Original research article

Recent vegetation changes linked to forestry legislation inferred from pollen and sedimentological analyses in northwest Spain

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Abstract

The decline of forest cover in the northwestern Iberian Peninsula during the recent centuries, driven by anthropogenic activities, has necessitated the establishment of a set of laws and regulations to ensure stricter control of the use of natural forest resources. However, the assessment of the effects of such legislation on plant populations is inaccurate and lacks a longer-term perspective. The present study aims to assess the impact of the most important forestry policies of the last centuries on past plant population dynamics using high-resolution pollen analysis of three sedimentary sequences extracted from the inner zone of the Ria of Ferrol, Galicia, northwest Spain. Pollen evidence suggest that plant populations are strongly influenced by the different reforestation and afforestation activities carried out during the last centuries. A substantial change in the regional vegetation is evident during the latter half of the 20th century, mainly attributed to the reforestation activities of *Patrimonio Forestal del Estado* (State Forestry Heritage), established in 1941, alongside changes in the socioeconomic dynamics of the region. Pollen signals preserved in the sediments along with changes in particle size, were driven by sedimentary processes associated with urban infrastructure development and changes in the erosive rate likely related the removal of the tree cover by increasing silvicultural activity. The high resolution of the radiometric chronologies obtained allows to detect changes in plant populations that can be correlated with specific historical events, thereby reinforcing the efficacy of high-resolution pollen analysis as a valuable tool for science-based forest management assessment.

Keywords

Anthropocene, human impact, forestry policies, pollen, sedimentation rates

1. Introduction

The past few centuries have been marked by intense human action on the landscape and the environment (Zalasiewicz et al., 2020). Exponential population growth and its demand for natural resources have induced significant modifications to the environment, impacting even fundamental geological processes (Syvitski et al., 2020). The extensive alteration of environmental functioning, encompassing changes in sedimentary dynamics, vegetation (including logging and reforestation), agriculture, atmospheric chemistry, erosion rates, and flooding, has led to the proposal of the Anthropocene as a distinct chronological interval succeeding the Holocene (Waters et al., 2016; Zalasiewicz et al., 2024). The study of the Anthropocene is essential for understanding the novel processes associated with human action and for attempting to mitigate and counteract the environmental effects predicted for the coming decades (Steffen et al., 2007).

Some of the factors contributing to landscape transformation and modifying the hydrological and sedimentary processes at global scale are the clearance of forests for commercial use, the establishment of cultivation areas, and reforestation with economically valuable species (Chakravarty et al., 2012; Kennish, 2016). Since the emergence of early civilisations, human populations have exploited natural resources to meet their basic needs for food and energy (Bogaard, 2004; Filipović et al., 2019). Forest harvesting has consistently been one of the main sources of fuel and building materials influencing the establishment and development of human settlements (Revelles, 2017).

Like the rest of Europe (Hublin, 2015; Müller et al., 2011), the northwestern Iberian Peninsula has been subject to human influence since ancient times (Guitián Rivera, 2001; Martínez-Cortizas et al., 2009). Since the Bronze Age, but particularly during the Middle Ages (López-Merino et al., 2014), the unsustainable exploitation of wood resources, as well as the removal of tree cover to create open spaces for agriculture and livestock (Ramil-Rego et al., 1998), has caused widespread deforestation throughout much of the region (Hernández-Beloqui et al., 2015). The absence of rules or structured processes for regulating resource use led to a significant decline in natural forest populations, which even extended into the 19th century (Guitián Rivera, 2001). In response, given the insufficient timber production, state forestry regulations were implemented with a production-oriented approach, aimed at planting fast-growing species (e.g., *Pinus* and *Eucalyptus*) to ensure rapid recovery and state control of the forests (Iriarte Goñi, 2013).

Nevertheless, the environmental degradation caused by the overexploitation of forest resources, the use of exotic species, and land use change highlighted the necessity to legislating from a conservationist perspective, leading subsequent legislation to consider the use of native species for reforestation (Pemán García et al., 2017). As mentioned by Kulkarni et al. (2021), conservation efforts are focused on mitigating past environmental degradation to enhance ecosystem resilience. However, the results and consequences of this forestry legislation have not been adequately evaluated in terms of regional vegetation change, nor have been systematically monitored by the governments that defined them. Consequently, the implemented legislation cannot be effectively utilised to understand ecosystem responses and to propose new guidelines for future biodiversity conservation. Potential explanations for this lack of evaluation and monitoring are government turnover and the occurrence of armed conflicts that have interrupted these processes (Rico, 2000).

In the context of intense human activity on ecosystems, particularly in population and economic centres, and in view of the growing environmental impacts that characterises the Anthropocene (Zalasiewicz et al., 2017), it is imperative to assess the effects of historical forestry legislation on plant populations and ecosystems. Only through such an assessment will it be possible to establish future guidelines for the restoration and conservation of ecosystems, thereby enabling sustainable development in the region (Willis and Birks, 2006).

Palaeoenvironmental reconstruction is a valuable tool for studying variations in plant community composition and their temporal changes (Ge et al., 2019). Despite the abundant research conducted in northwestern Spain documenting the human impact on ecosystems over the last millennia (García Antón et al., 2006; Gil García et al., 2002; Santos, 2004; Santos et al., 2000), few studies have provided a sufficient temporal resolution to assess the effect of specific historical events — such as the implementation of legal frameworks or land-use changes — on ecosystems in the recent geological record. Moreover, the most recent time, with more complex legislation, is the one that can reveal in greater detail the responses recorded by the vegetation. However, the limitations of traditional pollen analysis, stemming from the low chronological resolution of many Holocene sequences (Hájková et al., 2023; Ramil-Rego et al., 1998) hinder the observation of detailed vegetation changes that have occurred in recent decades and centuries.

The present study assesses the biological response of plant populations to the implementation of the most significant forestry policies during the last centuries, land-use change, and socio-economic development around the Ria of Ferrol, Galicia, northwestern Spain, using high-resolution pollen analysis of three short sedimentary sequences and a robust chronological model. The remarkable response of pollen analyses demonstrates the utility of this method as a key tool for verifying the effectiveness of legislative policies and determining whether they are conducive to the conservation and restoration of ecosystems and biodiversity.

2. Materials and methods

2.1. Study area

The Ria of Ferrol is located on the Galician Atlantic coast, in the northwest of the Iberian Peninsula (43.47 °N, 8.21 °W), and alongside the rias of A Coruña and Ares-Betanzos, it forms the Gulf of Ártabro. The ría exhibits a general east-west orientation, with an area of 21 km^2 and a length of 15 km (Muñoz Sobrino et al., 2022). Geomorphologically, it is characterised by three distinct zones (outer, middle and inner zones) with varying hydrological and hydrodynamic characteristics and the presence of a 2.7 km long x 0.5 km wide Ferrol Strait, near the mouth, modifies the flow and water re-mixing patterns (Figure 1).

In general, a decrease in depth and sediment particle size is observed towards the head of the ría, where two of its main freshwater tributaries (6 m^3 s^{-1} average annual flow), the

Xuvia (Xubia or Río Grande) and Belelle rivers, discharge into the ría (deCastro et al., 2004). This fining-upward granulometric trend, associated with the low tidal influence (mesotidal and semidiurnal regime) in the innermost zone, leads to the deposition of fine organic-rich muds in this section of the ría (Cobelo-García and Prego, 2004; Evans and Prego, 2003; Prego et al., 2003). Additionally, the presence of artificial barriers (urban infrastructure) in this area substantially reduces the water circulation and re-mixing, promoting the accumulation of particles and pollutants derived from the discharge of industrial effluents and wastewaters, currently processed in the Waste Water Treatment Plants (Cobelo-García et al., 2004).

Economic activities developed in this site encompass both industrial (shipbuilding and repair, metallurgy, petrochemicals, plastics manufacturing) and productive (wood and cellulose production, foodstuffs cultivation, fisheries) sectors. These activities are mostly concentrated on the margins of the middle and inner zones of the ría (Figure 1). This substantial productive capacity, combined with its strategic geographical position, establishes the Ria of Ferrol as one of the major industrial centres and commercial ports in the northwest of the Iberian Peninsula. However, the socioeconomic development of the region has exerted considerable pressures on the surroundings, further modifying the original configuration of the natural ecosystems.

The natural vegetation of the region is characterised by deciduous forests dominated by *Quercus robur*, *Corylus*, *Betula* and *Castanea*, riparian forests comprising species of the genera *Alnus*, *Salix* and *Fraxinus* (Lara et al., 2019) and heathlands and grasslands consisting of plants of the families Ericaceae, Poaceae and some ferns such as *Pteridium aquilinum* (Izco Sevillano, 1987). These plant assemblages are largely benefited of the favourable environmental conditions that maintain a low thermal contrast (average minimum temperature of 10.8°C and average maximum of 15.7°C) and considerable volumes of precipitation (1400 mm/yr on average) in the region (deCastro et al., 2004). However, large extensions of land are heavily exploited for silvicultural purposes (e.g., extensive cultivation of *Eucalyptus* and *Pinus*), leading to fragmentation and, in some cases, the extirpation of native plant communities (Figure 1).

