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On the Origin of Rural Landscapes: Looking for Physico-chemical Fingerprints of Historical Agricultural Practice in the Atlantic Basque Country (N Spain)

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Abstract

Evolution and change in agricultural practice is a major factor in the codification of social relations and represents one of the main resources employed by human societies to establish a durable relationship with their environment. Using a multi-proxy integrated approach, this paper seeks to decipher the long-term dynamics that have shaped agricultural landscapes in the Basque Country (N Spain). Social and economic indicators (archival records, toponymy and oral sources) are used along with geological core sampling (geochemistry, magnetic, palynological and carpological analyses) to reconstruct a diachronic sequence of human settlement and agricultural management in the village of Aizarna over the last ~1500 years. The oldest records obtained refer to non-agricultural human activities dating back to the Roman period. Later on, traces of agricultural landscape-transformation can be divided into four main phases: 1) the onset of terraced agriculture, defined by the clearance and terracing of previous forested areas during the Early Middle Ages; 2) a Late Medieval reorganisation, with new terraces being (re)constructed close to dispersed farmsteads, linked to the emergence of the modern rural landscape; 3) a new model of intensive polyculture developed during the Modern period as a consequence of the introduction of new crops of American origin; and 4) the mechanisation and commercialisation of the agricultural production over the 20th century. These results provide a valuable pathway for the investigation of currently inhabited rural contexts, and offer, for the first time in this region, an overview on long-term landscape construction in the Atlantic areas of the Basque Country.

Key words

Agriculture; geoarchaeology; soils; geochemistry; core sampling; social change.

1. Introduction

The rural landscapes we now call ‘traditional’ are the product of very complex histories, defined by the relationships established between a great variety of environmental and social agents (Wagstaff, 1987; Kluiving & Guttmann-Bond, 2012). One of the main factors in the formation of such landscapes is agriculture, which constitutes an example of human-induced artificialisation of the environment and its conversion into a means of production (Marcus & Stanish, 2006; Denham *et al.*, 2007). Agricultural management is therefore key to understand the ecological adjustment of human societies over time, closely linked to other aspects such as settlement, demography and technology. Consequently, in recent times, the material record of past agricultural practice has gained relevance in international archaeological research agendas, with a specific reflection on the role of historic agriculture as a primary factor of landscape modelling and, ultimately, of environmental change (e.g., Guilaine, 1991; Meeus, 1993; Kirchner, 2010; Stump, 2010; Quirós-Castillo, 2014). This kind of approach is of particular interest in those areas were traditional management practices have been abandoned as a consequence of industrialisation, often resulting in a degradation of the socio-ecological structure of the local communities involved (Ilbery, 1998).

Traces of ancient agricultural practice can be identified in the modern landscape and analysed using various methodologies, including archaeological and ethnographic surveys, documentary records, toponymy, remote sensing (e.g. cadastres, land surveys, aerial photography and LiDAR) and botanical and geological analyses. Many of these strategies have been combined to address different aspects of agricultural management in different contexts. The topics most often studied include the morphology of land parcelling (e.g., Chouquer, 1996; 2008; Brigand, 2011), manuring (e.g., Poirier, 2016), the construction of irrigation systems (e.g., Retamero, 2008; Kirchner, 2009; Puy & Balbo, 2013) and slope alteration through terracing (e.g., Wilkinson, 2003; Ballesteros-Arias *et al.*, 2006; Harfouche, 2007; Krahtopoulou & Frederick, 2008; Bevan *et al.*, 2012; Fall *et al.*, 2012; Fernández-Mier *et al.*, 2014; Ferro-Vázquez *et al.*, 2014; Quirós-Castillo *et al.*, 2014; Puy *et al.*, 2016). In particular, the use of geoarchaeological methods (e.g. sedimentology, geochemistry, micromorphology, etc.) opens up a range of possibilities for addressing issues such as the organisation and management of agricultural spaces over time; past production practices; the relationship between settlement and work areas; and the impact of human activity on environmental dynamics. Many human-induced slope alterations lead to the formation of ‘artificial’ colluvial deposits, which are especially suitable for the diachronic study of environmental and land use changes (e.g. Ferro-Vázquez *et al.*, 2015; 2017), and ultimately for assessing many social and environmental problems related to the formation and/or erosion of rural landscapes.

The present paper discusses the results of a recent research project aimed at identifying and characterising the imprints of agricultural management in the long-term construction of rural landscapes. The project was based on the integration of multiple records, including an intensive campaign of field surveying and geoarchaeological core sampling, applied to a microlocal case study in the Basque Country (N Spain). This approach permitted a wide overview on the close relationship between environment, society and agriculture, setting light on the main factors of landscape construction over the last ~2000 years.

2. Materials and Methods

2.1. Area of study

The area studied is located in the Atlantic region of the Basque Country, a narrow strip of land defined by deep fluvial valleys running from south to north, and mountain ranges — mostly comprising calcareous materials — rising progressively in height southwards from the coast. These geomorphological features, combined with a mild, humid Atlantic climate, have created an erosive topography, in which human settlement is generally located on the lower slopes of the mountains, or at the floor of the widest valleys, around fluvial terraces and meadows. The region is nowadays densely urbanised and industrialised.

The project was conducted in the village of Aizarna and the adjoining hamlet of Akoa, both belonging to the municipality of Zestoa (Gipuzkoa province) (Fig. 1), where the traditional rural landscape is relatively well preserved. Each settlement is located in small endorheic karstic depression (uvala) formed by the junction of dolines covered with fluvio-karstic deposits, siliciclastic sands and clays, which makes them particularly suitable for agrarian purposes (Ugalde 1984). The soils are frequently shallow and stony on steep limestone slopes (rendzina/rendzic leptosols), and shallow and little evolved mollisols (USDA, 2014) on hydromorphic alluvial sandy clays characterized by the presence of a surficial mollic or plaggen epipedon in the agricultural areas of the karstic valleys (e.g. Aizarna valley).

<<< INSERT FIGURE 1 >>>

The structure of human settlement is scattered, with individual households alternating with orchards and fields. There is a significant presence of land alterations (e.g. trenches, channels, terraces), creating a highly anthropized agricultural landscape. Such structures are intended to improve soil features by reducing the gradient of slopes, limiting erosion, and enabling drainage; and they thereby show the existence of complex and durable agricultural risk management strategies (Marston 2011).

The analytical work focused on detecting and characterising aggradational sedimentary sequences preserved in such terraced areas, with the purpose of identifying different proxies related to the onset of agricultural practices and major changes in these and the (palaeo)environmental conditions. The chronology and principal organic and inorganic geochemical and petrophysical properties of sedimentary records were obtained using geoarchaeological core sampling, and then interpreted together with archival records and the ethnoarchaeological survey.

2.2. Documentary and field survey

It consisted on establishing a general framework of landscape organisation and land uses at the local scale. Local and regional archival collections were consulted to identify documentary records of the historical socio-political organisation of the studied communities, their spatial layout, demographic charts, ancient images, and geographic descriptions from different periods. Toponymic data was obtained from the Municipal Map of Zestoa at 1:15.000 (Basque Government 2010) and from the testimony of local informants. Finally, regular use was made of the cartographic resources available at the Basque Infrastructure of Spatial Data (geo.euskadi.eus [consulted: 27/08/2019]), such as LiDAR and aerial photographs. These sources enabled us to identify a large number of elements linked to traditional agrarian management practices, and thereby to trace a general framework of anthropic impact in these contexts, which was then used as a guide for the selection of the points of core sampling.

