Anthropocene 48 (2024) 100453

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Human-induced landscape modification in the in the last two centuries in the Po delta plain (Northern Italy)

Luigi Bruno [a,*], Matteo Meli [b], Maria Luisa Garberi [c]

[a] *Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, Via Campi 103, Modena, Italy*
[b] *Department of Biological, Geological and Environmental Sciences, University of Bologna, Via Zamboni 67, Bologna, Italy*
[c] *Regione Emilia-Romagna, Settore Innovazione Digitale, Dati, Tecnologia e Polo Archivistico, Italy*

ARTICLE INFO

Keywords:
Historical maps
Land-cover and use mapping
Land reclamation
Carbon storage
Po delta plain

ABSTRACT

Historical maps with high degree of accuracy permit quantitative reconstructions of past land use and land cover (LULC), crucial to assess the impact of human activities on landscape evolution. After georeferencing in a modern reference system, the *Carta del Ferrarese* commissioned by Napoleon Bonaparte and completed in 1814, has been used to quantify the changes in LULC, occurred in the last two centuries in the Po delta plain. The map depicts a palaeo-landscape dominated by wetlands (49 % of the study area) and agricultural areas (41 %), whereas forests appear already largely depleted (5 %). The *Piantata Padana*, a traditional agroforestry system with live trees used to support grapevines, is dominant (62 % of the agricultural areas). The comparison with the 2014 LULC map highlights a dramatic reduction (85 %) of wetland areas and the replacement of the *Piantata Padana* with bare arable lands, with the consequent removal of 4–40 million trees. Soils of areas formerly occupied by wetlands show high organic-carbon content, highlighting the potential of humid areas in carbon sequestration. Land reclaiming, prompted by the introduction of steam pumps, favoured the economic development of the area, but concurred to CO_2 emissions through the oxidation of soil organic substances, energy consumption from pumping stations, and the extensive use of hydrocarbon fuels in agriculture. Although urbanisation is limited in the Po delta plain, this area appears nowadays largely shaped by human activities, with the dominance of lands devoted to agriculture, dissected by a dense network of draining channels. The landscape changes recorded in the last two centuries in the Po coastal plain have been uniquely driven by human activities, like in several coastal plains worldwide.

1. Introduction

Alluvial and coastal plains are densely populated regions, which experienced dramatic changes in land use and land cover (LULC) in the past centuries (Alves et al., 2007; Bajocco et al., 2012). Natural areas, including forests, swamps, marshes and coastal lakes, have been largely converted into lands of intensive crop farming (Goldewijk and Ramankutty, 2004; Popovici et al., 2013). Rapid urban sprawl, i.e., the ‘uncontrolled spread of towns and villages into undeveloped areas’ (F.O.E.N., 2016), and the development of a dense transportation network have drastically altered rural landscapes (Blondel, 2006; Dewan et al., 2012; Rawat et al., 2013), leading to significant soil degradation or sealing with impermeable artificial materials (Falcucci et al., 2007; Scalenghe and Marsan, 2009). The anthropization of lowlands resulted in significant increases in soil erosion, carbon emission, and surface-air temperatures (Oke, 1982; Houghton, 2002; Vose et al., 2004; Pal and Ziaul, 2017; Spalevic et al., 2020), exacerbating environmental degradation and the depletion of water reservoirs in the shallow subsurface (Schot and van der Wal, 1992; Moiwo and Tao, 2014; Panda et al., 2021, Meli and Romagnoli, 2022). Recent literature on LULC indicates that human activities have altered more than one-third of the Earth’s surface (Foley et al., 2005), primarily through deforestation for cropland expansion, resulting in significant global effects on climate and ecosystems over the past centuries (Houghton, 1994, Hu et al., 2021).

The extensive modifications in LULC, occurred over the last decades, have been documented worldwide through the analysis of multi-temporal satellite images (Yang and Lo, 2002; Ruberti and Vigliotti, 2017; 2022). This led to the availability of multiple highly detailed spatial LULC products with varying resolutions, ranging from a few kilometres to tens of metres (Bartholome and Belward, 2005; Friedl

* Correspondence to: Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, Via Campi 103, Modena 41125, Italy.
E-mail addresses: luigi.bruno@unimore.it (L. Bruno), matteo.meli7@unibo.it (M. Meli), marialuisa.garberi@regione.emilia-romagna.it (M.L. Garberi).

https://doi.org/10.1016/j.ancene.2024.100453
Received 15 March 2024; Received in revised form 7 July 2024; Accepted 22 October 2024
Available online 28 October 2024

et al., 2010; Chen et al., 2015), which, however, are limited in their temporal coverage. Changes occurred over centuries, instead, are estimated through modelling (see e.g., Fuchs et al., 2013; Meiyappan and Jain, 2012; Sohl et al., 2016; Moulds et al., 2018) or have been reconstructed in worldwide regions, where historical maps with sufficient resolution are available. Historical paper maps and drawings, such as cadastral, military, and topographic maps, which sometimes date back several centuries, are invaluable for capturing past landscapes in a spatially explicit manner and for studying long-term LULC history and dynamics (Cousins et al., 2015; Fuchs et al., 2015; Mäyrä et al., 2023). As historical maps often represent the only source of information on temporal LULC variations, their digital availability increased recently for different applications (e.g., Bičík et al., 2001; Haase et al., 2007; Skaloš et al., 2011; Bürgi et al., 2015; Kaim et al., 2016). However, the use of old maps for environmental analyses might be challenging due to various limitations. Inadequate survey methodologies and the subjective representation of spatial scales and features may results in an overall incompatibility with modern reference systems and map distortions (Petit and Lambin, 2002; Skaloš et al., 2011; 2018), which might require complex rectification (Cousins, 2001). Furthermore, extracting information from old maps often requires time consuming manual processing (e.g., Cousins, 2001; Skaloš et al., 2011; Cousins et al., 2015; Pavelková et al., 2016; Popelková and Mulková, 2018), as automatic extraction using computer image analysis algorithms (see Mäyrä et al., 2023 and references therein) can be very difficult, particularly in the fine-scale characterization of local landscapes (Liu et al., 2018).

With an area exceeding 4500,000 ha, the Po Plain is the widest alluvial plain in Italy. It hosts about one third of the Italian population and most of the industrial activities. About 40 % of the country's food is produced in this low-relief area, which experienced a long process of land reclamation since Roman times (Bruno et al., 2013; Curtis and Campopiano, 2014). Several historical maps dating back to the last four centuries, depict the progressive anthropization of the Po Plain. Among these maps, a few show an extraordinary level of accuracy, which permit the unequivocal definition of palaeo-land cover and use, and the precise measurement of areas after georeferencing in modern reference systems.

In this work we focused on the coastal sector of the Po Plain, and particularly on an area of 240,000 ha, roughly corresponding to the Ferrara District (Fig. 1). This area is depicted in several historical maps and in particular in the *Carta del Ferrarese* commissioned by Napoleon Bonaparte and completed between 1812 and 1814. By the comparison of this historical map with a map of LULC released in 2014 (available online at https://servizimoka.regione.emilia-romagna.it/mokaApp/apps/UDSD/index.html), and through a review of the historical documentation, this paper aims at addressing the following research questions: (i) what are the main changes in LULC occurred in the Po delta plain in the last two centuries? (ii) how much human activities impacted landscape evolution? (iii) to what extent palaeolandscape influenced present-day soil properties (i.e., organic carbon content)? (iv) changes in LULC concurred to carbon emissions?

2. Background

2.1. Late quaternary environmental changes and human presence in the Po Plain

The Po Plain is an alluvial plain fed by the Po River and its 161 tributaries, which drain the Southern Alps and the Northern Apennines (Fig. 1). Pleistocene fluvial and glacio-fluvial deposits are widely exposed north of the Po River, whereas Holocene alluvial and delta-plain deposits are dominant to the south and in the coastal plain, respectively (Fig. 1). Studies of subsurface stratigraphy, palaeontology and palynology highlighted dramatic environmental changes since the Middle Pleistocene, including rapid shoreline migrations largely driven by glacio-eustatic oscillations (Campo et al., 2020). During glacial lowstands, the area corresponding to the Ferrara District (red polygons in Fig. 2) has been an alluvial plain (Fig. 2a), representing a possible pathway for hominin migrations (Muttoni et al., 2010; 2011). At the peak of warm periods, instead, the area has been largely flooded due to rapid sea-level rise driven by glaciers melting. During the last two marine ingressions, around 125 ka BP (Marine Isotope Stage – MIS - 5e) and 7 ka BP (MIS 1), the Adriatic coastline was located about 35 and 25 km