2.2. Field work and laboratory procedures

2.2.1. Sampling

During a field sampling campaign in May 2021, three 50 cm-depth sediment cores were extracted from the intertidal zone of the inner Ria of Ferrol (Fene, Neda, and Xuvia; see Figure 1). Each core was manually extracted using 6-inch diameter PVC tubes, with four contiguous replicates collected for various sedimentological, physico-chemical, micropaleontological, radiometric and microplastic analyses (for details, see Gardoki et al., 2023). The sediment sequences were stored under refrigeration (4°C), subsequently subsampled at regular 1-cm intervals, and labelled according to its corresponding depth. For pollen analysis, subsamples were selected at 2-cm intervals, increasing the resolution (1-cm intervals) at intervals where evidence of apparent sedimentological and/or micropalaeontological changes was observed.

2.2.2. Pollen extraction

Each subsample, previously weighed, was soaked for 24 hours and homogenised with a glass rod. Given the marine-estuarine origin of the sedimentary sequence, 10 ml of 35% HCl was used for carbonate removal. Subsequently, due to the predominantly silt-clay granulometric characteristics, the chemical treatment for pollen extraction was carried out using a modified version to the conventional chemical treatment proposed by Riding and

Kyffin-Hughes (2004), incorporating sodium hexametaphosphate ($(NaPO_3)^6$) and concentrated detergent (close to boiling point) to facilitate the sediment deflocculation.

The subsamples were sieved at 250 µm to remove plant macroremains and minerals, and sodium polytungstate (density 1.95 g/cm^3) was employed to separate the organic (pollen, spores, and plant remains) from the inorganic component. The treatment residue was stored in glycerine jelly to reduce oxidation by preventing contact with air.

Pollen analysis was conducted by conventional optical microscopy at 400X magnification at the Laboratory of Terrestrial Natural Resources of the University of Sonora, Mexico. Several specialised atlases (Moore et al., 1994; Reille, 1998, 1992), the PalDat platform (PalDat, 2024) and the reference pollen collection of the University of Sonora (DICTUS) were used as reference material for the taxonomic identification of pollen grains.

Pollen grains corresponding to the Cerealia pollen type were categorised using the dimensional classification proposed by Joly et al. (2007): >47 µm grain diameter and 11 µm annulus diameter. The *Androsace*-type includes tricolporate, isopolar, prolate pollen grains with psilate ornamentation of dimensions less than 20 µm in diameter, which could correspond to *Castanea* due to the morphometric variation of this pollen type (Sedláčková et al., 2021), however this identification is tentative due to lack of evidence.

2.2.3. Sedimentological analysis and chronological model

Age model and temporal assignment of each sedimentary sequence were estimated from the vertical activity profile of the radionuclides ^{210}Pb, ^{226}Ra and ^{137}Cs, using the Constant Rate of Supply (Appleby and Oldfield, 1978) dating model for all sedimentary sequences. However, due to the lack of cancellation of the 210Pbxs activity at the base of the Neda sequence, it was not possible to obtain the total inventory. Therefore, an approximation based on a constant mass accumulation rate was necessary (Gardoki et al., 2023;

Sanchez-Cabeza and Ruiz-Fernández, 2012). All these radiometric analyses were carried out at the University of Cantabria, Spain.

The granulometric analysis was conducted by separating the sediment into three main fractions: gravels, sands, and muds (comprising silts and clays). This was done by sieving at 2 mm and 63 µm mesh sizes, followed by the estimation of the dry weight percentages of each of the fractions. For sedimentological classification, each subsample was plotted on a ternary diagram and the classification nomenclature proposed by Blott and Pye (2012), was employed.

2.3. Data arrangement and statistical analysis

At least 300 pollen grains were counted and identified from each of the subsamples analysed, except for those with low pollen concentration (primarily in the Fene sequence), where only ~100 pollen grains per subsample were attainable. Pollen analysis results are expressed as percentages of total pollen, including spores of pteridophytes and local aquatic plants. A CONISS stratified cluster analysis was generated based on a Euclidean distance measurement between the subsamples of each core (all pollen types included), without data transformation, using Tilia software (Grimm, 1987). This allowed the subdivision of each core into chronologically ordered, homogeneous pollen zones, denoted A to C.

Subsequently, pollen types were grouped according to their ecological affinities, distribution patterns, and relationship with anthropogenic activities (pollen functional types, PFT; Table 1). Low-dispersion PFT corresponds to Pteridophyta spores and pollen with morphological characteristics that impede anemophilous dispersion and suggest water transport (Ge et al., 2019).

3. Results

3.1. Chronology and sediment accumulation rate

The Xuvia and Fene sedimentary sequences reach the dating limit through radiometric analysis of ^{210}Pb and ^{226}Ra at 44 and 24 cm-depth, respectively. Subsamples below these depths were assigned with the nomenclature pre-1870 CE. In contrast, Neda core shows $^{210}Pb_{xs}$ values that persist at the base of the sequence and, based on the chronological model used, this base is placed in the early 1940s. The ^{210}Pb-based absolute ages of these sequences broadly coincide with the appearance and maximum activity profile of ^{137}Cs, with the first occurrence of this artificial radionuclide occurring along mid-20th century.

The sediment accumulation rate (SAR) trends of the three sequences analysed show broadly similar patterns, with a gradual increase in deposition towards the top of the cores. This similarity is more pronounced between the Fene and Xuvia sequences, which show similar ranges in their values (0.1 – 0.7 cm/yr), contrasting with Neda, which reaches up to twice the sediment accumulation rate (1.4 cm/yr; Figure 2).

3.2. Sedimentological analysis

Generally, the granulometric analysis of all subsamples from the three sedimentary sequences analysed exhibits a similar pattern, with high values for mud contents (silts and clays exceeding 50% of the total weight) and low values for the percentages of gravels and sands (Figure 2). The combination of weight percentages of the three granulometric variables analysed places all the subsamples in the muds group, showing slight variations related to inconsistent increases in particle size. Despite the overall homogeneity across the three sequences, smaller-scale variations in the sedimentary classification are discernible.

Fene core records two main depositional phases. The first is characterised by a predominance of *slightly sandy mud* and *very slightly sandy mud* followed by an increase in particle size at 17 cm depth (1961 CE). This sequence is considered the least variable of the three, exhibiting only three significant changes in particle size. The Neda sequence shows irregular oscillations in sedimentological content, with a predominance of coarser particles at the base of the core. From 45 cm-depth (around 1950 CE) to the top of the sequence, no gravel is present in the sediment. Xuvia core exhibits the greatest amplitude in the size range, with two main intervals: a) a grain-size variable base, with predominantly larger sizes and intercalations of coarse and fine sediments, and b) a top with low variation in particle size (predominantly fine).

3.3. Pollen analysis

3.3.1. Fene core

Pollen analysis of the Fene sedimentary sequence recorded 67 pollen types. The cluster analysis subdivided the sequence into three well-differentiated pollen zones with total sum of squares values of 0.8 and 0.5. Zone A (pre-1870 to 1941 CE; 50 – 20 cm-depth) shows the highest homogeneity among its subsamples with distance values below 0.3. This pollen zone registers the lowest values for *Pinus* with an average 3%, although, two peaks of around 10% can be recognised at 35 and 27 cm-depth (pre-1870 CE). *Alnus* and *Betula* also display low relative frequencies, with an average 8% and <1%, respectively. In contrast, *Corylus* shows high values (6% on average) and a relative stable trend in the pollen zone, with a drop in frequency below 1% at ~1900 CE (Figure 3).

Similarly, the frequencies of some grasses and low shrubs such as Asteroideae, Poaceae, Ericaceae and *Androsace*-type register high values close to 10%, with stable trends and some minor fluctuations. *Quercus robur*-type shows a consistent pattern (10% on average) throughout the pollen zone with an isolated maximum peak of 20% at 31 cm-depth (pre-1870 CE). Pteridophyta and *Pteridium aquilinum* spores exhibit the highest values in the sequence, 9.6 and 2%, respectively.

Zone B (1942 to 1998 CE; 19 – 11 cm-depth) shows notable differences in the frequencies of some of the main taxa in the analysis. For example, the representation of *Pinus* increases exponentially, reaching a maximum peak of around 30% at about 1946 CE. However, the increase is not sustained, with a further 15% drop after 1960 CE and a gradual recovery of frequencies towards the end of the zone. Some taxa, including *Betula* and *Salix,* exhibit an increase in frequency compared to the previous zone. The first occurrence of *Eucalyptus* pollen in the sequence is observed around 1946 CE.

Asteroideae, Ericaceae and *Pteridium aquilinum* show a significant decrease in their percentages and an overall downward trend. Similarly, *Alnus* and *Corylus* have lower values than in previous zone A, reaching their lowest values in the 1975-1985 CE interval.

Finally, in Pollen Zone C (1999 to 2021 CE; 10 – 0 cm-depth), there are important changes in the most represented taxa. *Pinus* reaches the maximum values of the sequence (43%) in 2007 CE with a subsequent slight drop to the present day. Similarly, *Alnus* also records its highest values in the period 2012 - 2021 CE. *Eucalyptus* significantly increases its frequencies and maintains continuous presence throughout the interval. *Androsace*-type, Asteroideae, Ericaceae and Poaceae show a significant decrease in their percentages to values below 5%.