2.3. Core sampling

Core sampling campaigns were driven in October 2016 (Aizarna) and May 2017 (Akoa). The samples were collected using a *Van Walt / Eijkelkamp* window corer, which permits the recuperation of the sedimentary record by accumulating 1 m-depth operations. Each sample was replicated to assure their representativity. Once collected, the samples were sealed and stored at 3-4 °C.

Two cores of 2 m depth were sampled, each of them located in a polycyclic terraced field for which evidence of agricultural uses exists since the Late Middle Ages. These fields are considered representative of the respective basins of Aizarna and Akoa, and of the local context formed by both as a whole (Figs. 2 & 3a). Core AIZ/2 (UTM: 30, X: 563501.822 m, Y: 4786690.151 m, Alt.: 243.171 m) was collected in a small lateral valley situated in the southernmost part of Aizarna, entirely occupied by a large terraced agricultural field close to the Aranguren farmstead, first documented in 1479 (MAZ/2). Core AKU/2 (UTM: 30, X: 561261.719 m, Y: 4787160.458 m, Alt.: 123.281 m) was collected in the lowermost of a system of 9 stepped terraces, on the edge of the sinkhole that drains the entire Akoa basin. The adjoining farmsteads of Akoabarrena and Akoarretxea are mentioned in documents dating back to 1479 (MAZ/2).

2.4. Geochemistry

2.4.1. Elemental analysis (XRF)

The records were analysed using an *Avaatech* XRF core-scanner, at the CORELAB laboratory of the University of Barcelona. This non-destructive method allowed a semi-quantitative analysis of the elemental chemical composition from Al to U, based on the proportion of counts (cps) for each element compared to the rest. The XRF was measured at 1 cm intervals, using a rhodium lamp and two measurement intensities. The first measurement was made with a voltage of 10 kV, a current intensity of 500 mA, and a measurement time of 10 s, which provided a count for Al, Si, P, S, Cl, Ar, K, Ca, Ti, V, Cr, Mn, Fe, Rh and Ag. The second measurement was conducted with a voltage of 30 kV, a current intensity of 1000 mA, and a measurement time of 25 s; a Pd filter was used, providing a count for Ni, Cu, Zn, Ga, Ge, As, Br, Rb, Sr, Y, Zr, Nb, Au and Pb.

2.4.2. Statistical analysis (PCA)

The XRF data were processed using multivariate statistical methods. In particular, Principal Component Analysis (e.g. Giralt *et al.*, 2007&2011; Margalef *et al.*, 2014) was performed on each core, and also to all data from both cores together, using the *SPSS 20.0* program. This enabled the number of variables to be reduced to a set of components (principal components, PC), representative of groups of features following similar trends (Hotelling, 1933). A total of 169 samples were included for the PCA of Core AIZ/2, while 187 samples for the PCA of Core AKU/2.

Prior to the principal component analysis, the geochemical data were normalised to Z-Scores and the elements showing low cps values and/or low communality values were discarded. The PCA was then performed using non-rotated and Varimax rotation settings, a minimum eigen value of 1 for representative PCs, 25 iterations and factorial scores of each chemical analysis were calculated using the regression method. We assigned high/moderate/low values to different factor loading intervals according to the amount of variance that they explain: >0.7 is high, explains >49% of the variance of the element considered; 0.7-0.5 is moderate, explains 49-25% of the variance of the element considered; and >0.5 is considered low, since it explains <25% of the variance. Considering these factors along with the initial elemental variables, a high-resolution chemo-stratigraphic characterisation was performed on the cores.

2.4.3. C/N analysis

The total C and N content of the samples was determined at the Laboratory of Soil Science and Agrochemistry of the University of Burgos. Subsamples of 0.2 g were collected from the cores every 2 cm, dried and milled using an agate mortar, then processed in an automated combustion analyser *LECO TruSpec*. In the absence of carbonate minerals, measured C could be a good indication of total organic carbon (TOC) content in the sediments; in our study it is true except for stratigraphic units where calcite has been detected (e.g. Khan *et al.*, 2015; Contreras *et al.*, 2018). The soil C/N ratio is an important soil fertility indicator due to the close relationship between soil organic carbon (SOC) and total N (N_t) (Matschullat *et al.*, 2018). It reflects the interaction or coupling between SOC and N_t. Although C/N values in agricultural soils are generally thought to lie within a relatively narrow range, between 9-12 (Oades, 1988), the soil C/N ratio is often influenced by many factors such as climate (Miller *et al.*, 2004), soil conditions (Galantini *et al.*, 2004; Diekow *et al.*, 2005; Ouédraogo *et al*., 2006; Yamashita *et al.*, 2006), vegetation types (Diekow *et al.*, 2005; Franzluebbers *et al.*, 2000; Puget & Lal, 2005), and agricultural management (Raun *et al.*, 1998; Dalal *et al.*, 2011; Liang *et al.*, 2011; Lou *et al.*, 2012).

2.5. Magnetic analyses

Magnetic properties of soils and sediments and their variation (e.g., magnetic enhancement) may indicate the occurrence of different natural and anthropic processes in the past. Different detrital inputs (e.g., Wang, 2013), inorganic and/or organic formation of iron oxides (e.g., Petersen *et al*., 1986), weathering of iron-bearing minerals (e.g., Maher *et al*., 2003; Su *et al*., 2015; Grison *et al*., 2017) and natural fires (e.g., Oldfield & Crowther, 2007; Roman *et al*., 2013) or crop burning (e.g., Petrosky *et al*., 2018) are some of the processes that could be envisaged through measuring rock magnetic properties (Evans & Heller, 2003). For that purpose a high-resolution volume-specific magnetic susceptibility of the core sediments was measured using a *Bartington MS2E* pointer sensor attached to a *GEOTEK* multisensory platform. This analysis was performed at a resolution of 0.5 cm. Additionally, representative samples from both cores (9 from AIZ and 6 from AKU) were selected to further constrain the magnetic mineralogy, the domain state and the thermomagnetic stability (Tauxe, 2010). Mass-specific low-field magnetic susceptibility was measured at room temperature for every sample with a *KLY4* susceptometer (*AGICO*, noise level 3×10^{-8} SI). Additionally, with the aid of a *Variable Field Translation Balance (VFTB)* different analyses were carried out on bulk samples (450 mg). These included measurement of progressive isothermal remanent magnetization (IRM) acquisition curves, hysteresis loops (± 1T), backfield coercivity curves and thermomagnetic curves up to 700 °C in air. VFTB results were analysed and the dia/paramagnetic signal removed using the *RockMagAnalyzer* software by Leonhardt (2006). Magnetic analyses were performed in the Palaeomagnetism Laboratory at the University of Burgos and the *CORELAB* laboratory at the University of Barcelona.

