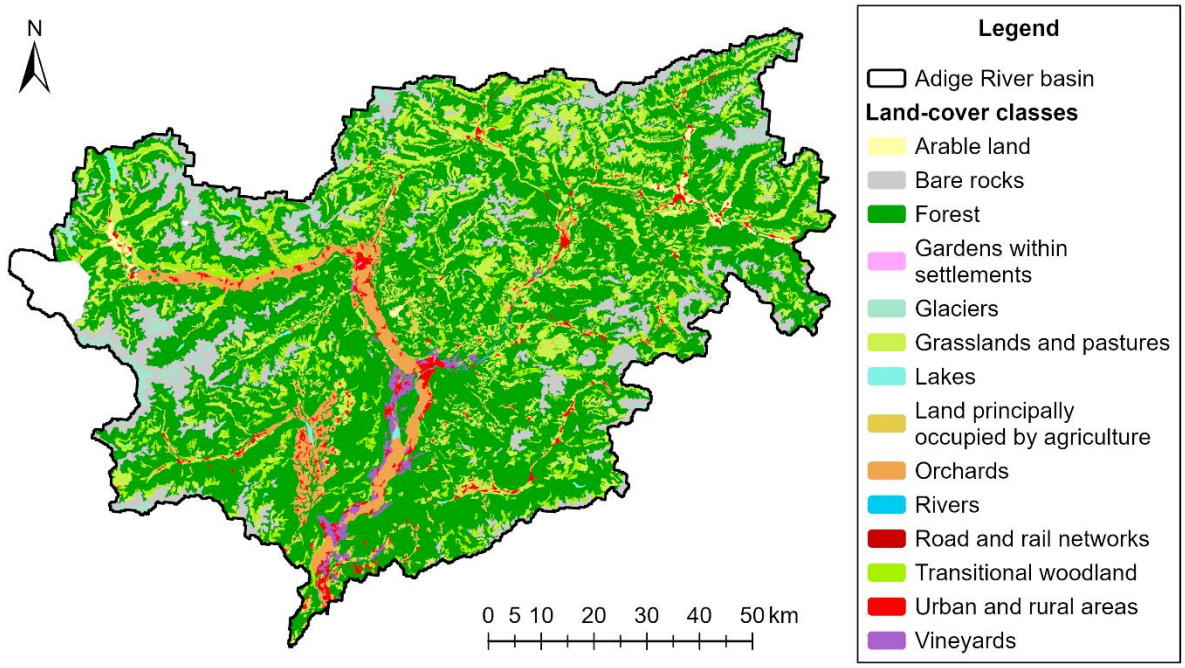


Figure 5: Reclassified CORINE Land Cover of the Adige River Basin (2018).

The most evident changes in the valley floors involved orchards and urban and rural areas. Orchards now cover 3.33% of the study area, due to an increase of 238.7 km^2. Urban and rural areas occupy 1.85% following an increase of 137.3 km^2. The road and railway network also strongly increased, accounting now for 0.02%. Shrublands included within the transitional woodland class in the historical map were no longer present in the valley floors in the 2018 dataset. Similarly, arable land, covering 0.48%, and rivers, covering 0.05%, both decreased more than 78%. In contrast, land principally occupied by agriculture, covering 1.93%, remained

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almost stable. Vineyards cover 0.83% following an overall increase of 10.9 km² although vineyards disappeared from the northern part of the basin and expanded in its southern part. The area occupied by lakes more than doubled, reaching 0.26% of the study area. Gardens within settlements remain marginal, by accounting for only 0.01%.

Land-cover transitions between 1816–1821 and 2018

The analysis of the transition matrix revealed the main land-cover pathways between the SMS land cover and the CLC. Transitions larger than 100 km², that is about 1.0% of the total study area, were used to develop the chord diagram plotted in Figure 6 (Gu et al., 2014). As can be seen, forest is associated with the largest transition that did not involve a class change, for 4105.20 km² (about 75.4% of the original land cover) remained in the forest class. The largest transition that involved a change in land cover was the conversion of grasslands and pastures to forest, covering 790.14 km² and representing approximately 80% of the original grasslands and pastures class. Nevertheless, forest areas also showed significant transitions towards other land cover classes, with 349.65 km² converted to transitional woodland, corresponding to nearly 38% of the original forest class. Additional transitions from forest included 59.19 km² to grasslands and pastures, as well as smaller areas converted to bare rocks and arable land (not shown in Figure 6). The transition from glaciers to bare rocks covered 241.96 km², representing 74.8% of the original glacier class. Other minor transitions from glaciers included 58.17 km² to forest and 11.09 km² to grasslands and pastures.