3.3.2. Neda core

The results of the pollen analysis of the Neda sequence yielded a total of 74 pollen types. The subdivision of the sequence and grouping of subsamples based on CONISS cluster analysis was poorly differentiated, and three pollen zones could be discerned: Pollen Zone A from 1942 to 1946 CE (50 – 48 cm-depth), Pollen Zone B from 1946 to 1963 CE (47 – 41 cm-depth), and Pollen Zone C from 1963 to 2021 CE (40 – 0 cm-depth).

Pollen Zone A (1942 to 1946 CE) shows the maximum statistical difference with respect to the other zones, with values of the total sum of squares of 0.2, whereas, within this zone, the values are lower than 0.06. This zone registers the lowest abundances of *Alnus* in the sequence with an average of 18%, reaching its minimum in 1945 CE. Similarly, *Androsace*-type and Pteridophyta also record their lowest percentages, with values below 1%. Poaceae has an average of ~8% in this pollen zone. In contrast, *Pinus* reaches high percentages, with an average 33% and a maximum 36.8% in 1943 CE. *Plantago* also shows continuously slightly high values >1% with an average 1.61% in the zone (Figure 4).

Pollen Zone B (1946 to 1963 CE) is characterised by an abrupt decrease in *Pinus* frequencies to average values of 22%, reaching the minimum of the sequence (19.5%) in 1955 CE. Asteroideae, *Androsace*-type and *Plantago* show average values below 1%. *Betula* registers the lowest frequencies of the sequence (1.88%) reaching the minimum value 0.32% in the year 1955 CE. *Quercus robur*-type display a slight decrease compared to the previously described zone of about 1.5%, with an oscillatory pattern and a stable trend throughout the pollen zone.

The percentages of *Alnus* gradually increased in this pollen zone until reaching the maximum percentage of the sequence (32.3%) in 1955 CE. *Corylus* and Poaceae show a slight increase in their percentages to 7 and 9%, respectively. In addition, during the interval covered by this pollen zone, *Fraxinus*, *Juglans*, *Myrtus* and *Ulmus* are recorded for the first time in the sequence.

Pollen Zone C (1963 to 2021 CE) demonstrates differences compared to the previous zone. *Pinus* frequencies increase again, reaching an average 27% for the zone, displaying a pronounced oscillatory pattern. Similarly, the representation of Androsace-type increases in the sequence, reaching average values of over 1%. *Betula* and Pteridophyta shows a slightly increase, with average values close to 3%. On the contrary, Poaceae registers a decrease (8.17%), with two peaks up to 12% in 2000 and 2008 CE. *Corylus* also exhibit a slight decrease in frequencies to values around 5%.

Although variations in the percentages of most pollen types identified in the sequence are observable, these do not exhibit clear trends and the discerning patterns in the time series are not entirely evident.

3.3.3. Xuvia core

Pollen analysis of the Xuvia sequence reveals the highest pollen diversity recorded in the cores. A total of 76 different pollen types were identified, which were categorised at distinct taxonomic levels and enabling the subdivision of the sequence into three well-defined pollen zones (Figure 5).

Zone A encompasses the interval from pre-1870 CE (beyond the chronological boundary) to 1960 CE (50 – 31 cm-depth); this lower zone is characterised by high percentages of *Pinus* with an average about 32%, *Pteridium aquilinum* and other Pteridophyta, with 5.5 and 2.23%, respectively, and high values of Ericaceae (3%, lower than those recorded in Fene). Conversely, *Alnus* (15%) and *Corylus* (4%) exhibit notable low frequencies, with the lowest values of this sequence. Furthermore, the first occurrence of *Eucalyptus* from Xuvia core was detected in this pollen zone, specifically in 1908 CE, with a subsequent substantial increase in frequencies at 1946 CE (Figure 5).

Zone B (1960 - 2012 CE; 30 – 12 cm-depth) shows very marked differences between the most representative taxa in the analysis. *Pinus* experiences a significant decrease in its frequencies, reaching an average of 21% in the zone (10% less than in the previous zone). However, there are two sporadic increases in 1999 and 1991 CE, with values above 25%. *Alnus* reaches its maximum value (38%) in 1970 CE and maintains a zone average 32%. Ericaceae and *Pteridium aquilinum* decrease their percentages to values close to 1%.

The zone C encompasses the period from 2012 to 2021 CE (11 – 0 cm-depth). This section shows a statistical difference of 0.3 of total sums of squares compared to Zone B and exhibits a greater similarity in the predominant taxa. *Alnus* slightly decreases its percentages to an average 26% for the zone. Similarly, Poaceae continues to decrease its percentages until its minimum values at the end of the sequence (4%). *Pinus* displays a recovery in its frequencies, with values similar to those observed in zone A. Some taxa such as *Corylus* and *Eucalyptus* show an increase in their percentages, with values of 8 and 1.3%, respectively. environmental conditions prior to intensive anthropogenic pressures/modifications in the mid/late-19th century

4. Discussion

4.1. Regional environmental conditions prior to intensive anthropogenic pressures in the mid-19th century

Deforestation process of mixed deciduous forests in the northwestern Iberian Peninsula began in the Neolithic period circa 7000 cal yr BP, as indicated by minor fluctuations in the pollen representation of these trees, interpreted as spatio-temporal punctual deforestations (López-Sáez et al., 2010; Ramil-Rego et al., 2001). However, since approximately 3500 cal yr BP, there was a pronounced decline in the percentage of arboreal pollen, particularly pronounced from 2800 cal yr BP, preceding the Roman period (Guitián Rivera, 2001). This decline intensified in the Middle Ages (12th and 13th centuries) and more recently in the modern period, driven by population growth, socio-economic development, and the land demand for agricultural and forestry production (Gil, 1991; Guitián Rivera, 2001; Ramil-Rego et al., 2001). Consequently, plant communities were reduced to critical levels, becoming confined to small, inaccessible enclaves (steep areas at higher elevations) unsuitable for harvesting (Lage Picos, 2003). The decline in plant populations is evident in the pollen analysis of Muñoz Sobrino et al. (2022), which revealed a significant decrease in *Quercus* and *Corylus* arboreal pollen since 800 cal yr BP (12th century, Middle Ages). The low percentages of dominant deciduous forest taxa (5-10% for *Corylus* and 10-15% for *Quercus*) are consistent with the values obtained in the present study. However, due to their higher temporal and analytical resolution, our new sedimentary sequences detect a greater number of historical events, which is consistent with, in a regional context, the results of López-Merino et al. (2011) in Lago Enol, in the Cantabrian Mountain Range, Spain, and globally with those of Ge et al. (2019) for the last 110 years in eastern China.

On the other hand, before the 19th century, the utilisation of public and private forests was directly related to primary economic activities, where the agricultural sector employed large sections of cleared land for the production of fodder, manure, cereal and other food crops (Lage Picos, 2003). This trend was also prevalent in other European countries coinciding with the onset of the agricultural revolution (Jones, 2011; Perez, 1944; Pretty, 1991). In the Ria of Ferrol, the area occupied by crops was then more extensive than in contemporary times, as inferred from the higher Cerealia values at the base of the Fene and Xuvia sequences (pre-1870 CE, Figures 3 and 5). Furthermore, considering the limited dispersion of cereal pollen grains related to their morphology and size (Vourela, 1973), it is possible to speculate that the areas selected for cereal cultivation were the margins or areas surrounding the Ría, proximate to the sampling sites, which have a less rugged topography conducive to tillage.

However, the agricultural sector was not the most important economic driver during this interval. The military-naval approach of the town of Ferrol and the increase in the demand and price of wood prompted a shift in the economic sectors towards timber production (Corbelle Rico and Tubío Sánchez, 2018; García, 2002). These economic changes, coupled with the industrial emergence experienced in Europe during the late 18th and 19th centuries, led to the cultivation of fast-growing wood species such as *Pinus pinaster* which became significant in the region (Molina Rodríguez, 2019).

The transition from intense deforestation to the planting of forest arboreal species is not an isolated phenomenon, but rather a widespread pattern in Europe from the 19th century onwards (Jeanrenaud, 2001). This is clearly evidenced at the base of the Fene sequence (Figure 3), which shows considerable increases in *Pinus* pollen in pre-1870 CE subsamples and at the base of the Xuvia sequence (Figure 5). Muñoz Sobrino et al. (2022) also documented a local, abrupt increase in *Pinus* frequencies in the middle zone of the Ria of Ferrol, dated to around 250 cal yr BP (beyond our radionuclides chronological boundary), which was directly related to a process of reforestation, generated by the demand for these silvicultural products.

4.2. Government legislation for forest recovery

4.2.1. Pre-1900: initial legislation and the onset of forest management with limited success

In the mid-19th century, the combined pressures represented by the rising temperatures and changes in precipitation patterns due to climate change, the development of more advanced industrial systems, the demand of land for productive activities, the introduction of allochthonous species, the excessive forest exploitation, and the unsustainable land-use change severely impacted native plant communities in the northwestern of the Iberian Peninsula, driving them to critical levels (Lage Picos, 2003; Le Roy Ladurie, 2020; Sanz Elorza et al., 2004).