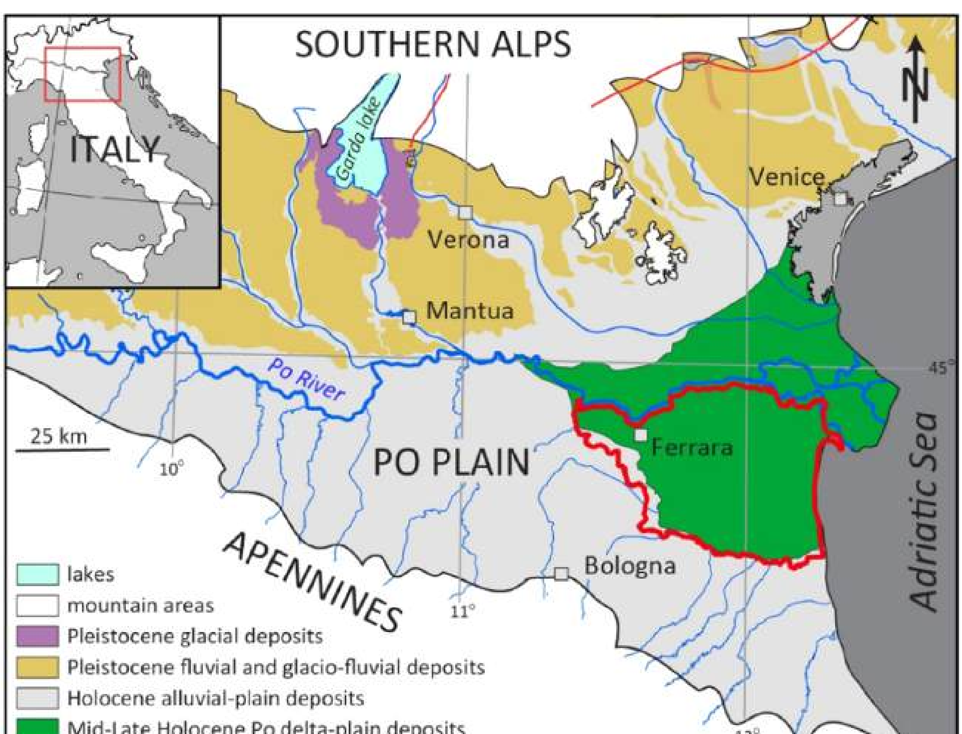

Fig. 1. - Geology of the Po Plain and location of the study area (red polygon). Modified after Bruno et al. (2022).

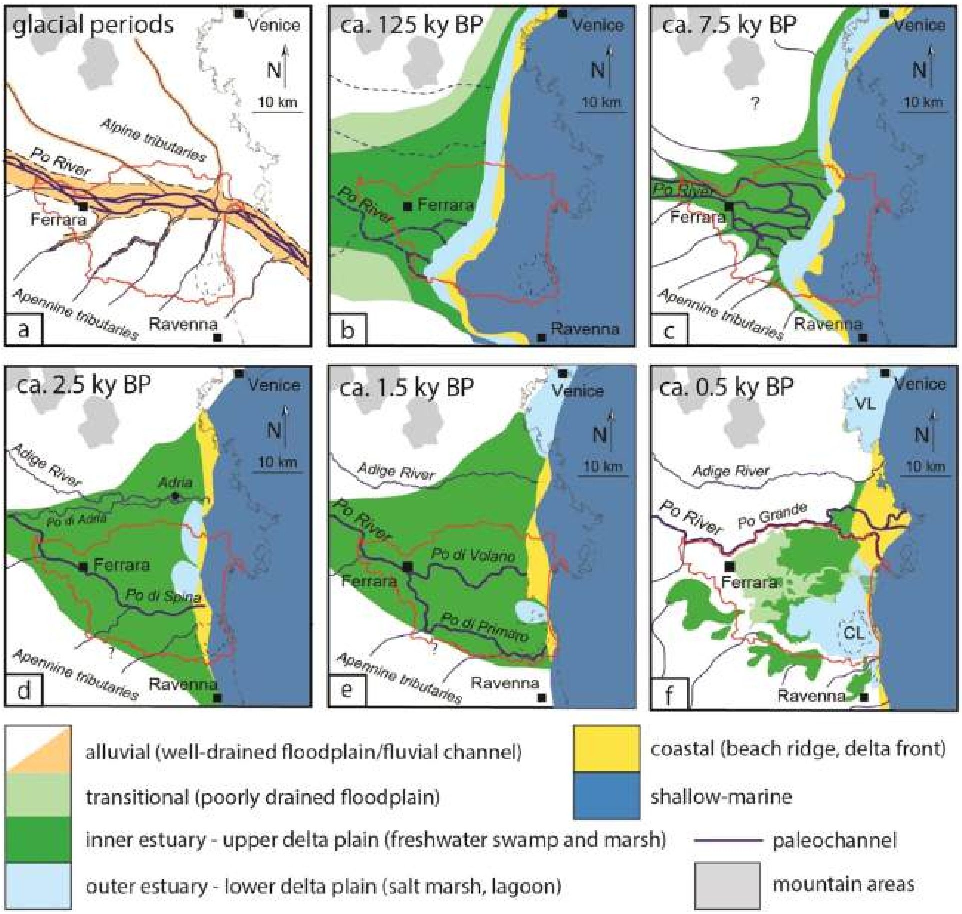

Fig. 2. - Palaeogeographic sketch maps depicting palaeogeography of the Po coastal plain and of the Ferrara District (black bold line) during Mid-Late Pleistocene glacial periods (a), MIS5e maximum marine ingression (b), MIS1 maximum marine ingression (c), Iron Age (d), Middle Ages (e) and Renaissance (f). Panel a is based on Bruno et al. (2017) and Morelli et al. (2017); panel b is modified after Campo et al. (2020), considering data from Marcolla et al. (2021); panel c is based on data from Amorosi et al. (2008) and Bruno et al. (2017); panel d is from Amorosi et al. (2017), whereas panels e and f are modified from Rossi et al. (2021). The *Carta dei Ducati Estensi* (Marco Antonio Pasi, 1580) and the map of the *Ferrariae Ducatus* (Egnazio Danti, 1582) have been also considered for the compilation of panel f. MIS: Marine Isotope Stage; VL: Venice Lagoon; CL: Comacchio Lake.

west of the modern one, respectively (see Figs. 2b and 2c; Bruno et al., 2017; Campo et al., 2020). During the MIS 1 maximum marine ingression, the Po mouth was a wave-dominated estuary, and the Ferrara area was characterised by extensive wetlands (Fig. 2c, Bruno et al., 2017). Following sea-level stabilisation (i.e., after 7 ka BP), the Po mouth turned progressively into a prograding delta (Amorosi et al., 2017; 2019). An increasing anthropogenic impact on landscape evolution is recorded in this phase in the piedmont areas of the Po Plain, due to radical changes in LULC. Forest clearance started during the Neolithic (ca. 7.0–5.0 ka BP) for agricultural practices and accelerated during the Eneolithic (ca. 5.0–3.0 ka BP) for transhumant pastoralism (Accorsi et al., 2004; Cremaschi and Nicosia, 2012). By contrast, no significant human-induced changes in vegetation are recorded in the pollen record of the Po delta plain (Rossi et al., 2021).

A vast documentation exists on the Late Holocene human presence in the Po Plain. Bronze Age sites are widespread (Mercuri et al., 2006; Nicosia et al., 2011; Bellintani and Saracino, 2015) and testify to improved hydraulic techniques for water exploitation (Cremaschi et al., 2006). During the Iron Age and Roman Period, human impact on the Po Plain landscape increased notably, especially in the proximal sector of the plain, with a strict control on the drainage network and large areas devoted to agriculture (Marchetti, 2002; Bruno et al., 2013; 2015). In this time span, humans also expanded in the Po delta plain, settling poorly extended areas, corresponding to fluvial ridges. Two main urban centres (*Adria* and *Spina*) were founded close to two Po River branches (Sassatelli and Govi, 2013; Mistireki and Zamboni, 2019). The *Po di Adria*, active between ca. 4.0 and 2.5 ka BP (Piovan et al., 2012; Demurtas et al., 2022), flowed a few km north of the study area, whereas the *Po di Spina*, active between ca. 2.5 and 1.5 ka BP, flowed across the study area (Fig. 2d).

Societal decline following the fall of the Western Roman Empire, resulted in the abandonment of the drainage network, river instability, spread of wetlands and flooding of several rural and urban areas (Bruno et al., 2013; 2015; Cremonini et al., 2013). Two new branches of the Po River became active in the delta plain during the Middle Ages (*Po di Volano* and *Po di Primaro* in Fig. 2e). The area around the former *Po di Spina* was sediment starved and progressively turned into a brackish lagoon (Rossi et al., 2021). In 1152 AD (0.8 ka BP), through an avulsion close to Ferrara (Ficarolo avulsion), the Po River shifted northward toward its present course (*Po Grande* in Fig. 2 f), which bounds the Ferrara district to the north. Low sediment supply, due to the progressive abandonment of the mediaeval branches, and subsidence induced by sediment compaction, led to the progressive flooding of the Ferrara district and the spread of wetlands and coastal lakes (Stefani and Vincenzi, 2005; Rossi et al., 2021). The Ficarolo avulsion was the last important natural event that strongly modified the landscape of the Po delta plain. The last-millennium history of this area is mainly marked by political changes. After being part of the Exarchate of Ravenna, around 984 AD, the Ferrara territory became property of the Marquis Tedaldo of Canossa. A short-lived period as a free municipality (1115–1208 AD) was followed by a longer period under the Papal State as a feud or as a ducky governed by the Lords of Este. Ferrara and the Po delta plain, passed in 1597 AD under the direct control of the Pope, who governed the area until the unification of Italy in 1861 AD, except for a decade (1805–1814 AD) when the area was part of the Napoleonic Kingdom of Italy, a client-state of the French Empire (Hearder, 1983).