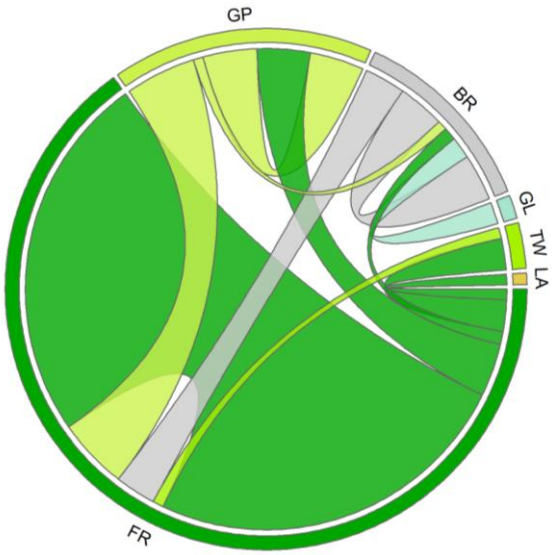


Figure 6. Land-cover transitions exceeding 100 km² from the Second Military Survey (1816–1821) land cover to CORINE Land Cover 2018. Chord width is proportional to the transition area. BR: Bare rocks; FR: Forest; GL: Glaciers; GP: Grasslands and pastures; LA: Land principally occupied by agriculture; TW: Transitional woodland (Gu et al., 2014).

The transition matrix made it possible to investigate transitions affecting specific land covers, as shown in Figure 7, where transitions greater than 5 km² involving orchards (panel a), urban and rural areas (panel b), and vineyards (panel c) are illustrated using chord diagrams. Although quantitatively less important than natural and semi-natural areas, these land covers are associated with important landscape and socio-economic dynamics in the Adige River basin.

The substantial expansion of orchards mainly involved transitions from land principally occupied by agriculture (90.49 km², 75% of the original class), arable land (45.52 km², 22%), and vineyards (27.21 km²). Forest and grasslands and pastures also contributed 58.07 km² and

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40.99 km², respectively. Only 28.26 km² of orchards remained in the same class throughout the period, while smaller transitions to urban and rural areas (22.62 km²) and vineyards (7.74 km²) were detected.

Urban and rural areas dramatically expanded at the expense of several natural and semi-natural land-cover classes, including grasslands and pastures (38.07 km²), forest (28.09 km²), arable land (27.24 km²), orchards (22.62 km²), land principally occupied by agriculture (18.64 km²), and vineyards (11.37 km²). Only 22.63 km² of urban and rural areas remained in the same class throughout the period. The disappearance of shrublands mainly resulted from conversions to orchards and urban and rural areas, accounting for 70.42% and 13.39% of the original shrubland area, respectively.

Despite the moderate increase, vineyards were affected by complex transition dynamics, with major transitions to orchards, urban and rural areas, and grasslands and pastures, and from forest (27.91 km²), grasslands and pastures (14.56 km²), orchards (7.74 km²), and land principally occupied by agriculture (7.32 km²). Only 15.04 km², corresponding to 18.86% of the current vineyard area, remained in the same class throughout the period.