In response to this multi-decadal decline of plant communities, a series of legislative modifications, decrees, and enactments focused on the conservation and recovery of forest stands were implemented. This series of regulations underwent a process of continuous adaptation according to changing political-economic interests, employing a combination of sanctions and restrictions (increasingly stringent) as well as occasional incentives to guide the action of private forest owners (Iriarte Goñi, 2013) and the utilisation and management of public forests.

The primary objective of these policies was the exploitation and economic development of the forestry sector, which led to the extensive use of fast-growing exotic plants (mainly *Pinus* and *Eucalyptus*) as reforestation species, prioritised over native species, due to their slower growth and lower economic yield.

In 1863, the *Ley de Montes* (Forestry Act) was enacted in Spain and represented the origin of a series of subsequent laws and regulations that led to a change in the management of public and private forests. Through this law, the State acquired the authority to expropriate areas devoid of vegetation and prohibited the sale of public forests of less than 100 hectares covered by pine, oak, or beech trees. It also assigned to the State the task of reforesting land devoid of vegetation and unsuitable for agricultural purposes. It also prohibited felling, pruning, or any kind of exploitation of public forests that could affect the interests of their afforestation and conservation.

The reforms proposed by this law and the one passed immediately afterwards (*Ley de Repoblación Forestal*; Forest Reforestation Act of 1877), represented an initial attempt to structured management of Spanish forests. However, due to several factors such as insufficient funding and inadequate infrastructure, the results obtained in terms of reforested area were limited (Pérez-Soba Diez del Corral, 2017). Pollen analysis of the Fene and Xuvia sequences potentially highlights the poor efficiency of these laws: in the subsamples adjacent to the lower boundary of the chronological model (25 to 30 cm-depth in Fene and the base of the Xuvia sequence), there are no abrupt changes in arboreal taxa indicative of plausible population modifications (Figures 3 and 5).

In contrast, the establishment of the *Plan Sistemático de Repoblación de las Cabeceras de Cuencas Hidrológicas* (Systematic Reforestation Plan for Hydrological Basin Headwaters,1888), which aimed to mitigating river flooding, stabilizing coastal dunes and guaranteeing water quality for large populations, demonstrated a clear effect on riparian forest populations, which is reflected in their increased frequencies (around 30%) recorded in the Xuvia sequence (Figure 6). Despite this, and the constant attempts at reforestation by the Spanish forestry administration, the 19th century ended with underwhelming reforestation results.

4.2.2. New legislation and impact of wars on vegetation: 1900 to 1940

At the beginning of the 20th century, specifically from 1901 CE onwards, a series of regulations and decrees were enacted, establishing the regulatory framework for the actions of the forestry administration throughout the 20th century (Pérez-Soba Diez del Corral, 2017). One of the most significant regulations was the creation of the *Divisiones Hidrológico-Forestales (*Hydrological-Forestry Divisions), which maintained continuous and intense activity until 1952.

Arboreal pollen percentages in the Fene and Xuvia sequences showed an increasing trend during the first half of the 20th century (Figures 3 and 5), correlating with the positive effect of reforestation activities and the time of growth and sexual maturity of the trees used in reforestation. Pollen percentages associated with grassland and heathland (Table 1; secondary vegetation in the region) displayed a decreasing trend in both sequences between 1900 and 1950 (Figures 3, 5 and, 6), potentially due to land-use changes, where areas devoid of arboreal vegetation (scrub and heathland) and covered with herbaceous vegetation (grassland and prairies) began to be reforested. The reconstructed changes in the composition of vegetation reflect, during the pre-1950 interval, the predominantly production-oriented interest of the State.

Another law that strengthened the Spanish reforestation plan and had observable effects in the pollen record was the *Ley de Repoblación* (Forestry Repopulation Act) of 1908, also considered to be of great historical significance. This law proposed a series of legislative modifications, including the creation and definition of so-called protective zones (*Monte Protector*), defined as public or private areas with essential functions in the maintenance of the natural environment or regular forestry exploitation. These new laws were accompanied by a series of prohibitions and requirements, compelling owners to initiate the reforestation process immediately after the declaration of their forests as protected areas. Furthermore, these laws did not permit vegetation removal activities for agricultural purposes, and minor logging was restricted to areas that would not affect the reforestation process.

The effects of this reform are evident in the pollen record of Fene (Figure 6), which exhibits an increasing trend in both PFT associated with tree taxa (30 to 60%) and those related to silvicultural activities (~3 to 35%), in response to the increase in the area covered by tree stands and environmental protection policies.

However, during the first four decades of the 20th century, the economic and political instability caused by the various armed conflicts (First and Second World War, Rif War, Spanish Civil War) in which Spain was involved hindered the proposed forestry policies from having a significant impact on the process of forest restoration. In this sense, the impact of wars on vegetation structure has been highlighted in several countries (Dudley et al., 2002; Omar et al., 2005; Zhang et al., 2023).

4.2.3. Industrialisation, increasing demand for wood and new forestry policies: 1940-1950

Since 1940, under the Franco regime in Spain, the persistent drive for productive self-sufficiency (especially in forestry), the accelerated industrialisation process and the increase in infrastructure works generated a substantial rise in the demand for wood products, leading to the proposal of new forestry policies (and the re-implementation of old laws) aimed at increasing the productivity of public and private forests (Iriarte Goñi, 2013). In this post-war period, various Europe governments established policies for restoration of forest resources (Edwards et al., 2022). In Spain, in 1941, the *Patrimonio Forestal del Estado* (State Forestry Heritage) was created, a public and private forest management agency that incentivised reforestation (through economic incentives and social repression activities), leading role in these efforts. This organisation managed an exhaustive process of reforestation, conditioning the use of forests for timber, consequently reflected in an increase of wooded areas.

The pollen record of the three sedimentary sequences analysed (Figures 3, 4, and 5) in general terms, revealed an increase in the relative frequencies of *Pinus* (plants mostly used for timber production) during the 1940s, which was more evident in Fene. Here, the Forestry PFT (Figure 6) reached values close to 30% in response to the increase of the reforested area, close to 58,500 ha (Lage Picos, 2003) and where the greatest differentiation in the pollen spectra (Figure 3) is discernible, according to the stratified cluster analysis (transition from Pollen Zone A to B). The percentage of Grassland PFT shows low values (around 20%), and Low-dispersion PFT (plants associated with riverbanks and characterised by limited wind dispersal) shows a decreasing trend. Ericaceae and *Pteridium aquilinum* fell below 5% (Figure 3) during the same period, reflecting the change in land use and the utilisation of areas devoid of trees for silvicultural purposes (Figure 6).

4.2.4. Post-1950: pollen responses to new reforestation laws

From the latter half of the 20th century onwards, the interest of Spanish State in public and private forests and their wood resources began to take on greater relevance (in the search for forest self-sufficiency). The escalating demand for timber products generated by growing industrial development and the reactivation of the shipbuilding industry in the region led to the new public policies to be focused exclusively on pure forestry production. This, coupled with the greater capacity of the Franco regime to impose its own policies, enabled the State to exert greater control over the areas destined for forestry use (Iriarte Goñi, 2013).

During the early 1950s, reforestation activities in Spain expanded considerably due to a budget increase and the modernisation of forest management techniques, reaching a peak of reforested areas in 1957, with approximately 140,000 hectares (Pemán García et al., 2017). This trend is clearly reflected in the pollen content of the Xuvia sequence, where the percentage of *Pinus* pollen reaches values exceeding 40% during that interval (Figure 5), indicating the predominant use of this taxon in reforestation work. Additionally, the

Arboreal PFT of the Fene sequence (Figure 6) attained percentages above 60%, showing the same pattern of increase in the wooded area.

Subsequently, in the early 1960s, the *Dirección General de Agricultura* intensified the *Plan de Mejora de Praderas y Pastizales* (Meadow and Pasture Improvement Plan), which had commenced in the Cantabrian region in 1958, and reached in 1963, the maximum number of experimental plots sown. The increased budgetary allocation and the specialised support in sowing facilitate the successful implementation of this plan in the region, as clearly visualised in the Grassland PFT of the Fene sequence, which has maximum values close to 30% during the years following its implementation (Figure 6). During the same interval, Forestry PFT frequencies show a significant decline, falling below 15%, potentially attributable to the effects of massive depopulation of rural areas experienced in Spain during the 1960s and 1970s, which modified the population structure and considerably reduced the exploitation of forests due to the absence of labour force (Lage Picos, 2003).

4.2.5. Reforestation with pine and eucalyptus after 1970 and the new trend in conservative legislation

Starting in 1970, a recovery of forest stands is recognized, reflected in the pollen content of Forestry PFT that reached ~30% in the 1990s (Figure 6). This is primarily attributed to the growing demand for raw material generated by the establishment in 1962 of the *Empresa Nacional de Celulosas* (National Pulp Company) plant, located in Pontevedra, Galicia, which started its productive process using pine and gradually *Eucalyptus* wood, which leading to its increased presence in Galician tree plantations during this interval (Calvo de Anta et al., 2019). Furthermore, during the early 1970s, a new pulp mill was opened in nearby Asturias, which considerably increased the demand for raw material in the region. Although *Eucalyptus* pollen is underrepresented in the pollen records, an increase in its frequencies is discernible in the Xuvia sequence during the early 1970s (Figure 5), directly linked to pulp production processes.