2.6. Palynology and carpology

Pollen and carpology studies are basic research methods for tracing ancient agricultural patches through the identification of different agricultural taxon remains (e.g., Pearsall, 2015). In the studied cores, pollen analyses were carried out on 7 samples of 1 cm thickness sampled from each stratigraphic unit of the sedimentary record of Core AIZ/2 (Units 1 to 6, including subunits 1a and 1b), with the aim of characterising the whole sedimentary sequence (Fig. 2). Laboratory procedures followed the classic chemical method (Moore *et al.*, 1991), modified according to Dupré (1992), and using Thoulet and *Lycopodium clavatum* tablets (Stockmarr, 1971). Due to poor preservation of the pollen grains in most of the samples, only a qualitative approach was taken. Both machine-assisted and manual flotation techniques were used to retrieve macro-plant remains from core sediments. Flots were processed using a column of sieves with mesh sizes of 2 mm, 1 mm, 0.5 mm and 0.25 mm.

2.7. Radiocarbon dating

Chemo-stratigraphic characterisation of the cores permitted the identification of different depositional units, from which the most suitable intervals for radiocarbon dating were selected. Seven bulk organic sediment samples were collected at these points and then sent for pre-treatment to the Centre for Isotopic Research on the Cultural and Environmental heritage (University of Campania). The preparation of the samples followed the protocol described in Passariello *et al.* (2007). It consists in heating the sediments in a baker at 80º, then acid washed (HCI 3%) for 1h and treated with alkali (NaOH 3.2%) for 1h more to solubilize the humic acids which are then precipitated for AMS dating. Finally, AMS measurement was performed at the Laboratory of Nuclear Techniques for the Environment and the Cultural Heritage (National Institute for Nuclear Physics, Florence).

3. Results

3.1. Documentary and field survey

The study of documentary, toponymic, ethnographic and cartographic sources provided a broad overview of the evolution of rural settlement and land uses over the last five centuries, although it was chronologically and thematically limited by the availability of the records. Although both Aizarna and Akoa are recognisable as distinct rural communities since the 14th century, documentary sources are virtually non-existent prior to the Late Middle Ages, and become more expressive only after the 16th century. Several farmsteads, appear documented since that moment on, forming the backbone of the settlement structure that has survived until our days.

3.2. Core records

The sedimentary records were similar in both cores, consisting of clays derived from underlying Plio-Pleistocene fluviokarstic sediments, within which the organic content increases towards the top (modern agricultural soil). Agricultural terraces can be recognised in the upper half of the cores. They consist of clayey anthropic fillings, sometimes slightly pedogenised, including abundant anthropic material (ceramic, lime, charcoal, etc.), root bioturbation and ploughing traces.

Core AIZ/2 was divided into six main stratigraphic units, subdivided into 8 clayey subunits in total (Figs. 2 & 3). Above the underlying original fluviokarstic sediments, a palaeosol (140 cm depth) and two phases of terrace-fill were identified. Terrace 1 was composed of a homogeneous rubified clay deposit (100-140 cm). Terrace 2 presented a stratified sequence composed of three intervals: a superficial organic clay level (0-30 cm), and two successive clay deposits (30-60 cm and 60-100 cm) (Fig. 2). Core AKU/2 was divided into four main stratigraphic units, subdivided into 6 clayey subunits in total (Figs. 2 & 3). Above the natural fluviokarstic sediments, an organic palaeosol unit was located between a depth of 100 and 120 cm. Above this level, two successive terrace-fills were identified. The first fill of terrace 1 was located between 70 and 100 cm. Terrace 2 was composed of a surface organic level and an underlying clay deposit (0-70 cm).

<<< INSERT FIGURE 2 >>>

3.2.1. Elemental analysis (XRF)

The elemental geochemical composition and its variations are very similar in both cores, the joint PCA analysis of geochemical data in both cores show that they are grouped in 4 different (Table II and Fig. 1 in Supplementary Information). The joint PCA explains the 76.6% of the variance of the analysed elements and show 4 principal components (PCs). PC1 explains 50.5% of the variance and includes Fe, K, Rb, Ti, Sr, Al, V, As, Y, Br, Si and Cr with very high to high loadings (0.9 to 0.7) (Table II and Fig. 1 in Supplementary Information). PC2 explains 11.3% of the variance and includes Pb, P, Zn and S with very high loadings. PC3 explains the 9% of the variance and include Ca and Mn with moderate loading. Finally, PC4 explains the 5,7% and include Cl (0,78) and Zr (0,6).

A similar grouping is yielded when different PCAs are made for each core (Fig. 4). In this case, they can be summarised in six PCs. The PCA explains 78.7% of the total variance in Core AIZ/2, and 77.3% in Core AKU/2. PC1AIZ/2 explains 34.3% of the variance in Core AIZ/2. K, Rb, Al, Sr, Fe and Ti show high positive loadings (over 0.7), Co, Si and V have a moderately positive loading (over 0.5) and Ca and S have a low negative factor loading, -0.45 and -0.64 respectively (Fig. 4). In Core AKU/2, PC1AKU/2 explains 39.7% of the total variance. K, Fe, Al, Ti, Rb, Si, Sr, V and P show high positive loadings (over 0.7), Mn and Sn have a moderately positive loading (over 0.5), and Ca and S have a very low negative factor loading, -0.32 and -0.3 respectively (Fig. 4). As suggested by previous studies, the chemistry of sediments is strongly controlled by the grain size of the dominant mineral host and subsequent particle size sorting (e.g. Das & Haake, 2003; Koinig *et al.,* 2003; Jin *et al.,* 2006). Ti, Rb and K are often associated with clay mineral assemblages, while Zr and Si are generally linked to coarser silt and sand size fractions (Kylander *et al.,* 2011). The lithogenic element content and the record of factor scores indicate that, in general, the amount of clay minerals decreases due to a greater organic matter content towards the top of the core (Figs. 3 & 4).

PC2 is also controlled by the same elements in both cores. $PC2_{AIZ/2}$ explains 16.85% of the variance in Core AIZ/2. P, Zn, Pb and Br show high positive loadings and Mn and S have a moderate positive loading. Si and Al have a low negative factor loading (Fig. 4). In Core AKU/2, $PC2_{AKU/2}$ explains 12.73% of the total variance. Zn and Pb show high positive loadings and Cu, Br and Ni have a moderately positive loading (Fig. 4). The high positive and moderate loadings of elements that usually bind organic matter is indicative of the organic matter content-controlled nature of PC2 (Alloway, 1990; Biester *et al*., 2006; Huang & Jin, 2008; Atafar *et al.*, 2010; Leri & Myneni, 2012). In general, the amount of biophile elements is quite uniform throughout the cores and increases exponentially in the surficial *ca.* 60 cm due to the greater content of organic matter towards the top (Fig. 3).

PC3 is again controlled by the same elements in both cores. PC3AIZ/2 explains 9.95% of the variance in Core AIZ/2. Zr shows a high positive loading and Si, Mn and Y have moderate positive loadings (Fig. 4). In Core AKU/2, PC3AKU/2 explains 7.9% of the total variance. Zr and Y show high positive loadings (Fig. 4). In finer-grained sediments Zr can be used as a proxy for changes in grain size, with lower values representing fine-grained material and higher values representing coarse-grained material (e.g. Dypvik & Harris, 2001; Kylander *et al.*, 2011). The high positive and moderate loadings of Zr and Si in PC3 are interpreted as indicative of grain size and compositional changes in the core sediments, related to a higher quantity of silt and sand-sized sediment where quartz grains (SiO_2) and heavy minerals (e.g. zircon-$ZrSiO_4$) are commonly present. In general, PC3 factor loadings reflecting relatively coarser granulometry of the core sediments are more abundant from Unit 2 towards the top (Fig. 3).