2.2. The Po delta plain in historical maps

The palaeogeography of the Po delta plain over the last five centuries is depicted in several historical maps. The oldest maps covering the Ferrara District date back to the sixteenth century, when the study area largely corresponded to the Duchy of Ferrara: the *Carta dei Ducati Estensi* by Marco Antonio Pasi (1580, Figs. 3a and 3b) and the map of the *Ferrariae Ducatus* by Egnazio Danti (1582, Fig. 3c). The more recent *Corografia del Ducato di Ferrara* (Ambrogio Baruffaldi and Andrea Bolzoni, 1758; Fig. 3d), was produced when the Ferrara area was part of the Papal State. These maps offer a detailed picture of the Ferrara palaeohydrography, characterised by a major Po River branch to the north (*Po Grande*) and two minor southern branches (*Po di Volano* and *Po di Primaro*). The *Corografia del Ducato di Ferrara* highlights, with good accuracy, the presence of extensive wetlands and coastal lakes between these branches. However, these maps provide little information about LULC beyond the aquatic environments.

The *Carta del Ferrarese* (Fig. 3a), used in this study, was commissioned by Napoleon Bonaparte and completed between 1812 and 1814, to facilitate the administration and development of the area, as well as to assist in military planning. The map, currently stored at the Kriegsarchiv in Vienna, consists of 38 sheets, at a scale of 1:15000, and covers 240,000 ha of the Po River lowlands, roughly corresponding to the present-day Ferrara District in northern Italy (Figs. 4b and 4c). Given its military purposes, the *Carta del Ferrarese* was drawn with great accuracy. For example, very local LULC which could hinder the movement of troops were reported and the presence and position of single trees were detailed as they could impact the use of cannons. Moreover, a detailed LULC legend was produced together with the map. The Carta del Ferrarese is, thus, the oldest map with sufficient accuracy to be considered a reliable source of two-century-old LULC information (see Section 4 for details).

A first attempt to create a map of palaeo-land use is the *Carta Storica Regionale – Uso del Suolo Storico*, published in 2007 and based on two maps completed between 1828 and 1856: the Austrian Topographic Chart to a scale of 1:86000 and the *Carta Topografica degli Stati di terraferma di Sua Maestà il Re di Sardegna* (1853) to scale of 1:50000. After

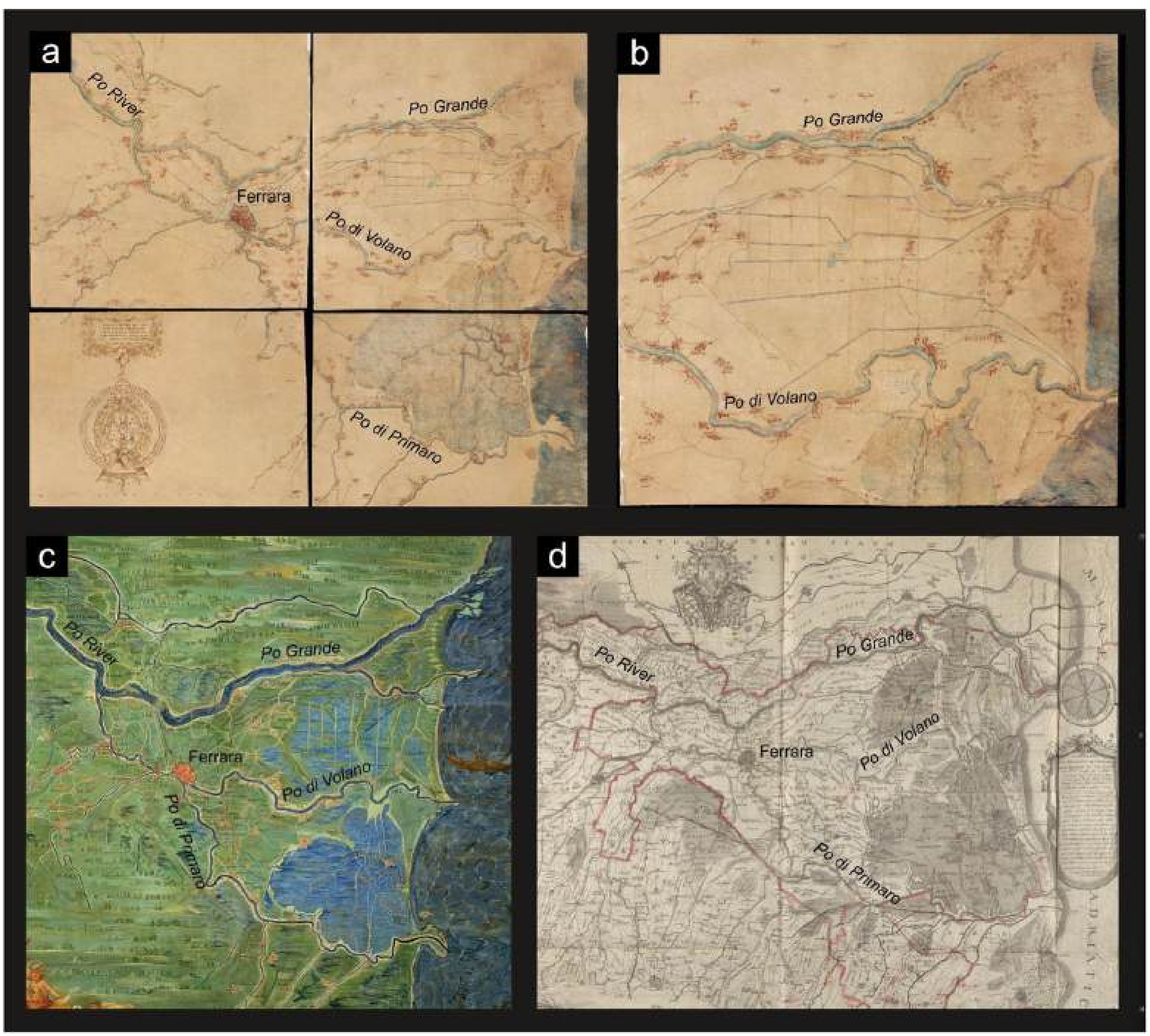

Fig. 3. - Historical maps depicting palaeogeography of the Ferrara District in the last five centuries. (a) *Carta dei Ducati Estensi* by Marco Antonio Pasi (1580), available online at https://edl.cultura.gov.it/item/dwj6xmkj2y. (b) close up on the *Carta dei Ducati Estensi* showing a first attempt of reclamation of an area east of Ferrara (Grande Bonificazione Ferrarese). (c) *Ferrariae Ducatus* by Egnazio Danti (1582), available online at https://geoportale.regione.emilia-romagna.it/applicazioni-gis/regione-emilia-romagna/cartografia-di-base/cartografia-storica/carte-storiche-in-emilia-romagna-dal-1580-al-1852. (d) *Corografia del Ducato di Ferrara* by Ambrogio Baruffaldi and Andrea Bolzoni (1758), available online at https://edl.beniculturali.it/beu/850013701.