In the subsequent years, the increasing trends in Forestry PFT and decreasing tendencies in Grassland PFT reflect the shift in land use in the region towards expanded silvicultural production at the expense of grassland and heathland. However, it is not until 1992, with the establishment and implementation of the *Plan Forestal de Galicia* (PFG; Galician Forestry Plan) that an abrupt change in regional tree populations is observed. This forestry plan, approved by the Galician autonomous government, was designed to enhance forestry production by implementing stricter forest fire control measures, improving administrative organisation, and stimulating private investments (Corbelle Rico and Tubío Sánchez, 2018; Ministerio de Medio Ambiente, 2002).

The results of this PFG are evident in the pollen records, with both the Arboreal PFT and the Forestry PFT in Fene (Figure 6), exhibiting a pronounced increasing trend, directly correlated with the expansion of wooded areas (Corbelle Rico et al., 2018). Moreover, some taxa such as Ericaceae, *Androsace*-type, Asteroideae and Poaceae shows a considerably decrease of their pollen frequencies, a consequence of their removal to facilitate the expanding cultivation of *Pinus* and *Eucalyptus*, both of which exhibit an increasing trend (Figure 5).

In subsequent years, the Spanish State initiated a process of incorporating conservationist measures through the enactment of laws that acknowledged the economic importance of the Galician forests, while emphasizing their ecosystemic function. The implementation of the new *Ley de Montes* (Forestry Act) 07/2012 sought to maintain a more sustainable management, aiming to preserve, protect and restore forest ecosystems through forest planning and collaboration of the different administrative levels. This law contemplated, as part of the reforestation efforts, new statutes that sought to protect the native species of the region by prohibiting new reforestations with plants of the genera *Eucalyptus*, *Pinus*, *Picea, Abies, Pseudotsuga*, and *Tsuga* in areas covered by deciduous forests. The effects of this law are readily apparent in the pollen record, where a marked decrease in the Forestry PFT in the Fene core is observed to values close to 30% (Figure 6). The taxa associated with riparian environments (Riparian PFT) in both the Fene and Xuvia sequences show a gradual recovery towards the top of the sequence, a result of the forest policies with conservationist objectives.

Although vegetation responses (and their expression in the pollen record) vary among the analysed sedimentary sequences due to local factors, the influence of forest policies on natural systems is clear. This evidence supports the utilisation of high-resolution pollen analysis as a valuable tool for the long-term evaluation of historical forestry legislation.

4.3. Secondary effects of forestry legislation on the sedimentation rate in the ria

The influence of forestry legislation, management plans and regulations as a controlling factor of plant population dynamics is clear at Ria of Ferrol. However, both the ongoing climate crisis due to global change (Ramil Rego et al., 2018), and the various human activities related to natural resources exploitation and their industrial transformation, human population growth, and urbanisation processes impacts the ecosystems stability, generating constant pressure on natural plant populations, even leading to their population decline.

One of the main ecosystem processes directly affected by human activities is the sediment dynamics linked to land clearing or partial removal of tree cover associated with logging. Although evidence suggests that the process of vegetation removal has been operating since the beginning of agriculture and livestock farming in the region (Pérez- Díaz et al., 2016), the increasing trend in tree plantations observed during the 20th and 21st centuries, as reflected in the Forestry PFT of Fene (Figure 6), is a response to the series of enacted laws and frameworks. This resulted in a larger cleared area, enhancing erosion rates and sediment accumulation (Kennish, 2016), as documented by the increasing sedimentation rates in the inner zone of the Ria of Ferrol (Figure 2).). In fact, rising sediment accumulation rates were also reported in the nearby Ría of Vigo owing land use changes, likely attributed to construction activities, deforestation and forest fires among other processes (Perez-Arlucea et al., 2005; Pérez-Arlucea et al., 2007). This is consistent with the general increasing trend in sediment accumulation rates since the mid-20th century observed in the northern Iberian margin transitional ecosystems (Bruschi et al., 2013).

The geomorphological configuration of the ría directly influences its fluvial-marine dynamics (Hamidifar et al., 2024) and regulates the input and retention of sediments transported by tides and waves, along with those materials delivered by tributaries that converge in the ría. However, disentangling of the effect of these processes from those modifications in sediment dynamics generated by other human activities such as land use change or the construction of urban infrastructures (e.g., artificial barriers, canalisations, jetties and walls) is challenging.

4.4. Additional causes of anthropogenic disturbance recorded by plant dynamics and sediment accumulation rates

In Ferrol, it can be inferred that the construction of the three main infrastructures on the inner ría (Railway, As Pias and Highway bridges) had a significant effect on estuarine and sedimentary dynamics. Specifically, the construction dates of these three artificial barriers correlate, in a distinct way, with changes in the granulometry of the sedimentary sequences. Despite being predominantly muddy (congruent with their position in the upper zone of the ría) they also reflect subtle modifications (Figure 2):

a) The installation of the Railway bridge circa 1913 (Figures 1 and 2), is contemporaneous with an increase in particle size in the Xuvia core at 40 cm-depth, with no discernible effect on the Fene core (not chronologically recorded in the Neda core). The Low-dispersion PFT from Xuvia shows an increasing trend following the construction of this bridge, indicating a rise in sediment accumulation at the head of the ría.

b) The beginning of the construction of the As Pias bridge in 1966 (Figures 1 and 2) is linked to a granulometric increase observed in the Fene core (17 cm-depth) and coincides in the Xuvia core with a maximum particle size point preceding the onset of a fining upward process at 28 cm-depth. Due to its proximity to the extraction site of the Fene sequence, the local effect of this infrastructure work is more pronounced. However, the Low-dispersion PFT of the Xuvia core also reflects a slight increase after the construction of this bridge.

c) Finally, the effect of the establishment of the Highway bridge between 2002 – 2003 (Figures 1 and 2) is only evident in the sediments of the Neda core, possibly due to its proximity to the deposition area, coinciding with a slight increase in particle size. However, its effect can also be detected in the Low-dispersion PFT of Xuvia, which shows a slight increase after the construction of the bridge. Due to its close position to the continental end-member of the Ria of Ferrol, the Xuvia sedimentary sequence is more prone to the sediment accumulation and the deposition of low-dispersion pollen content.

The anthropogenic evidence associated with the enactment of laws and the construction of urban infrastructure, as recorded by the sedimentological and palynological analyses, demonstrates the effectiveness of this methodological approach. The high resolution with which the response of both vegetation and fluvial-marine dynamics are detected enables this method to be used to assess the effectiveness of various laws implemented over time. These responses provide the basis for future selection of the most appropriate forestry policies in a context of intense anthropisation and urgent need for biodiversity conservation and restoration.

5. Conclusion

High-resolution pollen analysis and sedimentological characterisation of the recent sedimentary sequences from the inner zone of the Ria of Ferrol have enable the detection of modifications in vegetation dynamics, changes in land use, and granulometric patterns likely correlated with specific historical events, such as the enactment of forestry legislation, reforestation programmes and the construction of urban infrastructures. Furthermore, the high temporal resolution of the analysed sequences allows for the following conclusions:

- The pollen composition of the pre-1870 CE subsamples exhibits a clear difference from later subsamples, reflecting the modification of plant communities in response to anthropogenic pressure resulting from demographic and economic development.
- Pollen analysis reveals a significant change in regional vegetation since mid-20th century onwards, attributable to the implementation of legislation, notably to the establishment of the *Patrimonio Forestal del Estado* (State Forest Heritage) in 1941, where forestry policies and reforestation activities led to a substantial expansion of planted areas covered by fast-growing tree species.
- In recent decades, the high-resolution pollen record has demonstrated a faithful response to forestry policies, first of introducing pines and eucalyptus trees, and more recently focused on conservation, reflecting a pattern that was applied in other European countries.
- Pteridophyta spores and low dispersion pollen (classified within the Low-dispersion PFT), which are transported exclusively by water currents, serve as key indicators

of sediment transport and reflect the process of sediment retention and accumulation. This indicator enables the assessment of the effects of various drivers on sedimentary dynamics and can be employed as a complementary tool to sedimentological analyses.

6. Acknowledgements

This research was funded by RTI2018-095678-B-C21, MCIU/AEI/FEDER, UE (MINECO) and IT1616-22 (EJ/GV) projects. Carlos Galaz is supported by predoctoral fellowship granted by Mexican Consejo Nacional de Humanidades, Ciencia y Tecnología (CONAHCYT 771105). Jon Gardoki is supported by a predoctoral fellowship granted by the Basque Government (PRE_2020_1_0035). Víctor Villasante-Marcos (National Geographic Institute of Spain) and Ane García-Artola (University of the Basque Country UPV/EHU) are kindly acknowledged for their help with fieldwork. This is a contribution of the Geo-Q Zentroa Research Unit (Joaquín Gómez de Llarena Laboratory).