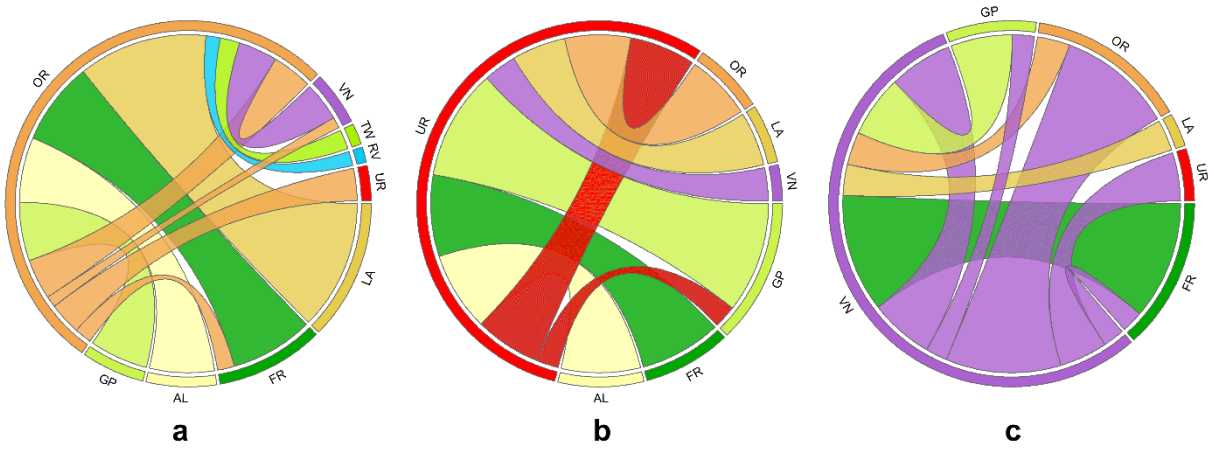


Figure 7. Land-cover transitions exceeding 5 km² from the Second Military Survey (1816–1821) land cover to CORINE Land Cover 2018 involving specific land covers: Orchards (panel a), Urban and rural areas (panel b) and Vineyards (panel c). Chord width is proportional to the transition area. AL: Arable land; FR: Forest; GP: Grasslands and pastures; LA: Land principally occupied by agriculture; OR: Orchards; RV: Rivers; TW: Transitional woodland; UR: Urban and rural areas; VN: Vineyards (Gu et al., 2014).

Discussion

Historical land-cover reconstruction

The reconstruction of the historical land cover of the Adige River basin demonstrates that the SMS can be successfully transformed into a quantitative GIS dataset suitable for comparison with modern standardized land-cover inventories. Despite the inherent limitations of nineteenth-century cartography, the adopted workflow produced a consistent land-cover dataset that enabled both quantitative estimates of land-cover distribution and the reconstruction of long-term land-cover transitions.

Several methodological challenges nevertheless emerged during the preparation of the historical dataset. Variations in positional accuracy, map quality, and cartographic representation introduced unavoidable sources of uncertainty. In particular, the limited availability of suitable ground control points, especially in high-elevation areas lacking settlements and road networks, affected the positional accuracy of features in some map tiles and may explain the magnitude of

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positional errors in these areas. Rotational errors may instead be attributed to distortions in the original map projection and inconsistencies in the cartographic methods used. However, the implications of these inaccuracies differ according to the type of analysis performed. While small positional errors have only a limited influence on the overall area estimated for each land-cover class, they may substantially affect transition-matrix analyses. Even slight spatial misalignments between historical and contemporary datasets can generate artificial transitions along class boundaries, thereby increasing the uncertainty associated with individual land-cover trajectories.

The manual interpretation of land-cover classes was also complicated by differences in color tone, shading, and cartographic conventions among adjacent map sheets. To reduce these inconsistencies, visually similar classes were merged into broader categories, improving the internal consistency of the historical dataset and facilitating its harmonization with the CLC classification. Although this simplification inevitably reduced thematic detail, it represented a necessary compromise between the characteristics of the historical source and the requirements of a standardized modern classification. Nevertheless, the harmonized classification provides a consistent framework for comparing historical and contemporary land-cover information. This approach enables quantitative analyses of long-term landscape dynamics while maintaining compatibility with widely adopted land-cover products such as CLC. Where supported by historical sources, a more detailed thematic classification would further enhance quantitative analyses. For example, distinguishing between different forest or vegetation types would improve hydrological applications, as different land-cover classes are characterized by substantially different interception, evapotranspiration, and infiltration processes.

The comparison with contemporary datasets also highlighted that uncertainties are not restricted to historical cartography. Local inconsistencies observed between CLC and recent satellite imagery indicate that modern land-cover products should not be regarded as error-free reference datasets. Consequently, some of the discrepancies identified in the transition matrix may originate from uncertainties affecting both the historical reconstruction and the contemporary land-cover dataset rather than representing actual landscape change.

Despite these sources of uncertainty, the adopted methodology successfully reconstructed the dominant land-cover patterns and the principal long-term transition pathways within the Adige River basin. Although positional inaccuracies and thematic simplifications may influence the interpretation of individual transitions, they do not compromise the identification of the main landscape dynamics at the basin scale. The adopted workflow therefore provides a reliable framework for integrating historical cartography with modern standardized land-cover datasets and supports quantitative analyses of long-term environmental and hydrological change.