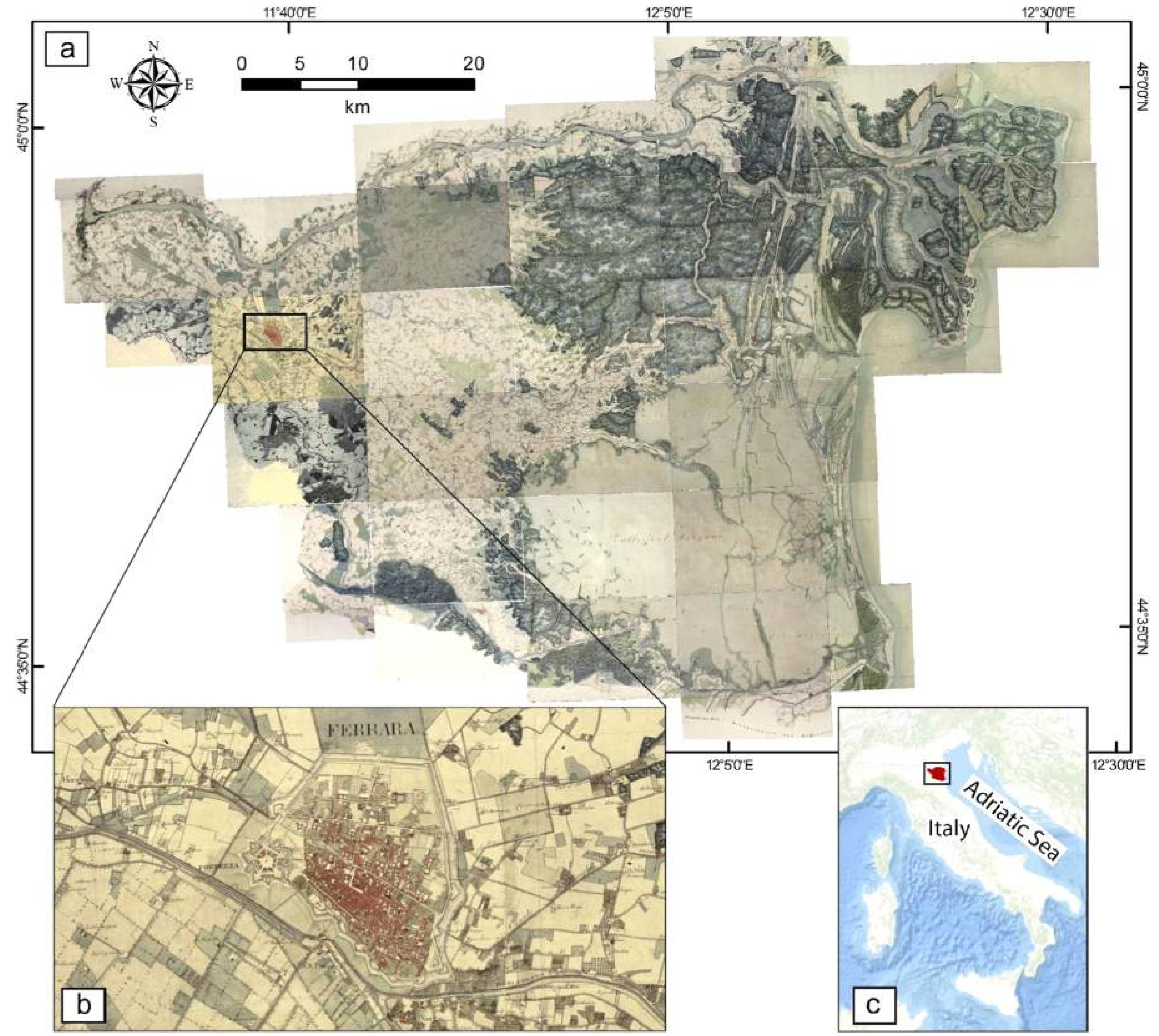

Fig. 4. (a) *Carta del Ferrarese*, depicting the 1814 geography and LULC of the Ferrara District. (b) A close-up on the city of Ferrara). (c) Location of the Ferrara District (red polygon) in the Italian peninsula.

the unification of Italy (1861), several detailed topographic maps were produced by the *Istituto Geografico Militare* (Geographical Military Institute – IGM), with an increasingly high accuracy. All these maps were taken into account to depict the major changes in LULC in the last two centuries in the Po delta plain.

3. Materials and methods

The *Carta del Ferrarese* (Fig. 4a; hereafter CF) has been used in this study to reconstruct the LULC of the Ferrara territory at the beginning of the 19th century. The CF was first captured on high-resolution film photography, in order to avoid the image quality deterioration induced by scanning the hard copy, and then georeferenced using geospatial technologies and techniques to align it with the current reference systems and make it usable for geographic analysis. The reference system used for georeferencing the CF is based on the Gauss-Boaga West projection, Monte Mario Italy 1. The map was registered with ground control points to adjust position, rotation, and scale to the reference system; these points were identified by comparing the features on the historical map with corresponding features on modern maps (Regional Base Map at 1:5000 scale). The mapping has been carried out in a GIS environment, through manual vectorization by digitising and characterising more than 32,000 polygons, each with its specific LULC attribution. LULC interpretation has been based on the Corine Land Cover (CLC) classification system (Heymann et al., 1994; https://land.copernicus.eu/pan-european/corine-land-cover) for the first three levels, while a fourth level provides higher details among LULC classes according to the CISIS specifications (https://www.cisis.it/). In detail, the first CLC level is represented by five high-rank groups: artificial surfaces, agricultural areas, forest and semi-natural areas, wetlands, and waterbodies; each order is then subdivided in subgroups. Artificial areas include, e.g., urban areas, residential structures and roads. Agricultural areas are arable lands, permanent crops (e.g., orchards), pastures, and heterogeneous fields with mixed annual and permanent crops. Wetlands are subdivided in inland (freshwater) and coastal (brackish) marshes, whereas water bodies include rivers, canals and artificial reservoirs. The mapping work was preceded by a careful interpretation of individual features in the drawing, also by comparing it with current features, with the support of the original CF legend (Fig. 5). The code 2.4.1.1 of the CLC-CISIS classification, used to depict the modern vineyard, has been used to map a vineyard system existing at the CF time, called *Piantata Padana*. The *Piantata Padana* was a traditional agroforestry system used in the Po Plain since the Middle Age (and possibly since Etruscan age; Sereni, 1961), but now no longer practised. Trees, planted in rows at a predetermined distance, were used to support grapevines. In the local system, the typical distance among trees and among rows was 3.8 m, but this could vary up to 6 m (among trees) and to 30 m (among rows; Campiani and Garberi, 2008; Cillis, 2012).

In order to highlight the major changes in LULC that occurred in the last two centuries, the CF has been compared with more recent historical maps (e.g., the Austrian Topographic Chart to a scale of 1:86000, the 1853 Carta Topografica degli Stati di terraferma di Sua Maestà il Re di Sardegna to scale of 1:50000 and the post-1861 maps of the Istituto Geografico Militare (Geographical Military Institute – IGM) and with the 2014 LULC map of the Emilia-Romagna Region (Fig. 6). In this map, compiled by the Cartographic Service of the Emilia-Romagna regional

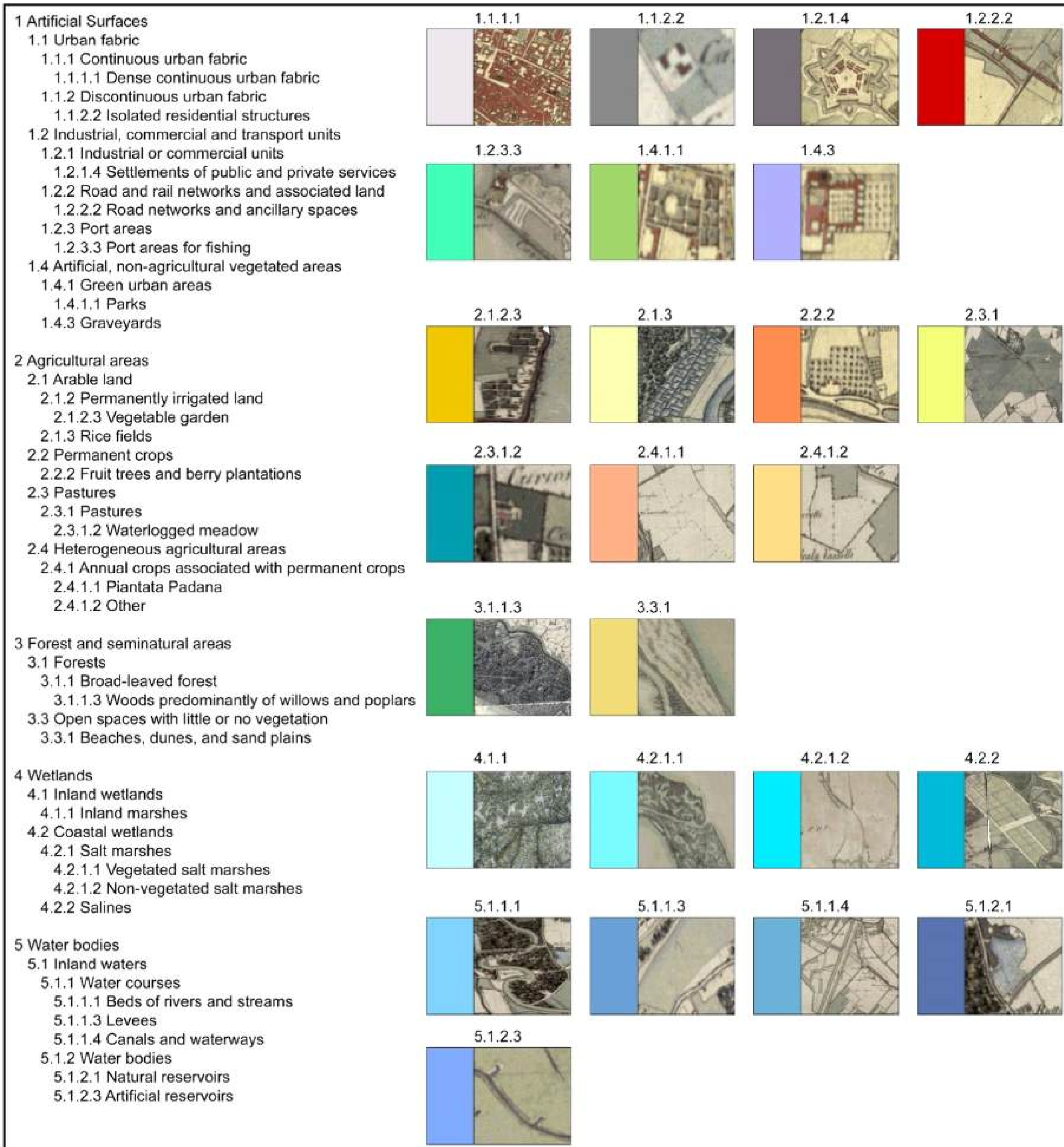

Fig. 5. - LULC classes considered for the characterization of the *Carta del Ferrarese*, along with the associated colour and CLC and CISIS codes (see Section 3 for details).