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Tables

Table 1. Assignment of pollen types in Pollen Functional Types.

Pollen Functional Type	**Pollen type assignation**
Low-dispersion	Cerealia, Cyperaceae, *Pteridium aquilinum* and, Other Pteridophyta.
Riparian forest	*Alnus, Betula, Corylus, Dryopteris filix-mas*[1], *Fraxinus, Juglans, Osmunda regalis*[1], *Salix* and, *Sambucus*
Grassland	Apiaceae, Asteroideae, Cichorioideae, *Plantago* and, Poaceae
Arboreal pollen	*Acer*[2], *Alnus, Betula, Carya*[2], *Castanea sativa, Celtis, Corylus*, Cupressaceae, *Eucalyptus, Fraxinus, Ilex*[2], *Juglans, Myrtus, Olea europaea, Ostrya*[2], *Pinus, Pterocarya*[2], *Quercus ilex, Quercus robur*-type, *Salix, Tamarix* and, *Tilia*[2]
Forestry	*Eucalyptus* and, *Pinus*
Heathland	*Daboecia cantabrica,* Ericaceae and, *Pteridium aquilinum*

[1] Pollen types included in Other Pteridophyta. [2] Pollen types not included in the pollen diagrams due to their low frequency (<1%).

Figure captions

Figure 1. Geographical location, land use and vegetation of the inner Ria of Ferrol, Galicia, NW Spain, obtained from the *Sistema de Información sobre Ocupación del Suelo de España* (SIOSE; Spanish Land Cover/Land Use Information System). Upper panel: Land use related to anthropogenic activities. Lower panel: Surrounding vegetation. Intertidal zone delimitation obtained of Infrastructure for Spatial Information in Europe (INSPIRE).

Figure 2. Sedimentological analysis of the Fene, Neda and Xuvia sequences from Ria of Ferrol, Galicia, NW Spain. Upper panel: Granulometric classification based on the content (%) of gravels, sands and muds proposed by Blott and Pye, (2012). Lower panel: Sediment accumulation rate in cm/yr and graphical representation of granulometric changes. Black pin: location of the intertidal cores analysed.

Figure 3. Selected pollen types from the Fene sequence, Ria of Ferrol, Galicia, NW, Spain. Taxa grouped by life form. Data in percentages. Right panel, CONISS (Grimm, 1987) stratified cluster analysis of all pollen types. Dot symbol, percentages less than 1%. See details of the sedimentological column in Figure 2.

Figure 4. Selected pollen types from the Neda sequence, Ria of Ferrol, Galicia, NW, Spain. Taxa grouped by life form. Data in percentages. Right panel, CONISS (Grimm, 1987) stratified cluster analysis of all pollen types. Dot symbol, percentages less than 1%. See details of the sedimentological column in Figure 2.

Figure 5. Selected pollen types from the Xuvia sequence, Ria of Ferrol, Galicia, NW, Spain. Taxa grouped by life form. Data in percentages. Right panel, CONISS (Grimm, 1987) stratified cluster analysis of all pollen types. Dot symbol, percentages less than 1%. See details of the sedimentological column in Figure 2.

Figure 6. Selected pollen functional types from the Fene and Xuvia sequences. Dates of enactment of primarily forestry legislation: 1 - *Ley de Montes* in 1863; 2 - *Ley de Repoblación Forestal* in 1877; 3 - *Plan Sistemático de Repoblación de las Cabeceras de Cuencas Hidrológicas* in 1888; 4 - *Divisiones Hidrológico-Forestales* in 1901; 5 - *Patrimonio Forestal del Estado* in 1941; 6 – *Ley de Montes* in 1957; 7 – Establishment of *Empresa Nacional de Celulosas* plant in 1962 and Intensification of the *Plan de Mejora de Praderas y Pastizales* in 1963; Expansion of eucalyptus cultivation in 1972 CE. 8 – *Plan Forestal de Galicia* in 1992 CE. 9 – *Ley de Montes* 7/2012.

Figure 1

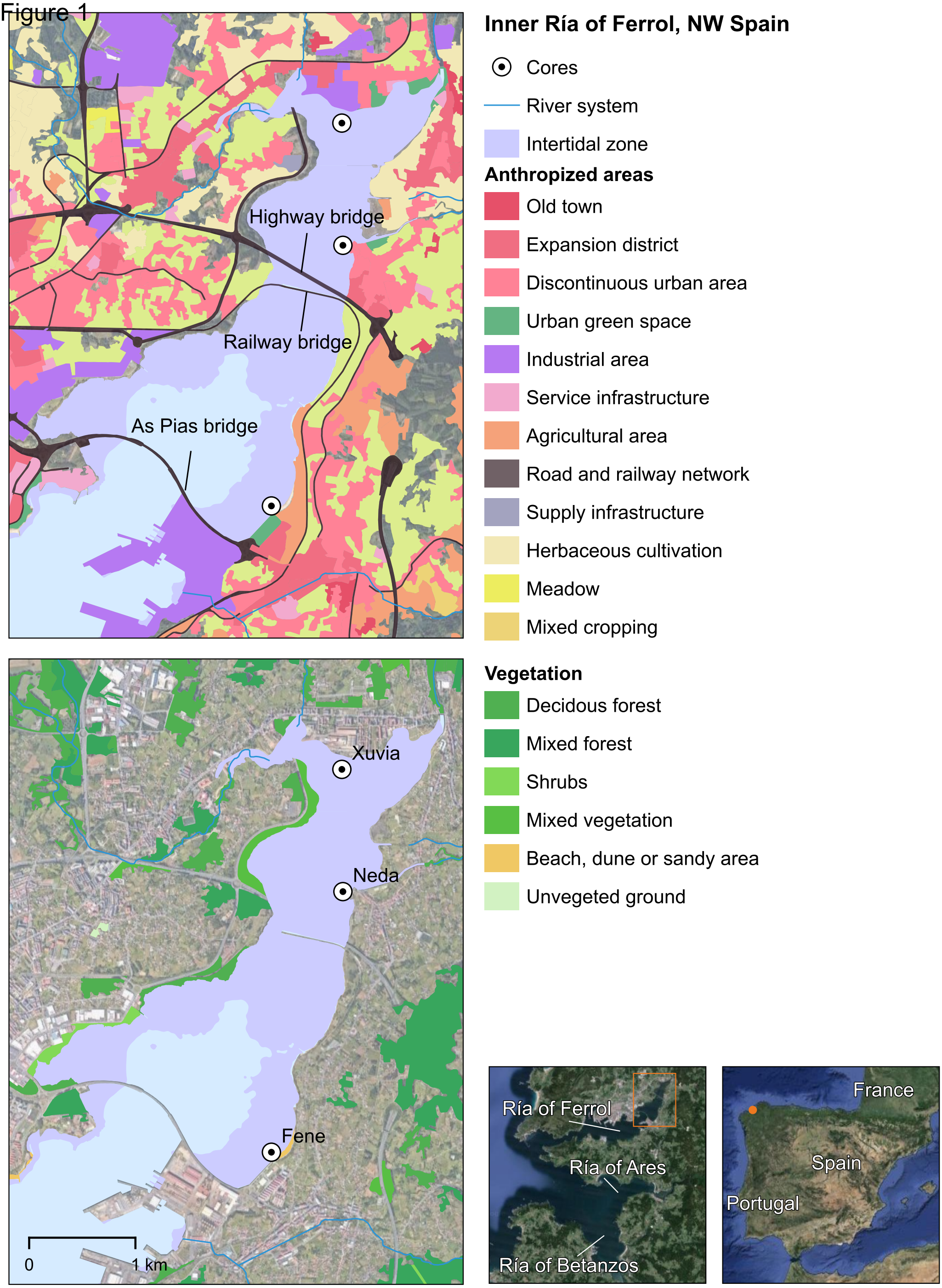
Inner Ría of Ferrol, NW Spain
Cores
River system
Intertidal zone
Anthropized areas
Old town
Expansion district
Discontinuous urban area
Urban green space
Industrial area
Service infrastructure
Agricultural area
Road and railway network
Supply infrastructure
Herbaceous cultivation
Meadow
Mixed cropping
Vegetation
Decidous forest
Mixed forest
Shrubs
Mixed vegetation
Beach, dune or sandy area
Unvegeted ground
Highway bridge
Railway bridge
As Pias bridge
Xuvia
Neda
Fene
0
1 km
Ría of Ferrol
Ría of Ares
Ría of Betanzos
France
Spain
Portugal