$PC4_{AKU/2}$ from Core AKU/2 and $PC5_{AIZ/2}$ from Core AIZ/2 are controlled by similar elements. $PC4_{AKU/2}$ explains 6.6% of the variance. S shows high positive loading and Ca has a high negative loading (Fig. 4). $PC5_{AIZ/2}$ explains 7% of the total variance. Cl shows a high positive loading and Ca has a moderate negative loading (Fig. 4). Both PCs are interpreted as indicative of the relative presence of Ca in the core sediments, which is present in units $4b_{AIZ/2}$ and $2b_{AKU/2}$ (see also Ca content in Fig. 3).

Finally, with respect to the other PCs, $PC4_{AIZ/2}$ and $PC6_{AIZ/2}$ from Core AIZ/2 and $PC5_{AKU/2}$ and $PC6_{AKU/2}$ from Core AKU/2 explain small proportions of the variance (7.2%, 6.5%, 6.4 % and 5.4% respectively). They are controlled by one element (As for $PC4_{AIZ/}2$, Cl for $PC5_{AKU/2}$ and Cr for $PC6_{AIZ/2\&AKU/2}$) which does not normally show important variations throughout the core record and is poorly explained by the PCA showing relatively low communality. These PCs are not considered relevant for the present study.

<<< INSERT FIGURE 3 >>>

<<< INSERT FIGURE 4 >>>

3.2.2. Soil C/N ratio

The two cores studied show similar total carbon (C_t), nitrogen (N_t) and C/N trends and variations, again suggesting that they have recorded similar stratigraphy and agricultural practices. In both cores, the soil C_t, N_t and C/N ratio is much higher at surface depth (0–5 cm) (Fig. 3). The C/N ratio tended to decline with depth in both cores, parallel to the relative increase in soil clay content with depth (Fig. 3) and more decomposed organic matter with lower C/N ratio (Diekow *et al.*, 2005; Ouédraogo *et al.*, 2006; Yamashita *et al.*, 2006). Superimposed on the general decreasing trend, different intervals of increase of soil C_t, N_t and/or C/N ratio at depth are also found (Fig. 3). Finally, some C_t, N_t and C/N enriched intervals showing homogeneous values with depth are observed in the top 10-15 cm of some terrace units in the cores, suggesting a higher presence of SOC. This is probably the result of agricultural practices carried out at the surface of these units, since traditional tillage promotes incorporation of residues and manure (fertilisers) into the soil (enhancing C/N), and these can therefore be uniformly distributed with depths of up to 20 cm due to ploughing (Düring *et al.*, 2002; Mrabet, 2002; Sá & Lal, 2009; Wright *et al.*, 2007). The increase in C/N observed in stratigraphic units 5 (AIZ/2) and 3 (AKU/2) (Fig. 3) is related to the presence of calcite that obscures the organic C content of the sediments.

3.2.3. Magnetic analyses

In Core AKU/2, MS values are relatively low and homogeneous. They show values ranging from *ca.* 44 to 278 SIx10^{-5}, with a mean value of 107 SIx10^{-}5 in all stratigraphic units, which is typical of the parent Plio-Pleistocene fluviokarstic sediments (Unit 1) (Fig. 3b). Some spot increases in MS from 320 to 1035 SIx10^{-5} are visible, coinciding with (hydro)oxide nodules in Unit 1a and tile remains in Units 2 and 3 (Figs. 2 & 3b). It is worth noting that the presence of ancient (Unit 1b) and modern (Unit 4b) (palaeo)soils rich in organic matter slightly alters the MS signal, diminishing its values, probably due to a greater presence of organic matter and consequently less Fe-rich sediment per unit of volume.

In Core AIZ/2, the MS shows more heterogeneous values (Fig. 3a). The parent sediments from Unit 1a have average values of *ca.* 50 SIx10^{-5}, becoming higher (maximum value: 255 SIx10^{-5}) towards the top of Unit 1b. Unit 2 shows strikingly higher values, gradually increasing towards the top, from 281 to 854 SIx10^{-5}. In Unit 3 the MS falls to background values similar to those of the parent sediments from Unit 1, but encompasses MS peaks that might indicate mixing with sediment with a higher MS, possibly reworked from Unit 2. MS values from Unit 4 are again substantially higher; they have an average value of 475 SIx10^{-5} with some peaks reaching maximum values of 855 SIx10^{-5}. Finally, the surficial units 5, 6a and 6b show lower and more homogeneous values, with an average of 264 SIx10^{-5}, similar to Units 1b and 3.

The mass-specific low-field magnetic susceptibility values concur with the high-resolution MS values and tendencies obtained with the core scanner in both cores (Figs. 3, 5 and Table III in

Supplementary Information). The MS values of representative samples from Core AKU/2 oscillate between 1.17 x 10^{-6} and 7.09 x 10^{-7} m^3kg^{-1} whereas those from Core AIZ/2 are higher and vary between 7.45 x 10^{-6} and 7.43 x 10^{-7} m^3kg^{-1}. The thermomagnetic curves indicate that the main ferromagnetic mineral present in core sediments is a Ti-low titanomagnetite with Curie temperatures of around 580 ºC (Fig. 5a, 5b and Table III in Supplementary Information). However, haematite is also present, given the characteristic red colour observed and because the IRM acquisition curves are not fully saturated up to 1 T. The remanence contribution of haematite is not relevant and is masked by the magnetite (Evans & Heller 2003). Variations of up to one order of magnitude in MS are also observed in the intensity of the thermomagnetic curves from Units 2 and 4 in Core AIZ/2 (Figs. 3, 5 and Table III in Supplementary Information), which are the only ones that do not show a jump around 250-300 ºC in the heating cycle observed in all the other samples. This fact suggests that sediments from both units (2 and 4) were thermoaltered, burnt, in the past (Fig. 5 and Supplementary Information).

<<< INSERT FIGURE 5 >>>

3.2.4. Palynology and carpology

Sediment flotation in search for carpological remains was unsuccessful, since no plant macroremains were retrieved, only small microcharcoal samples.