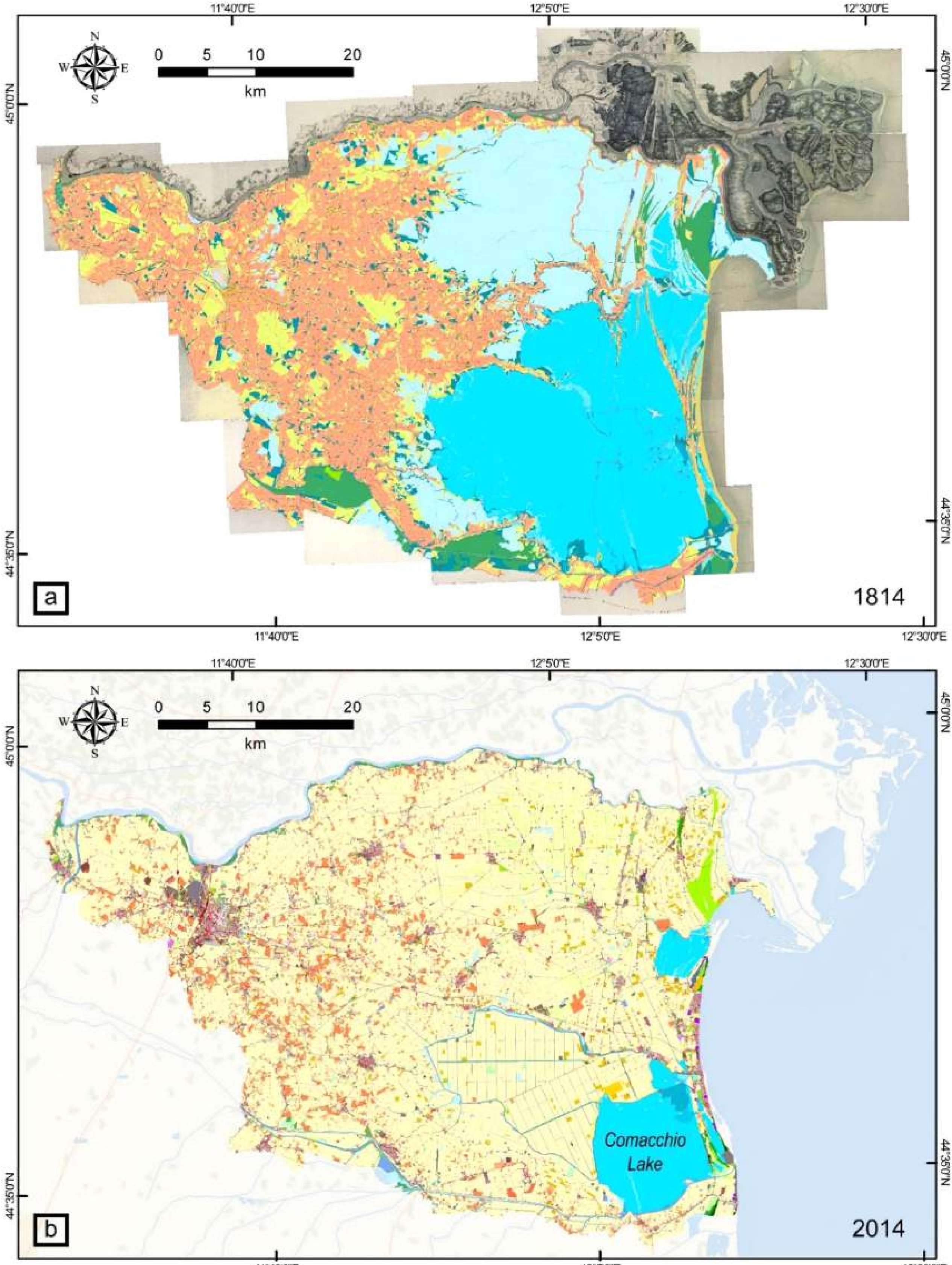

Fig. 6. - (a) 1814 LULC map obtained from the georeferencing and interpretation of the *Carta del Ferrarese.* (b) 2014 LULC map of the Emilia-Romagna Region available online at https://geoportale.regione.emilia-romagna.it/approfondimenti/database-uso-del-suolo (see also Corticelli et al., 2018). Legend of LULC classes in Fig. 5.

administration by interpreting and digitising aerial pictures with a 50 cm spatial resolution, the modern Ferrara territory is depicted through 83 LULC classes, grouped in the five high-rank groups described above. As several modern features did not exist in the early 19th century (e.g., hippodromes, highways, bathing facilities), only the five high-rank groups have been considered for comparison between the two maps. Historical documents relative to the reclamation of different sectors of the study area were considered to reconstruct the progressive reduction of wetland areas.

In order to assess the influence of palaeo-landscape on present-day soil properties (i.e., content in organic carbon), the CF has been compared with two maps depicting the percentage of organic carbon (hereafter OC) in the uppermost 30 and 100 cm of modern soil profiles (Staffilani et al., 2016; Ungaro et al., 2023). In these maps, the percentage of OC is represented through a mesh structure with cells with sides of 500 m. The value of OC content for each cell has been estimated with the geostatistical analysis of 18,393 data points for the first map (uppermost 30 cm) and of 3971 for the second one (uppermost 100 cm). Additional 15 samples were collected from six sampling points located in four reclaimed areas, at depths < 100 cm with a hand auger, for the determination of the total organic carbon (TOC, Table 1). For TOC determinations, the samples were dried, granted and treated with 10 % HCl to remove inorganic carbon. A radiocarbon date was obtained from a peat sample which underwent alkali-acid-alkali pretreatment before AMS counting. The conventional 14 C age was calibrated using OxCal 4.4 (Ramsey and Lee, 2013), with the IntCal 20 curve (Reimer et al., 2013; see Table 2).

4. Results

Due to the high resolution and accuracy of the CF, about 32,000 polygons, belonging to 25 different LULC classes have been recognized and mapped. The 1814 palaeogeography and LULC, depicted in the CF (Fig. 6a), highlights the dominance of two environments: wetlands, which represent about 49 % of the territory, and agricultural areas which cover 41 %. The remaining 10 % of the Ferrara province is occupied by forests (ca. 5 % of the total area) and artificial surfaces (3.5 % of the total area). Among wetlands, inland marshes and swamps (code 4.1.1 in Fig. 5) cover an area of almost 46,000 ha, whereas non-vegetated salt marshes (code 4.2.1.2) of 54,200 ha. The *Piantata Padana* (code 2.4.1.1), described in Section 3, represents the dominant agricultural LULC, with ca. 61,000 ha (62 % of the agricultural areas). Subordinate agricultural areas are pastures (code 2.3.1) and waterlogged meadows (code 2.3.1.2).

The comparison with the 2014 LULC map (Fig. 6b) shows a marked decrease in wetlands in the last two centuries, from 116,578 to 16,328 ha, which nowadays consist of isolated water bodies. The area between the northernmost branch of the Po Delta (*Po Grande*) and the *Po di Volano* branch (ca. 28,600 ha), which nowadays lies at ca. 3 m below mean sea level, was drained at the end of the nineteenth century (1872 AD) with the Grande Bonificazione Ferrarese (GBF in Fig. 7), through the realisation of the Codigoro pumping station. Land reclamation in the Ferrara district proceeded in the following centuries (see Figs. 7 and 8a) with the draining of the Gallare area (1873 AD, 12,500 ha), Argenta and Filo (1878 AD, 6840 ha), Galavronara and Forcello (1888 AD, 2270 ha), Montesanto, Denore, Campocieco, Benvignante, Sabbiosola, Martinella, Tersallo, Bevilacqua, Trava (AD 1891, 13,660 ha), Trebba and Ponti (1923 AD, 4600 ha), Sant'Antonino (1925 AD, 2300 ha) and many other smaller areas. The last important reclamation works were carried out in the Mezzano area (M in Fig. 7) in 1964 AD, when ca. 23,800 ha of the southeast salt marshes were drained and devoted to intensive agriculture. A remnant of these salt marshes is represented by the Comacchio Lake (Fig. 6b).