Figure 2

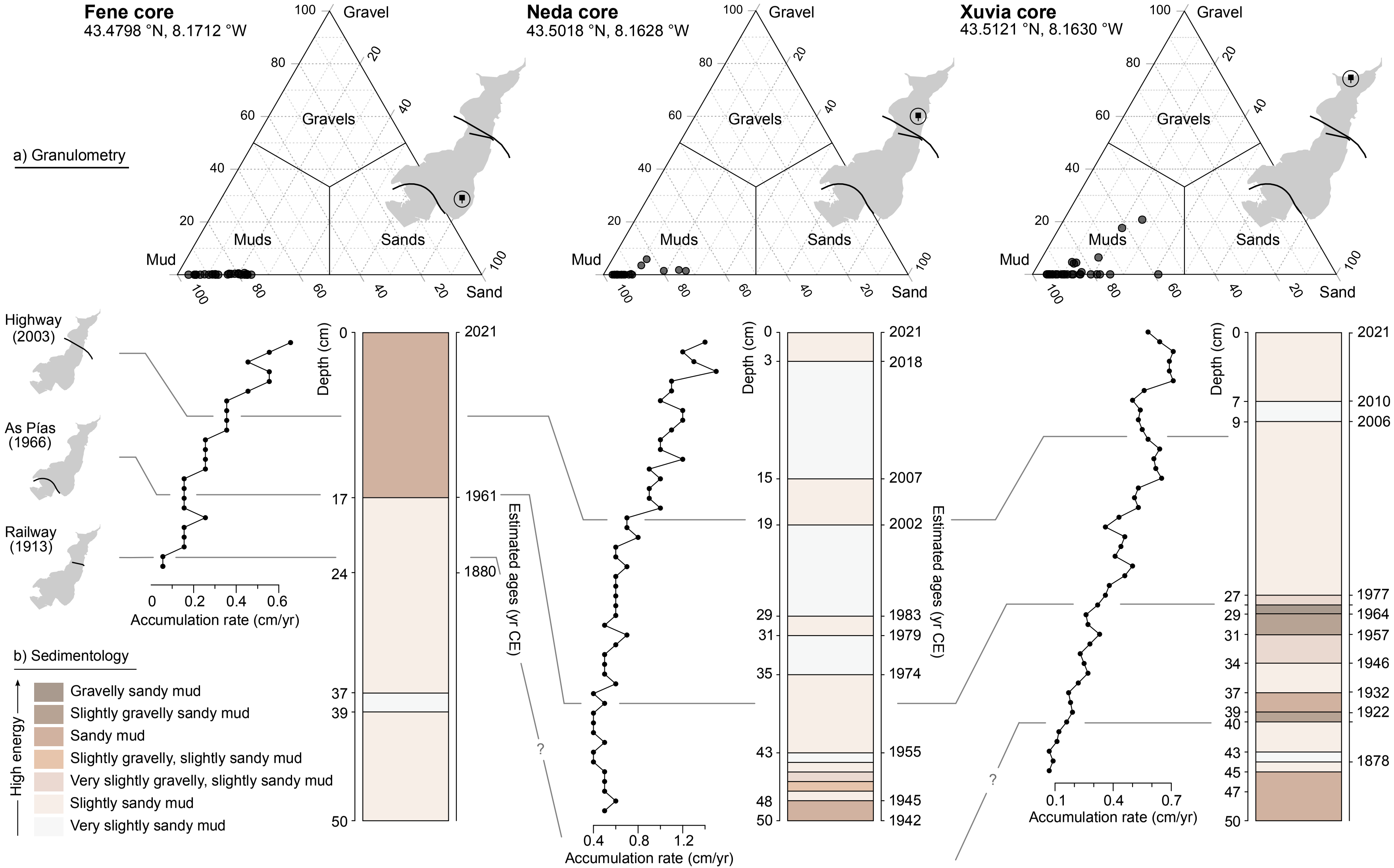
a) Granulometry
Fene core
43.4798 °N, 8.1712 °W
Neda core
43.5018 °N, 8.1628 °W
Xuvia core
43.5121 °N, 8.1630 °W
Gravel
Mud
Sand
Gravels
Muds
Sands
100
80
60
40
20
Highway (2003)
As Pías (1966)
Railway (1913)
Accumulation rate (cm/yr)
0
0.2
0.4
0.6
0.8
1.2
0.1
0.7
Depth (cm)
Estimated ages (yr CE)
0
17
24
37
39
50
2021
1961
1880
3
15
19
29
31
35
43
48
2018
2007
2002
1983
1979
1974
1955
1945
1942
7
9
27
34
45
47
2010
2006
1977
1964
1957
1946
1932
1922
1878
?
b) Sedimentology
High energy
Gravelly sandy mud
Slightly gravelly sandy mud
Sandy mud
Slightly gravelly, slightly sandy mud
Very slightly gravelly, slightly sandy mud
Slightly sandy mud
Very slightly sandy mud

Figure 3

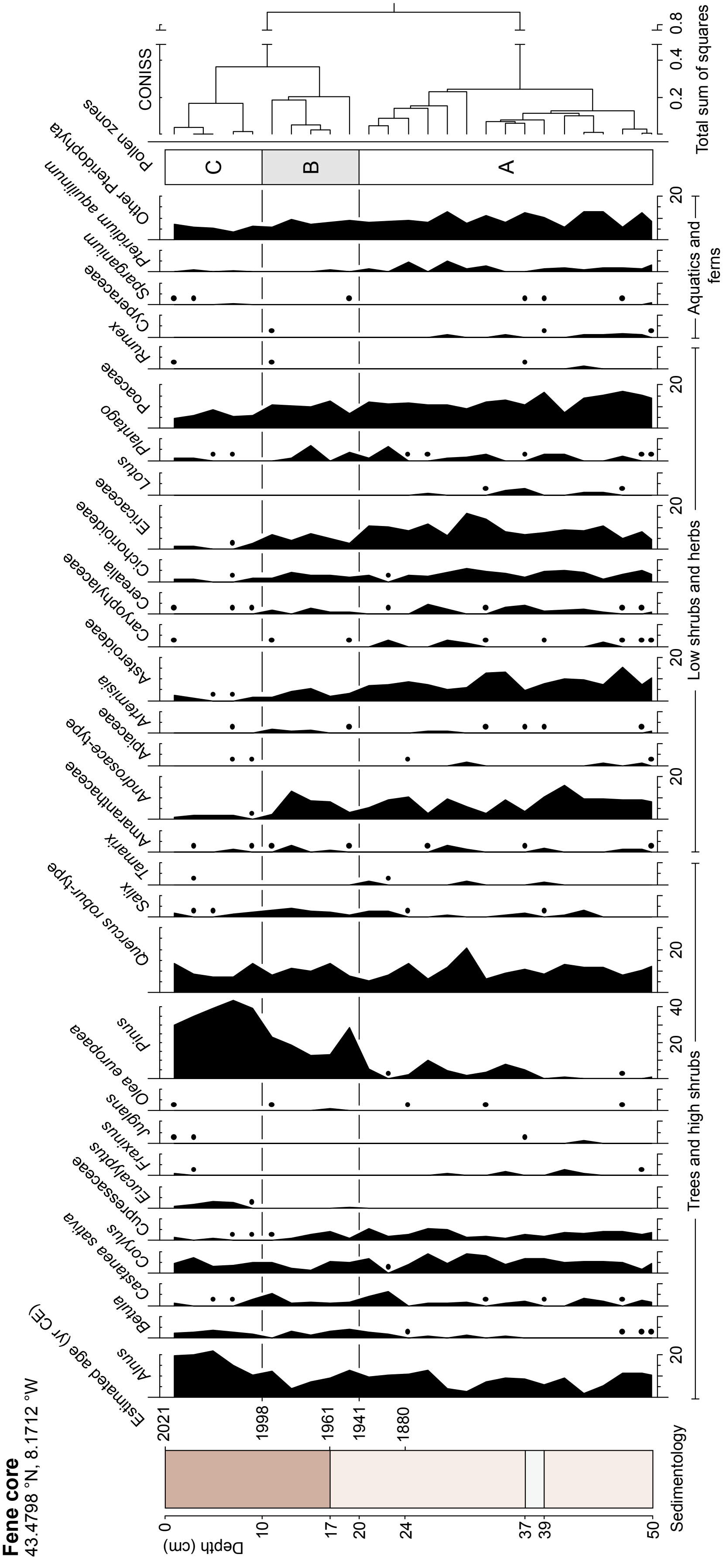
Fene core
43.4798 °N, 8.1712 °W
Depth (cm)
0
10
17
20
24
37
39
50
Sedimentology
Estimated age (yr CE)
2021
1998
1961
1941
1880
Alnus
Betula
Castanea sativa
Corylus
Cupressaceae
Eucalyptus
Fraxinus
Juglans
Olea europaea
Pinus
Quercus robur-type
Salix
Tamarix
Amaranthaceae
Androsace-type
Apiaceae
Artemisia
Asteroideae
Caryophylaceae
Cerealia
Cichorioideae
Ericaceae
Lotus
Plantago
Poaceae
Rumex
Cyperaceae
Sparganium
Pteridium aquilinum
Other Pteridophyta
Pollen zones
A
B
C
CONISS
20
20
40
20
20
20
20
20
20
Trees and high shrubs
Low shrubs and herbs
Aquatics and ferns
0.2
0.4
0.8
Total sum of squares