Interpretation of land-cover transitions

The transition matrix analysis highlights several major landscape transformation processes affecting the Adige River basin over the last two centuries. The reconstructed land-cover distribution also reveals a clear elevational zonation, with forests, transitional woodland, and grasslands and pastures progressively giving way to bare rocks and glaciers at higher elevations. This zonation reflects the strong topographic control exerted by elevation on land-cover distribution in Alpine environments and provides further confidence in the consistency of the reconstructed historical dataset. Overall, these results indicate that the mountain slopes were primarily affected by a moderate afforestation process accompanied by a marked glacier retreat

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over the last two centuries.

The conversion of grasslands and pastures to forest represents the most relevant transition detected, with 790.14 km² transferred between the two classes. This change can be associated with long-term afforestation processes, natural vegetation succession, and the abandonment of marginal mountain pastures. In Alpine environments, the reduction of traditional pastoral activities has favored the expansion of forested areas into former agricultural and grazing lands.

The transition from forest to transitional woodland (349.65 km²) requires a more cautious interpretation. This change may reflect modifications in vegetation structure associated with forest disturbance, management practices, or phases of degradation-regeneration. Since transitional woodland represents an intermediate vegetation condition, this category may include different ecological trajectories that cannot be distinguished solely through land-cover classification.

The conversion of glaciers to bare rocks (241.96 km²) represents a major environmental transformation detected in the basin. This transition reflects the reduction of glacier-covered surfaces and the exposure of previously ice-covered terrain. The additional transitions from glaciers to forest (58.17 km²) and glaciers to grasslands and pastures (11.09 km²) indicate the progressive colonization of formerly glacierized areas by vegetation following glacier retreat.

The transition from land principally occupied by agriculture (90.49 km²) and shrubland (11.36 km²), herein included in transitional woodland, to orchards reflects changes in the agricultural structure of the study area. Apple cultivation has become one of the main agricultural sectors in the region due to the high economic value of this crop compared with traditional agricultural systems. The expansion of orchards therefore represents a shift toward more specialized and economically profitable agricultural production. Other agricultural transitions, such as land principally occupied by agriculture to forest, grasslands and pastures, and urban and rural areas, may reflect a combination of land-use change, agricultural abandonment, and differences between historical and modern classification systems.

The conversion of grasslands and pastures to urban and rural areas, forest to urban and rural areas, and orchards to urban and rural areas reflects the progressive expansion of built-up areas within the basin. This process is particularly evident in northern Italy and has been widely investigated in relation to demographic growth, economic development, and spatial planning. In Alpine environments, settlement expansion is strongly concentrated along valley floors and areas with favorable accessibility, where agricultural and natural areas have historically been subjected to increasing urban pressure. Accordingly, the valley floors experienced the most pronounced anthropization within the basin, accompanied by a marked decline in natural and semi-natural land-cover classes. The reduction of river areas, the substantial decrease in arable land, and the disappearance of shrublands from the valley floors illustrate the progressive replacement of natural and traditional agricultural landscapes by more intensive agricultural and urban land uses. Furthermore, the transition matrix analysis revealed unexpected land-cover changes over the study period. For example, moderate transitions were observed from forest to bare rocks, glaciers to forest, and forest to grasslands and pastures. These changes may be affected by inaccuracies in the vectorization of the historical map, limitations and polygon misplacement in the CLC dataset, or misinterpretations during the analysis process.

Conclusions

This study highlights how historical maps can be combined with modern geospatial data to

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provide valuable insights into how landscapes have changed over time. A detailed picture of the Adige River Basin's land cover about 200 years ago was reconstructed through refined georeferencing and manual land-cover vectorization of Second Military Survey map tiles of the Habsburg Empire dating from the early 19th century. Although some challenges were encountered, especially in areas where reliable ground control points were missing or where the map quality was poor, the historical maps still provided crucial information. The comparison with CORINE Land Cover 2018 revealed major long-term land-cover changes, including moderate afforestation and severe glacier retreat in the mountain slopes, as well as increasing anthropization and agricultural specialization in the valley floors. At the same time, some inconsistencies were found in the CORINE Land Cover dataset, raising questions about its reliability, such as the possible misclassification of certain features. These inconsistencies highlight the importance of carefully validating and interpreting modern datasets. This work emphasizes the importance of manual digitization, especially when automated methods struggle due to the complexity or poor quality of historical maps.

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