Another significant change regards agricultural areas, which expanded over reclaimed lands reaching a total extent of 185,629 ha (Fig. 8b). The last two centuries record the decline of the *Piantata Padana*. Ca. 61,000 ha of this agroforestry system were replaced by arable lands (Fig. 6). Forests were reduced by 68 % (from 12,175 to 3910 ha) and artificial areas increased by 156 % (from 8408 to 21,524 ha).

Table 1
- Results of chemical analyses on soil samples collected from reclaimed areas. Location of sampling sites in Fig. 9.

Location	depth (cm)	TOC (%)
GBF2	10	4.79
	25	1.74
	50	23.79
GBF4	5	2.60
	45	2.59
GBF6	5	2.05
	25	1.50
G	5	3.13
	35	2.73
A	10	4.51
M4	10	13.88
	45	13.10
	80	3.87
	90	15.24
	100	1.96

5. Discussion

5.1. Influence of palaeogeography on soil properties and implications for carbon storage

The comparison of the 1814 palaeogeography (Fig. 6a) with the distribution of organic carbon (OC) in modern soils (Figs. 9a and 9b) highlights a close match between former wetlands and present-day areas with high OC content. In wetlands depicted in the *Carta del Ferrarese* and in previous historical maps (Figs. 3 and 4), reducing conditions may have favoured litter accumulation and preservation (Vepraskas et al., 2000). In these areas, the content of OC in the uppermost 30 cm of soil profiles (Fig. 9a), is slightly lower than the one averaged in the uppermost 100 cm (Fig. 9b). This difference may reflect organic-matter mineralization and oxidation in the topsoil after draining (Bini and Zilocchi, 2004; Kalisz et al., 2010), favoured by seasonal ploughing, which incorporates large quantities of oxygen in the uppermost 30 cm. This hypothesis assumes that the uppermost 100 cm of the soil profile accumulated in the humid areas depicted in historical maps and that the lower OC content in the uppermost 30 cm depends uniquely on the post-reclaiming processes.

However, a closer inspection of soil profiles carried out in the Mezzano area (M in Fig. 7) and in the Grande Bonificazione Ferrarese (GBF in Fig. 7) highlights a more complex picture (Fig. 10). At site M4 (see Fig. 9 for location), OC decreases with depth in the uppermost 80 cm from 13.88 % to 3.87 % and sharply increases at 90 cm to 15.24 % (see also Table 1), where a peaty horizon has been observed (Fig. 10); in the lowermost 10 cm, between 90 and 100 cm depth, OC drops down to 1.96 %. At site GBF2, OC decreases with depth in the uppermost 30 cm from 4.79 % to 1.74 %, whereas the analysis on a peat layer sampled at 50–60 cm depth, returned a value of 23.79 %. This organic horizon, radiocarbon dated to the Iron Age (2585 ± 140 cal y BP; Fig. 10 and Table 2), has been reported in several papers (Bruno et al., 2017, 2019; Giacomelli et al., 2018; Rossi et al., 2021) and is referable to the palaeogeographic setting of Fig. 2d rather than the 1814 palaeogeography. Therefore, whereas the OC content in the topsoil (uppermost 30 cm, Fig. 9a) clearly reflects the 1814 palaeogeography, OC values in Fig. 9b average the OC content of different layers, referable to different palaeogeographic settings. The overlap of the areas with high OC content of Fig. 9b with the 1814 humid areas (Fig. 6a) may be influenced by the morphology and elevation of the modern topographic surface. The 1814 wetlands correspond to present-day topographically

Table 2
Details on the radiocarbon date used in this work.

location	depth (cm)	lab sample code	14 C age (y BP)	± uncertainty	Calibrated age (cal y BP)		δ13 C	± error (‰)
					median value	± 2sigma		
GBF2	50	KGM-OWd200624	2500	± 26	2585	± 140	−28.91	± 1.1

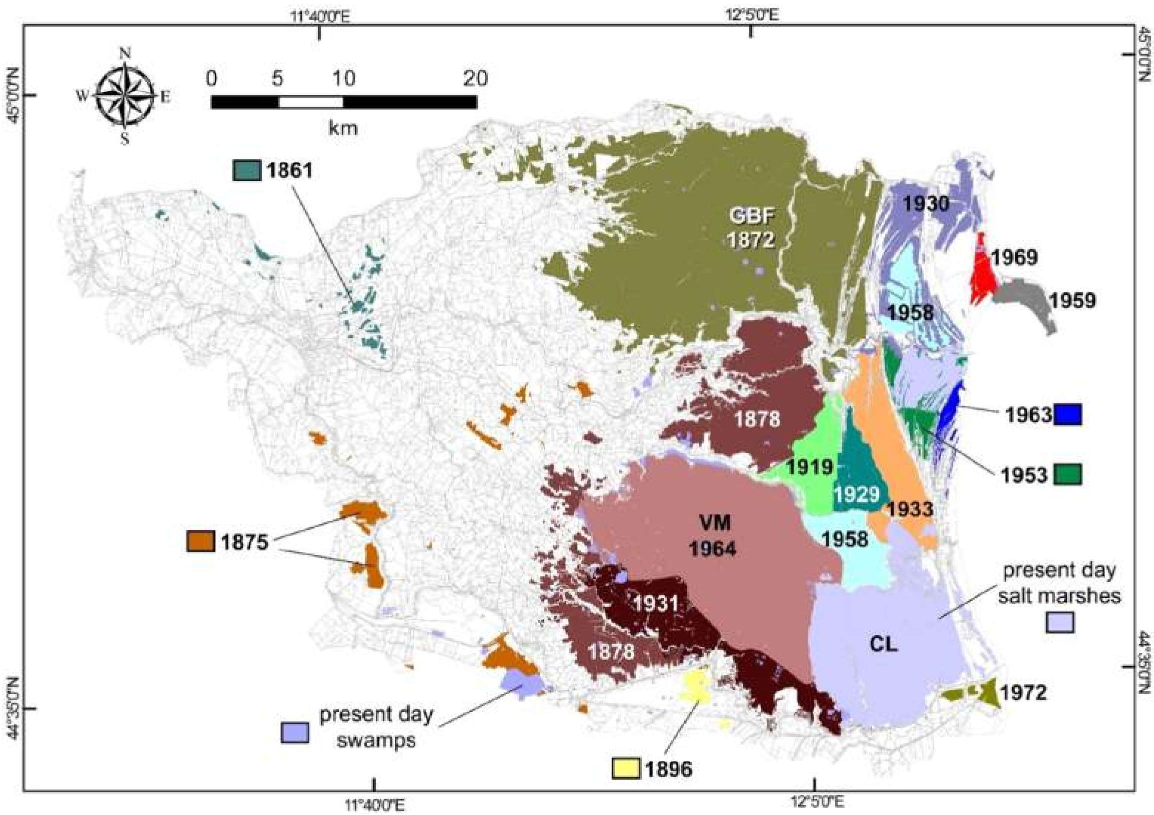

Fig. 7. - Areas of the Ferrara District reclaimed in the last two centuries (coloured areas) and relative year of draining (modified after Bondesan, 1990).

depressed areas where the Iron Age peat layer can be more likely encountered at depths < 1 m. The same horizon can hardly be detected in the uppermost metre beneath fluvial ridges (see Bruno et al., 2017, 2019). In conclusion, the comparison between the OC content in the topsoil (Fig. 9a) and the one at higher depths (Fig. 9b) cannot be used to quantify the effects of land reclaiming (e.g., organic-matter mineralization and oxidation to CO_2).

Some authors proposed a comparison between the Mezzano and the Grande Bonificazione Ferrarese, drained in different periods, to estimate the carbon loss after reclaiming (Bini and Zilocchi, 2004; Di Giuseppe et al., 2017). In particular, higher OC values in the Mezzano topsoil are argued to reflect the more recent draining of the Mezzano area, carried out a century after the Grande Bonificazione Ferrarese (Fig. 7). However, the comparison between these two areas should be considered with caution, because litter accumulation occurred in different environments, as depicted by the different texture used in the *Carta del Ferrarese* (Fig. 4a). The Mezzano was a salt-marsh, in partial communication with the open sea, whereas the GBF area was a freshwater swamp, separated by salt-waters from a system of beach ridges. Palaeoecological data (Rossi et al., 2021) highlighted the presence of different plant species and salinity that may have, at least in part, influenced the amount of accumulated carbon and its preservation.

Although data presented in this paper are not sufficient for the quantification of carbon emission after reclaiming, the high amount of OC in soil developed in place of former wetlands highlights the potential of humid areas for carbon sequestration. The carbon accumulated in the 1814 wetlands could have been in part oxidised to CO_2 after draining. The lack of preserved plant fragments in the topsoil of all the analysed areas support the hypothesis of organic-matter mineralization and oxidation. The preservation of the Iron-Age peat layer, instead may have been favoured by rapid burial or by the local persistence of a submerged environment in the last 2500 years (Figs. 2d, 2e and 2 f).