Figure 4

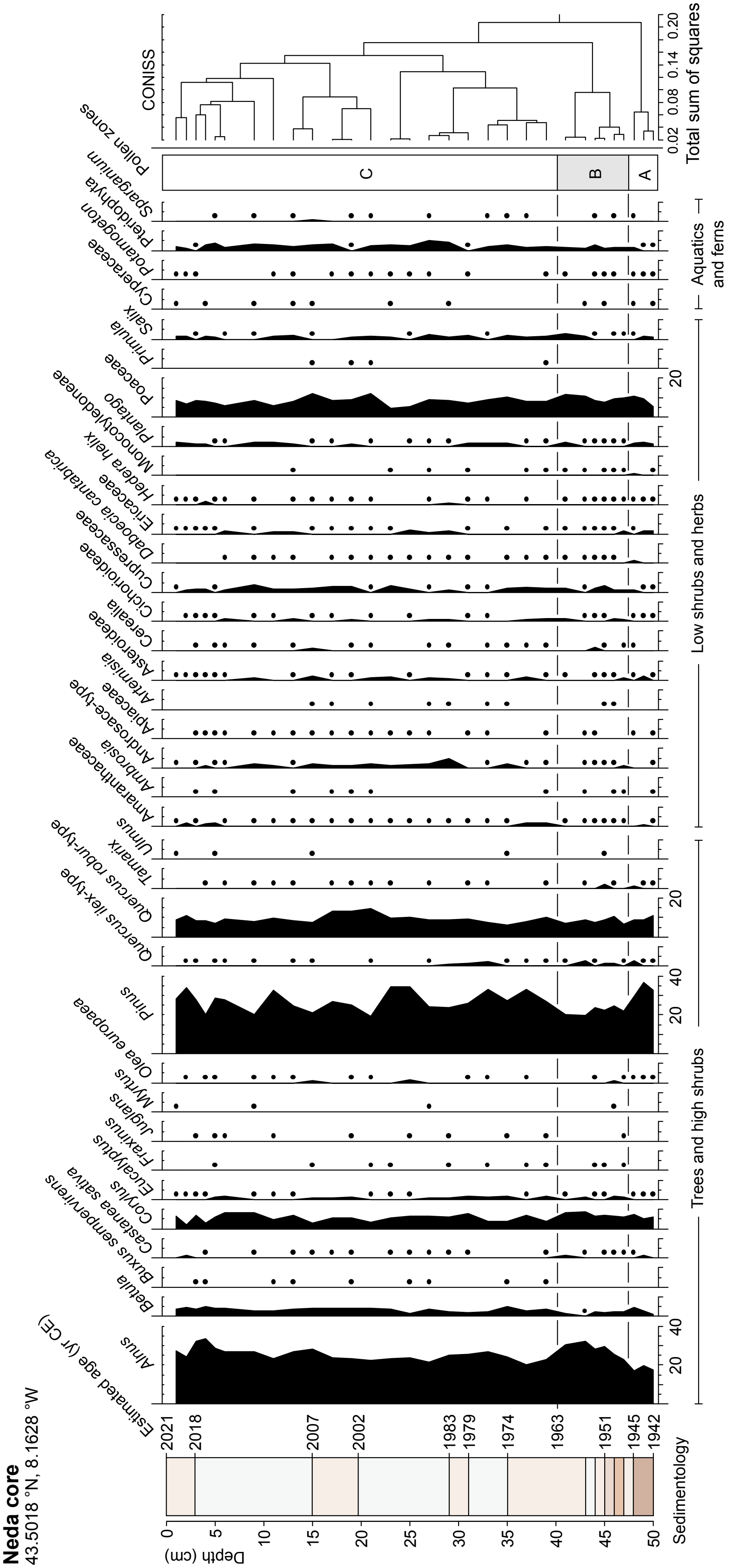
Neda core
43.5018 °N, 8.1628 °W
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
Sedimentology
Estimated age (yr CE)
2021
2018
2007
2002
1983
1979
1974
1963
1951
1945
1942
Alnus
Betula
Buxus sempervirens
Castanea sativa
Corylus
Eucalyptus
Fraxinus
Juglans
Myrtus
Olea europaea
Pinus
Quercus ilex-type
Quercus robur-type
Tamarix
Ulmus
Amaranthaceae
Ambrosia
Androsace-type
Apiaceae
Artemisia
Asteroideae
Cerealia
Cichorioideae
Cupressaceae
Daboecia cantabrica
Ericaceae
Hedera helix
Monocotyledoneae
Plantago
Poaceae
Primula
Salix
Cyperaceae
Potamogeton
Pteridophyta
Sparganium
Pollen zones
A
B
C
CONISS
Total sum of squares
0.02
0.08
0.14
0.20
20
40
Trees and high shrubs
Low shrubs and herbs
Aquatics and ferns

Figure 5

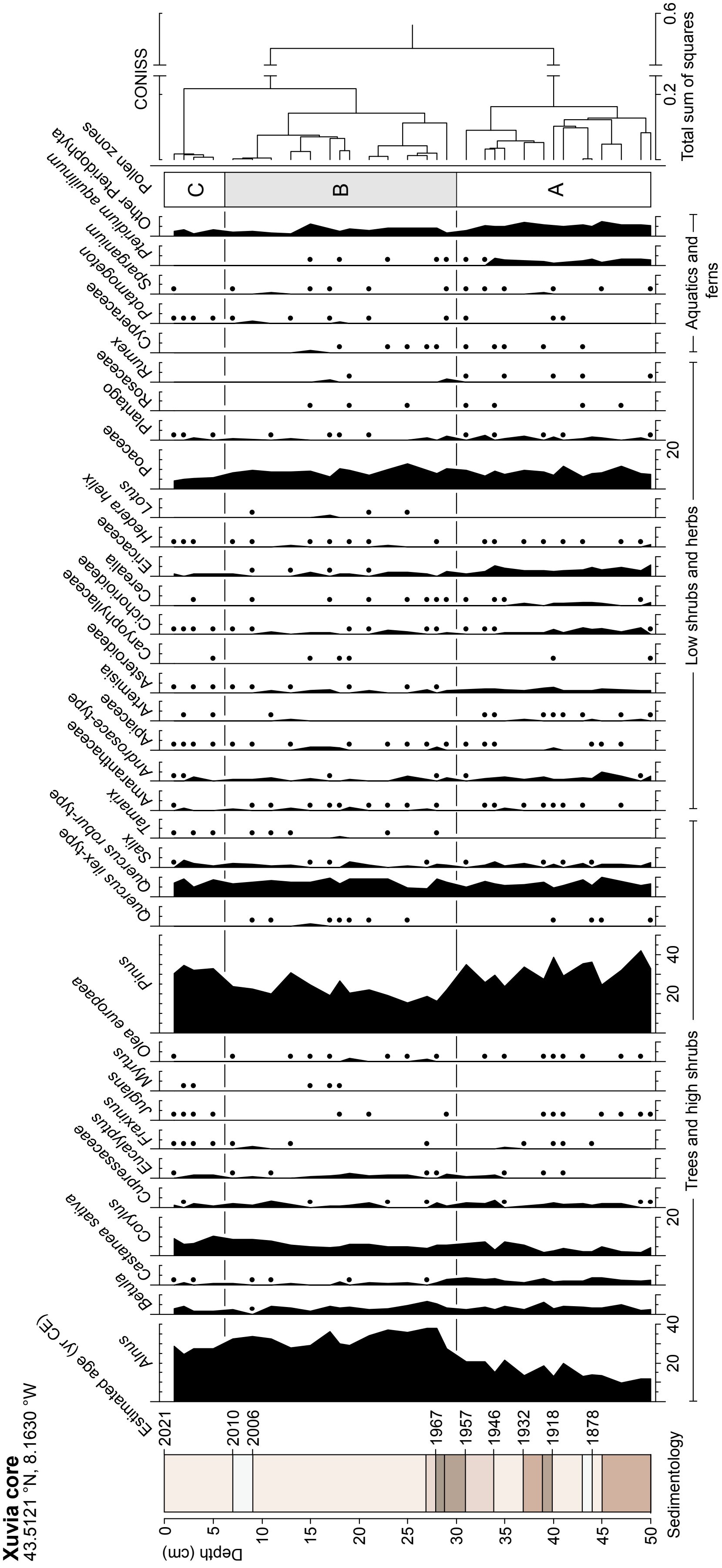
Xuvia core
43.5121 °N, 8.1630 °W
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
Sedimentology
Estimated age (yr CE)
2021
2010
2006
1967
1957
1946
1932
1918
1878
Alnus
Betula
Castanea sativa
Corylus
Cupressaceae
Eucalyptus
Fraxinus
Juglans
Myrtus
Olea europaea
Pinus
Quercus ilex-type
Quercus robur-type
Salix
Tamarix
Amaranthaceae
Androsace-type
Apiaceae
Artemisia
Asteroideae
Caryophyllaceae
Cichorioideae
Cerealia
Ericaceae
Hedera helix
Lotus
Poaceae
Plantago
Rosaceae
Rumex
Cyperaceae
Potamogeton
Sparganium
Pteridium aquilinum
Other Pteridophyta
Pollen zones
C
B
A
CONISS
Total sum of squares
0.2
0.6
20
40
Trees and high shrubs
Low shrubs and herbs
Aquatics and ferns

Figure 6

Selected Pollen Functional Types