Regarding pollens, due to low preservation regarding both variety of taxa and quantity of palynomorphs for statistical robustness in most of the samples, only a qualitative approach has been possible (Table IV in Supplementary information). The samples from basal stratigraphic Units 1a (190 cm depth) and 1b (150 cm), Unit 2 (at 120 cm), Unit 3 (104 cm) and Unit 4 (80 cm) have similar palynological results with very low content and diversity (Table IV in Supplementary information). The preserved pollen assemblage is dominated by different types of fern spores (mainly Pterydophyta monolete and trilete, and *Polypodium*) and few grasses

(Poaceae) besides juniper (*Juniperus* sp.) pollen grains, some Fabaceae and anecdotic presence of *Pinus*. No cereal pollen type was found (Table IV in Supplementary information). Unit 5 (sampled at 35 cm depth) has a more abundant pollen content including pine (*Pinus* sp.), ruderals (Cichorioideae and *Plantago* sp.), wild grasses (Poaceae) and some junipers again (*Juniperus* sp.), besides Cyperaceae and *Typha* such as typical taxa of water-saturated areas (wetlands, floodplains, etc.). Finally, the pollen content of Unit 6 (sampled at 5 cm depth) is entirely different; it is very abundant and dominated by pines (*Pinus* sp.) and cereals, e. g. rye (*Secale cereale*) and oat (*Avena sp.).* It also contains legumes (Fabaceae), wild grasses (Poaceae) ruderals (Carduae and Cichorioideae) and Cyperaceae and *Ranunculus* as indicators of water presence or humid wetlands. Other arboreal taxa are also present in this sample such as a few oak (deciduous *Quercus*), chestnut (*Castanea* sp.), willow (*Salix* sp.) and juniper (*Juniperus* sp.) pollen grains. Some coprophilous *Sordaria* spores were also retrieved.

3.2.5. Radiocarbon dating

A total of 7 samples were selected for radiocarbon dating, 3 from Core AIZ/2 and 4 from Core AKU/2. The results are summarised in Table 1.

Table 1. *Radiocarbon dating of Core Samples AIZ/2 and AKU/2.*

CORE	**DEPTH**	**SAMPLE TYPE**	**LAB CODE**	**^{14}C CONCENT. (pMC)**	**t_{rc} (YEARS BP)**	**CAL. AGE (YEARS - 1s)**	**CAL. AGE (YEARS - 2 s)**
AIZ/2	82 cm	sediment OM	FI3495	96.16 ± 0.45	314 ± 38	**[1516-1597 AD]** [1618-1643 AD]	**[1473-1650 AD]**
AIZ/2	97 cm	sediment OM	FI3494	95.19 ± 0.48	396 ± 41	**[1443-1514 AD]** [1600-1617 AD]	**[1433-1528 AD]** [1553-1634 AD]

AIZ/2	142 cm	sediment OM	FI3557	82.91 ± 0.56	1545 ± 45	**[535−614 AD]** [435−448 AD] [472−487 AD]	**[506−641 AD]** [428−497 AD]
AKU/2	77 cm	sediment OM	FI3741	82.98 ± 0.41	1499 ± 40	**[536-622 AD]** [477-483 AD]	**[529-644 AD]** [429-494 AD] [510-518 AD]
AKU/2	97 cm	sediment OM	FI3673	81.83 ± 0.50	1611 ± 50	**[486-535 AD]** [395-438 AD] [443-473 AD]	[336-563 AD]
AKU/2	117 cm	sediment OM	FI3674	78.29 ± 0.39	1966 ± 46	**[2 BC - 77 AD]** [36-31 BC] [21-11 BC]	**[56 BC - 131 AD]** [88-76 BC]
AKU/2	137 cm	sediment OM	FI3675	71.61 ± 0.53	2682 ± 50	**[854-803 BC]** [895-868 BC]	**[930-791 BC]**

4. Discussion

The combination of the physiochemical analyses of sediments, field survey and documentary sources allowed us to trace a long diachronic sequence of land management in Aizarna and Akoa. Similar trends and variations, represented by similar PCs in both cores, indicate that analogous anthropic and environmental processes controlled landscape dynamics in the two relatively nearby settings (Fig. 6). This probably means that the anthropic and natural factors behind such processes and their evolution may be related to certain general trends on a regional scale.

The chronology of each stratigraphic sequence was established by radiocarbon dates from the humic fraction of selected soil horizons or charcoal remains in the surficial horizon or setting of selected stratigraphical units. Since the dating of agricultural terraces constitutes a long-standing problem (e.g. Grove & Rackham, 2001; Wilkinson, 2003; Price & Nixon, 2005; Boixadera *et al.*, 2016; Puy *et al.*, 2016; Kinniard et al., 2017; Ferro-Vazquez *et al.*, 2018), their results must be handled with prudence. However, when considered in combination with the geoarchaeological study of the terraces' formation processes, the obtained results were coherent not only within each soil sequence, but also in terms of general landscape dynamics. Hence, four distinct phases were identified in both cores.

<<< INSERT FIGURE 6 >>>

4.1. Phase 1. From Antiquity to the Early Middle Ages: the construction of the present rural landscapes

In the local context, the oldest evidence of human settlement dates from the Roman period. Along with two coins from the 1st century BC recorded in the nearby cave of Amalda (Armendariz, 1990), a wooden architectural structure has been excavated in the centre of Aizarna, close to the parish church, associated with material culture ―mainly pottery― that suggests that this area formed part of regional exchange networks (Narbarte-Hernández *et al*., 2018). The record of rural occupations from the Roman period that do not correspond to the *villa* model is an emerging issue across Europe (e.g., Reddé, 2017; Allen *et al*., 2017), and opens new pathways for the investigation of rural settlement and resource management dynamics in peasant societies. Nevertheless, this is a period for which very little is still known in the Atlantic sector of the Basque Country. Indeed, no substantial signs of human land management could be traced in the core records of AIZ/2 and AKU/2 prior to the Early Middle Ages.

In both cores, the basal units (Units 1a and 1b) are formed by Plio-Pleistocene parental sediments where the lithogenic element concentration (PC1) diminishes gradually in Unit 1a and stabilises in Unit 1b due to the greater concentration of biogenic elements (PC2) and total carbon (C_t). This fact, together with the presence of root bioturbation, probably reflects the existence of a surficial organic matter-rich A horizon (palaeosol), which has been dated at 56 cal BC - 131 cal AD in Core AKU/2, and at 506−641 cal AD in Core AIZ/2. Conversely, charcoal-rich sediments from Unit 1a in Core AKU/2 date from 930-791 cal BC. This chronological context seems to indicate that the palaeosol covers at least seven centuries, roughly coinciding with the so-called Roman Warm Period (McCormick *et al.*, 2012; Büntgen *et al.*, 2016). The few qualitative pollen assemblages found in Units 1 and 2 from Core AIZ/2, included in this phase, show very poor pollen content but particularly few arboreal pollen grains (AP), perhaps reflecting the presence of open deforested areas with wild grasses (Table IV in Supplementary Information). In fact, the most abundant taxa are ferns, indicating a probable perturbed landscape.

Subsequently, a first event of terrace construction can be identified from stratigraphic and geoarchaeological proxies, and ascribed to Early Middle Ages, in both cores AIZ/2 and AKU/2. In both cases, the Roman-era palaeosols are covered with thick terrace-fills (Unit 2) that correspond to a phase of anthropogenic fire activity and slope alteration, that is to say, the oldest traces of terraced agriculture documented in the area. These terrace fills showed large amounts of allochthonous sediments, mainly rubified clay aggregates and millimetric charcoal fragments. Unit 2 from both cores shows relatively lower values of elements grouped in PC1, related to fine clayey sediment, towards the top due to the presence of a slightly higher content of coarser sediment (higher Zr and/or Si content) and some biogenic elements (e.g. P and S) and C_t (Figs. 5 & 6).