5.2. *The anthropization of the Po Plain*

The pre-Holocene history of the Po coastal plain is characterised by dramatic environmental changes driven by natural factors (Amorosi et al., 2017, 2020; Campo et al., 2020). Human activities started to significantly influence landscape evolution since the Bronze Age (Cremaschi et al., 2006), and increased their impact over time, In the pre-Industrial era, the innermost sectors of the Po Plain experienced substantial modifications, that mostly consisted in the conversion of natural areas into croplands. Inland wetlands were filled with river sediments (Curtis and Campopiano, 2014) or drained through the realisation of channels and other engineering works, which favoured the natural drainage of surface waters. The last two centuries record a dramatic modification of the Po delta plain, consisting in two major changes: the decline of the *Piantata Padana* and wetland reclamation.

The western sector of the Ferrara District (i.e., the upper delta plain) appears in 1814 already deforested and devoted to agriculture. However, the dominant agricultural system, the *Piantata Padana* was highly sustainable compared to modern ones. The tree cover provided multiple

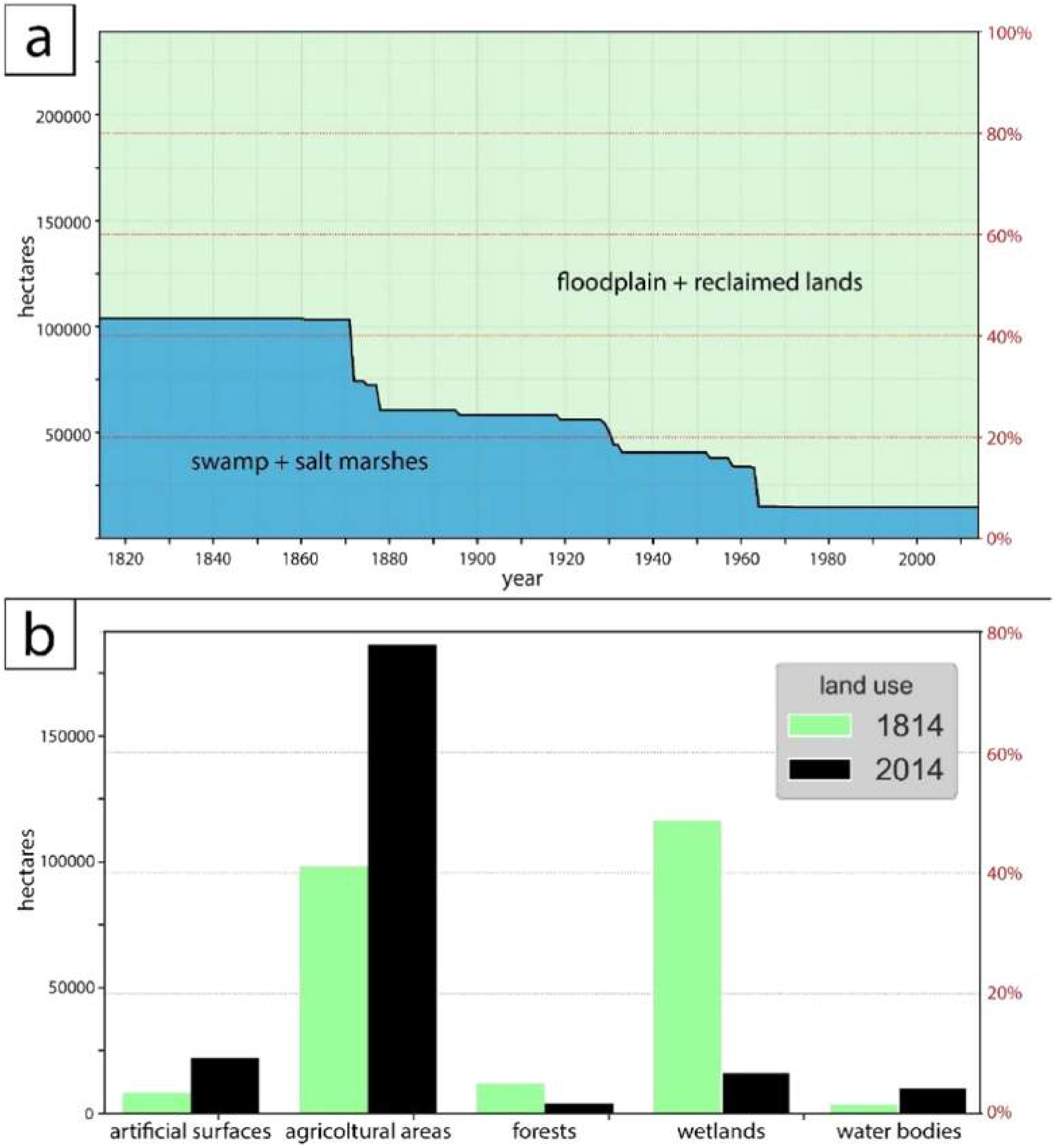

Fig. 8. - (a) Extent of freshwater swamps and salt marshes in the Ferrara District from 1814 to present day. (b) Comparison between LULC in 1814 (green columns) and in 2014 (in black).

advantages (Campiani and Garberi, 2008; Cillis, 2012), such as soil protection from erosion through limitation of the mechanical action of rain waters and wind; shading and maintenance of soil humidity during dry seasons. Repeated pruning operations guaranteed maximum sun exposure to the grape clusters, promoting ripening, and reducing the risk of mould. Tree branches were used as: building material, fuel for domestic heating and cooking and food for the livestock. The advent of Industrial Revolution led to the mechanisation of harvesting operations, the spread of fuels and building materials alternative to wood, and the use of industrial feed. All these changes made trees supporting the vines, useless and obstructive to harvesting operations, with the consequent decline of the *Piantata Padana* and its replacement with bare arable lands (Figs. 6 and 8b). Based on the maximum and minimum spacing of supporting trees locally used for this agroforestry system (see Section 3), we calculated that 4–40 million trees were removed from the study area in two centuries (this number does not include trees from forests and vegetated swamps, characterised by higher plant density).

The eastern sector of the Ferrara District (i.e., the lower delta plain), in 1814 was still in a quasi-natural state. The colonisation of this area since Iron Age, remained limited to fluvial ridges between swamps and marshes (Sassatelli and Govi, 2013; Mistireki and Zamboni, 2019). Coastal wetlands were difficult to drain with traditional methods because of the low gradient of the area (with few sectors lying below sea-level), and thus were preserved since the 19th century AD. A first attempt to reclaim the Ferrara lowlands dates back to the 16th century, as highlighted by the *Carta dei Ducati Estensi* and from the *Ferrariae Ducatus* (Figs. 3b and 3c, respectively) which depicts a regular grid of draining channels in the area between the northernmost branch of the Po Delta (*Po Grande*) and the *Po di Volano* branch. However, this attempt rapidly failed, likely due to compaction-induced subsidence. Low-gradient coastal wetlands started to be drained only after the Industrial Revolution and the introduction of steam pumps. About the 85 % of wetlands disappeared in less than one century, from 1872 to 1964. This trend, recorded in several coastal areas worldwide

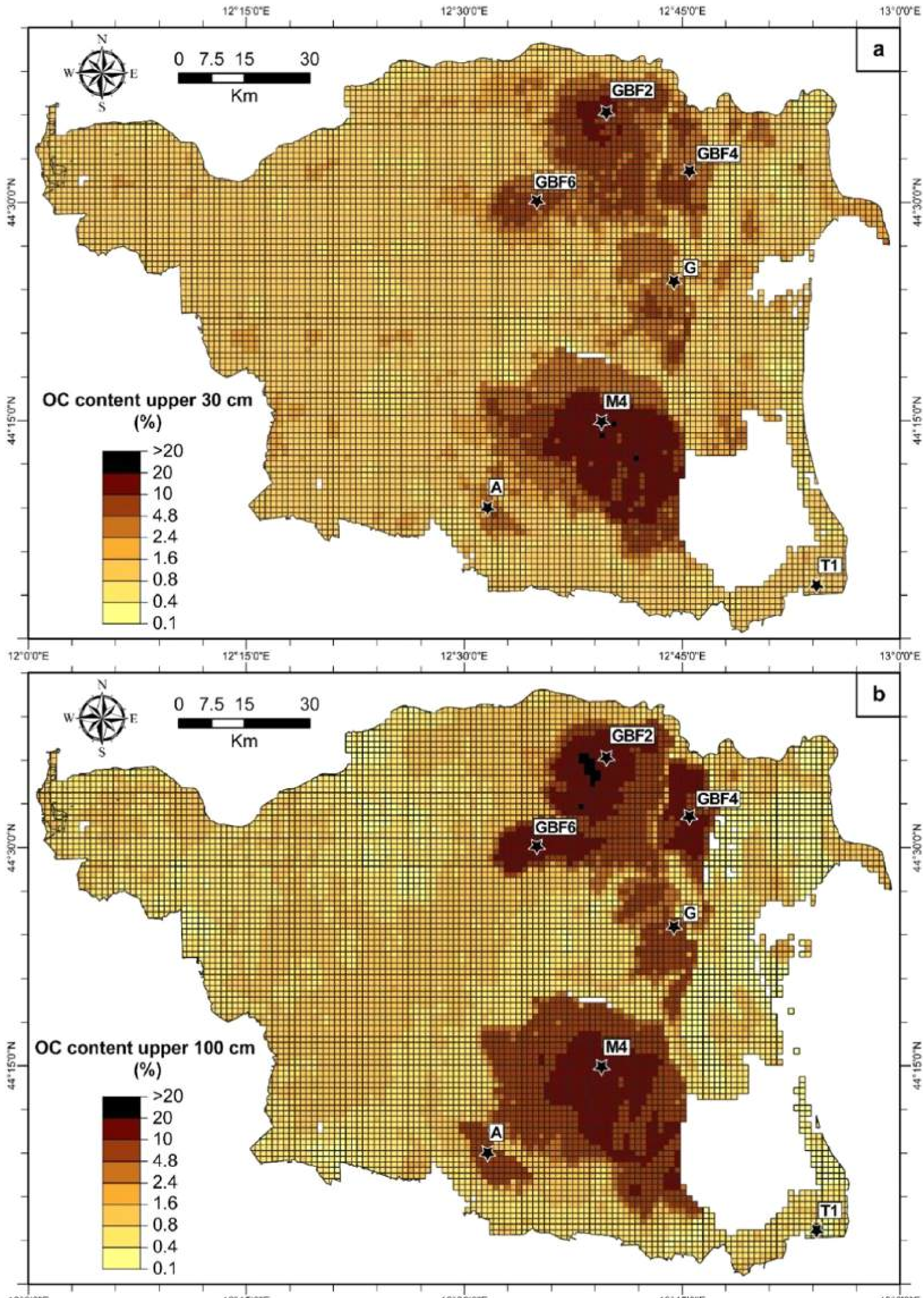

Fig. 9. - (a) Map depicting the percentage of organic carbon in the uppermost 30 cm of modern soils (Ungaro et al., 2023). (b) Map depicting the percentage of organic carbon in the uppermost 100 cm of modern soils (Staffilani et al., 2016). The location of the sampling points of Table 1, is represented in both maps.

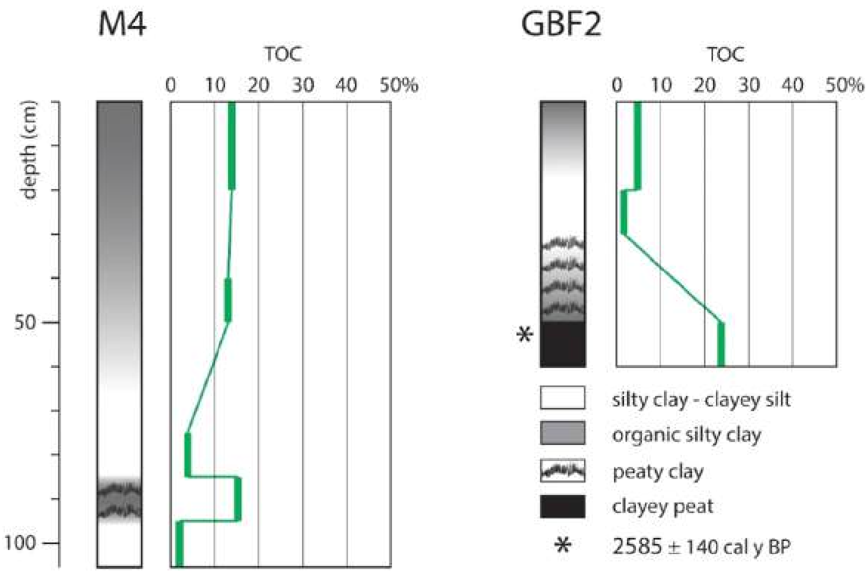

Fig. 10. - Soil profile and changes in Total Organic Carbon with depth at two sampling points (location in Fig. 9).

(Davidson, 2014; Fluet-Chouinard et al., 2023), has consequences at a local (e.g., loss in biodiversity, soil erosion, increase in temperature) and global scale (e.g., CO_2 emissions). Another consequence of wetland loss is the increase in energy demand for pumping operations. About 44 % of the Ferrara District, lying below sea level, is kept drained through more than 4000 km of draining channels and 168 pumping stations, with a total power of 47,780 kW (ca. 400 million kWh have been used since 2006). The energy required to keep the reclaimed areas drained is expected to increase in the near future due to the combined effect of subsidence and sea-level rise (Meli et al., 2021; 2023; Meli, 2024).

Although, urbanisation is limited to the town of Ferrara and to a few small villages, the Po delta plain appears nowadays as largely shaped by human activities, with the exception of few remnants of the past wetland landscape (see Fig. 6b). The sharp acceleration in anthropization recorded in the Po delta plain after the industrial revolution, is also recorded in several alluvial and delta plains worldwide (Goldewijk and Ramankutty, 2004; Popovici et al., 2013). In most cases, urban areas and the related network of linear features (e.g., roads and railways) expanded over the rural territory (Dewan et al., 2012; Rawat et al., 2013). It should be noted that, despite the limited dimension of territory occupied and related LULC consumption, linear features might have a severe impact on surrounding ecosystems by causing habitat and environmental fragmentation and alteration (Trombulak and Frissel, 2000; Benítez-López et al., 2010).

In conclusion, the changes occurred in the Ferrara area in the last two centuries consist in the transition from a rural landscape with sustainable agroforestry practises (to the west) and natural wetlands (to the east), to a territory largely devoted to agriculture and dominated by bare arable lands. These changes favoured the economic development of the Ferrara area, but strongly concurred to carbon emissions through tree removal, soil oxidation, energy consumption from pumping stations and the extensive use of hydrocarbon fuels in agriculture.

6. Conclusions

Historical maps, when characterised by high degree of accuracy, may provide information on past LULC. The *Carta del Ferrarese* commissioned by Napoleon Bonaparte and completed in 1814, has been used to quantify the major changes in LULC that occurred in the last two centuries in 240,000 ha of the Po delta plain. The main outcomes of this research can be summarised as follows:

(i) After georeferencing in a current reference system and interpretation of the textures adopted in the historical map, five high-rank LULC classes were mapped: artificial surfaces (e.g., urban areas, roads), agricultural areas (e.g., arable lands, permanent crops, pastures), forest and semi-natural areas, wetlands (freshwater and salt-marshes), waterbodies (rivers, artificial basins and drainage channels). The 1814 palaeogeography is dominated by wetlands (ca. 49 % of the study area) and agricultural areas (41 %), whereas forests appear already depleted, occupying just 5 % of the total area. The *Piantata Padana*, a traditional agroforestry system with live trees used to support grapevines, is the dominant agricultural LULC (62 % of the agricultural areas). The comparison with the 2014 LULC map highlights a dramatic reduction of wetland areas, with 85 % swamps and marshes reclaimed from 1872 to 1964, and a parallel increase in agricultural areas, which expanded over reclaimed lands. The last two centuries record the decline of the *Piantata Padana* and its replacement with bare arable lands, with the consequent removal of 4–40 million trees. Although representing a minor component of the Po delta plain territory, forests were further reduced (by 68 %) and artificial areas increased by 156 %.

(ii) The Po coastal plain experienced several environmental changes since the Middle Pleistocene, driven by natural factors, such as glacio-eustatic fluctuations, river avulsions and delta-lobe switches. The changes recorded in the last two centuries, instead, have been uniquely driven by human activities. Similar changes have been observed in several alluvial and delta plains worldwide, in most cases, with the expansion of urban areas and of related roads and railways. Although urbanisation is limited in the Po delta plain, this area appears nowaday largely shaped by human activities, with the dominance of lands devoted to intensive agriculture, kept drained by more than 150 pumping stations and by a dense network of draining channels.

(iii) The areas formerly occupied by wetlands show high OC content in soils, highlighting the potential of humid areas for carbon sequestration. Particularly, OC content in the uppermost 30 cm is unequivocally referable to the 1814 palaogeography, whereas OC, content in the uppermost 100 cm averages the carbon content of different layers referable to different paleogeographic settings.

(iv) The data presented in this work do not permit to quantify the OC oxidation to CO_2 after reclamation. However, the lack of plant macrofossils in the topsoil of reclaimed areas suggest rapid oxidation and mineralization of organic substances after draining. Land reclaiming, prompted by the industrial revolution and the introduction of steam pumps, resulted in carbon emissions not only through the oxidation of soil organic substances, but also through energy consumption from pumping stations and the extensive use of fuels for agriculture.

CRediT authorship contribution statement

Maria Luisa Garberi: Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Matteo Meli:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luigi Bruno:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matteo Meli reports financial support was provided by European Union. Matteo Meli reports a relationship with European Union that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was partly carried out within the RETURN Extended Partnership and received funding from the European Union Next-Generation EU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005). We gratefully thank Gianluca Malavasi for access and support in the laboratory of chemical analyses of the Department of Chemical and Geological Sciences, University of Modena.

Data Availability

Data will be made available on request.

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