One meaningful proxy in this unit are the high values of magnetic susceptibility (MS) measured in Core AIZ/2 (Fig. 6). Several processes have been proposed to explain the magnetic enhancement in soils and sediments (Evans & Heller, 2003), including detrital input from atmospheric pollution (e.g., Wang, 2013), inorganic *in situ* formation of ultrafine magnetite, bacterial microorganisms influencing the precipitation of iron oxides (e.g., Petersen *et al.*, 1986), weathering of iron-bearing minerals during soil wetting and drying cycles (e.g., Maher *et al.*, 2003; Su *et al.*, 2015; Grison *et al.*, 2017), and natural fires or crop burning (e.g., Oldfield & Crowther, 2007; Roman *et al.*, 2013). Some of them might be responsible for the magnetic enhancement observed at the sites studied. However, it should be noted that these are anthropic contexts, where burning activities were often carried out in the past, as evidenced by the presence of thermo-altered sediments and charcoal fragments. MS results show a magnetic enhancement of around one order of magnitude between samples from Unit 2 and 4 and those from the parental substrate, non-disturbed fluvio-karstic sediments and palaeosols from the underlying stratigraphic Unit 1.

The absence of magnetomineralogical alteration during the re-heating of the samples from Units 2 and 4 in the laboratory (Fig. 5 & Supplementary Information) suggest that the magnetic enhancement observed in these sediments may be due to heating processes, in contrast with the rest of samples which do not show such thermal behaviour. This MS enhancement contrasts with the absence of variations in the concentration of Fe throughout the core, which is explained by the neoformation of fine-grained ferrimagnetic minerals from other iron oxides, hydroxides or most probably from paramagnetic minerals such as phyllosilicates (not by the addition of Fe-bearing sediment), and is indicative of firing forested areas (Blake *et al.*, 2006; Oldfield & Crowther, 2007; Roman *et al.*, 2013; Eldiabani *et al.*, 2014). The use of fire as a strategy of land management is widely known, one of its most common applications being forest clearance (Caldararo, 2002; López-Sáez, *et al.* 2017), often as a preliminary step in preparing agricultural fields (e.g. Quirós-Castillo *et al.*, 2014). Besides, the expansion of ferns is usually related to post-fire events due to recolonization of heliophythic taxa (López-Merino *et al.*, 2012), in agreement with the abundant presence of Pteridophyta in AIZ/2 palynological content.

Moreover, magnetic susceptibility in Core AIZ/2 increased in the uppermost 20 cm of the terrace-fill from Unit 2, the interval commonly affected by animal ploughing. This indicates more intense thermoalteration on the terrace surface. The use of fire between fallow and ploughing is well-documented in the framework of extensive rotation crop systems (e.g. Rippon *et al.*, 2006). This magnetic enhancement could reflect a strategy of regular brush-burning and the addition of ash/charcoal to the topsoil (Petrovský *et al.*, 2018) as a way of ensuring soil fertility over time and can be regarded as a long-term management strategy within the framework of a stable, planned agricultural system.

The stratigraphy of both soil sequences therefore indicates that, at some point in the Early Middle Ages, considerable land reorganisation work was undertaken after clearance, leading to the construction of the highly anthropized agricultural systems that lie beneath the present rural landscape. This work may have implied: 1) clearing previously forested lands, for which fire was used in at least one case (Core AIZ16/2), and 2) terrace-construction, possibly involving thermally altered sediment/soil redeposition from the surrounding slopes, due to anthropic additions (e.g., Ballesteros-Arias, 2010) and/or natural erosion, colluviation.

Roman-era palaeosols buried by anthropic terraces from the 6th-7th centuries have been reported in other similar studies in the westernmost area of the Atlantic Iberia (e.g. Ferro-Vazquez *et al*. 2014). More generally, early agricultural terracing phases, roughly stretching from the 6th to the 10th centuries, have been documented in several nearby regions (e.g. Ballesteros-Arias *et al.*, 2006; Quirós-Castillo, 2009a; Ballesteros-Arias, 2010; Varón-Hernández *et al.*, 2012; Fernández-Mier *et al.*, 2014). This evidence overlaps with the formation of present-day settlement networks in the whole of western Europe (Quirós-Castillo, 2009b), suggesting that, far from the traditional image of economic simplification and social and technological poverty, the Early Middle Ages may be defined as a period of considerable peasant dynamism and a starting point for the codification of long-lasting local identities in the rural world (Wickham, 2005).

4.2. Phase 2. Late Middle Ages: the appearance of modern farmsteads

In Core AIZ/2, the Early Medieval terrace-fill of Unit 2 appeared partially truncated by a layer of gravels (Unit 3) and silty sediment, which is interpreted as a record of an erosion and sedimentation process resulting from a flood of a stream. In fact, the presence of a channelled stream of water through the agricultural terrace where Core AIZ/2 was collected is mentioned in documentation from 1479 (MAZ/2). The fluvial sediments from this unit have much lower values of MS, while the geochemistry reflects an increase in PC1, probably resulting from an input of allochthonous siliciclastic terrigenous sediments eroded from upstream surficial organic soil horizons and/or agricultural soils, due to their relatively higher organic matter (C_t) content (Fig. 3a). Similar flood events have been documented in other Atlantic regions for the same chronologies (Benito *et al.* 2008; Fernández *et al.* 2017) and can be related to the onset of the Little Ice Age (Oliva *et al.* 2017).

In any case, this flood record appears covered with a new terrace fill (Unit 4) in Core AIZ/2, radiocarbon dated between the 15th and the 16th centuries and possibly coetaneous to the cited mention to a channelled stream in 1479. The pollen assemblage found in this unit indicates, as in the previous period (Units 1 and 2), the presence of open areas with junipers as relatively abundant in the few arboreal pollen taxa, herbaceous formations with grasses and abuntant ferns. Considering the absence of crop pollen and the fact that Unit 4 is an anthropic terracing layer, this probably indicates that the sediment for the agricultural terrace of this phase (Unit 4) was excavated from nearby slope sediments from Unit 1 (or even Unit 2).

Similarly, a second terrace fill was identified in Core AKU/2 (Unit 2b), indicating that the Late Middle Ages may have constituted a moment of profound reorganisation of land uses, including a reconstruction of the pre-existing agricultural spaces in both Aizarna and Akoa. The geochemical proxies indicate a decrease in the lithogenic elements related to the basal siliciclastic sediment (PC1) and a parallel increase of biogenic elements (PC2), as well as the regular presence of microcharcoal inclusions, could suggest a continuous input of organic amendments such as domestic waste, manure and ashes (Fig. 6). In this regard, the high MS values and the characteristics of the thermomagnetic curves for Unit 4 in Core AIZ/2 (Fig. 3a) evidence the use of fire or previously microcharcoal-rich thermoaltered sediments (e.g. from burned slope sediments from Unit 1 and/or even Unit 2) in terrace construction. This is not the case in Core AKU/2, where the terrace sediments do not exhibit any evidence of thermoalteration (Fig. 3b).

The regular upkeep of the fields may have been enhanced by their proximity to the habitational areas. Documentary evidence reveals the emergence of new household units by the 14th–15th centuries, to which these fields still belong today: the farmsteads named Aranguren and Gorosarri are mentioned close to Core AIZ/2, and Akoabarrena and Akoarretxea close to Core AKU/2. Overall, the current settlement networks in the study area and in the region can be said to have been shaped by the 15th century, their main patterns being a dispersed distribution of the households, named *baserria* in Basque, and the integration of multiple land resources: gardens, cereal fields (wheat and millet), and orchards (mainly apple, walnut and chestnut trees) (e.g. García, 1997; MAD/1; MAZ/2). In the regional context, several archaeological and architectural studies indicate that the first modern farmsteads in this territory date back to the same period, the 15th–16th centuries (Ibáñez-Etxeberria & Agirre-Mauleón, 1998; Santana *et al*. 2001; Santana & Pereda, 2003; Santana *et al.*, 2003; Mendizabal-Sandonís, 2014; Campos-López, 2015; Susperregi *et al.*, 2017). A characteristic of these farmsteads is that a single structure contains very diverse spaces for food storage and processing, as well as farmyards, cellars and the dwelling itself.

This is a period of economic growth linked to the rise of the transatlantic trade and socio-political transformations following the overcoming of the 14th century-crisis (Arizaga & Bochaca, 2003; Childs, 2003; Priotti, 2003). In 1383, both Aizarna and Akoa had been incorporated into the jurisdiction of a newly chartered burg, Zestoa (MAZ/1), in the framework of a wide process of centralisation of political decision-making in a few small to medium-sized urban centres (Truchuelo, 1997). Thus, the spread of intensive landholdings such as those documented in Aizarna and Akoa for this period might also be interpreted as a response to the creation of new markets, with part of the outputs being consumed outside the domestic units.

4.3. Phase 3. The Modern period: intensive polyculture

The physico-chemical proxies analyzed in the cores seems to reflect profound changes in agricultural management above the second phase of terrace construction, hence during the Modern period. A clearly distinct deposit was identified in Cores AIZ/2 (Unit 5) and AKU/2 (Unit 3) (Fig. 3). In this sense, the pollen content of sediments from this phase (Core AIZ/2, Unit 5) indicates the presence of human-impacted landscape with few pines and junipers, again Poaceae (grassland) and new taxa related to ruderals plants such as Cichorioideae and Plantago. The presence for the first time in the sequence of Cyperaceae and *Typha* (Table IV in supplementary information), which indicate water-saturated soils, probably linked to higher precipitation rates and/or less efficient drainage of the cultivated terraces.

The main feature of these deposits is the abundance of Ca, which is absent in the basal sediments (Fig. 4) and is explained by the presence of lime nodules (Fig, 2). Equally, the remarkable intervals of increasing C_t and C/N in this phase (Unit 5a in Core AIZ/2 and Unit 3 in Core AKU/2) are related to a very high C_t content derived from the addition of lime (CaO) and its recarbonation ($CaCO_3$) (see Ca curve in Fig. 3), reflecting the onset of the use of this amendment for the correction of the acidity in those units.

Lime is an amendment that facilitates the liberation of nutrients and balances soil acidity (Holland *et al.*, 2018; Rheinheimer *et al.*, 2018). These properties were already known by the mid-18th century in the Basque Country, when Larramendi (1756) stated that "[…] fields tend to weaken within a few years. To address this, every nine years the fields are amended with lime, and for this reason almost every household has its own limekiln, used to produce lime with much work and much expenditure of wood”. Several mentions of limekilns in Aizarna and Akoa appear as early as 1706 (MAZ/4; MAZ/5; MAZ/6; MAZ/7); the remains of many of these structures are still visible in both communities, where oral memory of their use has been widely documented (Fig. 7).

<<< INSERT FIGURE 7 >>>

Additionally, organic content proxies (C_t and PC2) also display a tendency to increase towards the surface (Figs. 3 & 6). The remarkable presence of pottery in this level could be an indicator of some form of manuring, like the use of domestic waste (e.g. Poirier & Nuninger 2012; Poirier 2016). Oral memory of the use of manure is widespread in Aizarna and Akoa, where ferns and gorse were mixed with animal dung and then left to ferment for a variable period before being spread on the fields (Fig. 7). In a context of dispersed settlement, the presence of such extra inputs is a strong indicator of intensive agrarian management, favoured by the plots’ proximity to the settlement (Van der Veen, 2005).

All of these factors reflect a change in the agricultural management of Aizarna and Akoa during the Modern period. This statement is chronologically coherent with the information provided by documentary sources, which outline an agricultural revolution having occurred in this period as a consequence of the introduction of American crops, In this line, the oldest reports of maize cultivation in the Basque Country date to the 16th century, but its general expansion probably occurred during the 17th century. Soon, the new crop completely replaced other spring cereals, with total maize production exceeding wheat (Bilbao & Fernández de Pinedo, 1984). Similar chronologies have been proposed in the case of beans (Aragón-Ruano, 2015). In any case, the introduction of these new products did not imply a general substitution of previous crops, but rather the implementation of complex systems of crop rotation, based on the alternation of, principally, wheat, maize and tubers (e.g. turnips) in the same plots. These systems might have developed in a relatively short time; by the mid-17th century, F. Bertaut (1669) stated that, in the nearby Bidasoa valley, “when a field has provided wheat and once they have collected it, they sow maize at the end of August, which they harvest shortly after”. By the end of the 18th century, G.M. Jovellanos described a regional context that was entirely dominated by such rotation: “the order seems to be maize, wheat, turnip, maize, etc. […] Not even a vineyard or a meadow; turnip and maize, and nothing else” (Caso-González, 1994).

As described above, the agroecosystems that preceded these changes developed in the very long term. In contrast, the introduction of American crops occurred in a short period of time and led to a radical transformation in the physiognomy of these villages. This change was coetaneous with a sustained demographic progression; a comparison between the censuses of 1543 (MAZ/3) and 1776 (MAZ/8) shows that, in Aizarna and Akoa, the number of households increased from 53 to 82 in this period, resulting in a subdivision of the local space into smaller landholdings. This increase of the anthropic pressure on the land might have enhanced a trend towards intensive polyculture, with multiple crops being alternated in the same plots, allowing an increase in yield per unit of area but also requiring large inputs of manure and labour to balance the lack of fallow. The new model, for which extensive ethnographic literature exists in the regional context (Lefebvre, 1933; Caro-Baroja, 1944; Douglass, 1975; Greenwood, 1976), predominated until the first half of the 20th century, as evidenced by photographs taken in Aizarna during the early 20th century (Fig. 7e).

4.4. Phase 4. Industrialisation: agricultural extension and abandonment

The 20th century was defined by a radical transformation in agricultural management practices in this area. The uppermost horizons of both core records (Unit 6 in Core AIZ/2 and Unit 4 in Core AKU/2) show a concurrent increase in the concentration of PC2, that is to say biogenic elements (P, Zn, Br, S, Pb). C/N ratio is also much higher at surface depth (0–5 cm), which may be explained by the high contribution of crop residue input on the surface of the present grasslands and the presence of less decomposed organic matter in surface soil (Puget & Lal, 2005; Lou *et al.*, 2012; Yamashita *et al.*, 2016) and modern intensive manuring (e.g. Nicholson *et al.*, 1999; Zhang *et al.*, 2012). In fact, oral sources inform about a trend towards increasingly intensive manuring within the last few decades (Fig. 7f).

Instead, the concentration of Ca decreases to background levels that can be observed in the basal, unaltered siliciclastic parental sediments. These changes might indicate a decline of the preceding model based on intensive polyculture and individual household estates, with 'traditional' practices such as manuring or liming agricultural fields, being replaced by liquid slurry applications to meadows (Fig. 7), and the introduction of industrial fertilisers, such as phosphates (Rodríguez-Martín, et al., 2006; Huang & Jin, 2008; Atafar et al., 2010).

The pollen sample at 5 cm depth corresponds to Unit 6 (current grassland). Here, the preserved palynological assemblage records pine pollen grains as dominant taxa for the first time in the sequence. This change in the palynological content could be related with the introduction and spreading of allochthonous pine plantations, documented in the 18th to 20th centuries in the neighbouring mountain areas (Michel & Gil, 2013). These plantations replaced the autochthonous atlantic forests, which however probably persist in small areas following the data recorded in the pollen content (presence of deciduous *Quercus* and *Castanea*: Table IV in Supplementary Information). A patched varied landscape is also deduced by the still presence of grasses, legumes, ruderals and, also for the first time in the sequence, abundant Cerealia-type (including *Secale cereale* and *Avena*). Moreover, the presence of spores from the coprophilous *Sordaria* fungi suggests the presence of animal dung as a result of manuring of the arable fields.

In the Atlantic Basque Country, this was a period of industrialisation and sharp demographic growth (Hernández-Marco & Piquero Zarauz, 1988), leading to a boom in demand for perishable agrarian products, such as vegetables and milk, in the urban markets of the region. In a context where a considerable part of the rural population was switching to industrial occupations, a shift towards mechanisation and commercialisation of the agricultural production was strongly encouraged by local and national government. A ‘Model Farm’ was created and funded by the provincial government with the scope of developing agronomic research and promoting mechanised arable and dairy farming among the peasants of the region. From the beginning of the 20th century, this farm provided chemical fertilisers at cost price, while a number of prizes were awarded to those who applied the latest technical improvements in their holdings (MAH/1).

The consequence was an increasing specialisation of the agricultural estates throughout the 20th century, with a dramatic impact on the spatial layout of these villages. A comparison between aerial images from 1956-1957 and present-day orthophotographs shows a general abandonment of subsistence agriculture during the second half of the 20th century, and the conversion of former cereal fields into grasslands for livestock feeding (Fig. 7). In turn, the old mountain pastures were generally displaced by the widespread introduction of pine plantations, which became, by the mid-20th century, an essential economic resource for these communities (Michel & Gil, 2013). Local informants reported that all of these changes were already completed by the 1960s–1970s, in keeping with ethnographic observations in other nearby contexts (Douglass, 1975; Greenwood, 1976).

The crisis of the peasantry as a defining class in European societies, and its replacement by a market-oriented model of agricultural production, has been widely discussed in recent decades (Mendras, 1967; González de Molina & Guzmán, 2006; Van der Ploeg, 2012). Such trends involved a disruption in the forms of land management that had characterised the previous centuries, setting agricultural production under the influence of international market fluxes that were external to the rural communities themselves. The recent liberalisation of the milk market, promoted by the EU’s Common Agricultural Policy has aggravated the abandonment of many agrarian landholdings across Europe (Corselli-Nordblad & Martins, 2011). This trend has been so marked in Aizarna and Akoa, that agricultural activity is now marginal to local economic structures and many local people openly express concern about the future sustainability of their agricultural landscapes.

5. Conclusions

For the first time in this geographic area, the multidisciplinary research methodology applied in this study has allowed to decipher the origin and evolution of the rural landscape, at a local scale, in two rural communities of the Atlantic Basque Country. Although the precision of the information recorded was naturally higher for the most recent periods — partly due to the availability of documentary, toponymic and ethnographic sources with which the geoarchaeological records could be confronted — the results obtained show the usefulness of implementing research programs founded on the long-term decryption of agroecological adjustment. In this sense, the exhaustive physiochemical characterisation of soil records was decisive in observing continuities and changes in the forms of agricultural management, mainly represented by two types of evidence: 1) human-induced ground alterations such as channels and backfill terrace-construction; and 2) changes in the soil properties due to specific management practices, such as clearance, manuring and liming.

In the contexts studied, the oldest records obtained show the presence of non-agricultural human activities dating back to the Roman period. This initial phase encompasses the existence of forested and habitational areas, although the lack of systematic archaeological records complicates the interpretation of such evidence. On this basis, certain indicators of agricultural landscape-transformation can be divided into four main phases (Fig. 9). 1) The onset of agricultural activity in these contexts is characterised by clearance and terracing of previously forested areas in the 5th–7th centuries. 2) In the Late Middle Ages (14th–16th centuries), a major change was detected in forms of agricultural management, new terraces being (re)constructed close to the dispersed farmhouses associated with integrated productive resources (gardens, cereal plots, orchards, etc.) which still occupy these areas today. This period can be defined as marking the birth of the modern rural landscape. 3) During the Modern period (17th–20th centuries), a new model of intensive polyculture was established as a consequence of the introduction of new crops of American origin. The development of new forms of agricultural management induced a radical change in the physiognomy of the rural landscapes, with a great demographic and socio-economic impact. 4) Finally, the 20th century involved a process of mechanisation and commercialisation of the agricultural production, replacing the "traditional" practices from the previous phases with a specialised market-oriented model aimed at satisfying the demands of the growing urban population resulting from the industrial revolution.

<<< INSERT FIGURE 8 >>>

In short, the results of this work reveal that transdisciplinary research can be of great interest for an integrated understanding of the history of rural landscapes in the long term, with relevant ecological and socio-economic implications. This kind of approach requires conducting highly intensive local interventions, in order to take in the many actors intervening in such processes. In the future, similar research projects currently ongoing in other locations in the Atlantic area of northern Spain will assuredly make it possible to extend the significance of the results obtained from a local to a more regional scale, thus helping to include agrarian activity and its impact in our understanding of the historical development of human societies.

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Figure 1. (a) Location of the study area. Data source: *Eurostat*, *GeoEuskadi*. (b) General view of the village of Aizarna. (c) General view of the hamlet of Akoa. Photo: ©*Paisajes Españoles*. (d) Aerial view of the study area and the locations of core sampling. Data source: *GeoEuskadi*.

Figure 2. High-resolution core and close-up photographs of the studied core records. Core AIZ/2 (up): a) Organic surface horizon (Unit 6b); b) Inclusions of lime (Unit 5); c) Inclusions of rubified clay (Unit 2); d) Bioturbations caused by tree-roots (Unit 1a/b). Core AKU/2 (down): e) Organic surface horizon (Unit 4b); f) Inclusions of lime and pottery (Unit 3); g) Buried palaeosol (Unit 1b); h) Bioturbated basal fluviokarstic sediments (Unit 1a). Main sampling points are also pointed with different symbols.

Figure 3. Summary of geochemical XRF-CS, C_t, N_t and geophysical MS analyses of the studied cores. a) AIZ/2 core analysis and inferred stratigraphy. b) AKU/2 core analysis and inferred stratigraphy. Horizontal red bars refer to MS on a mass-specific basis (*Kappa*, cm^3kg^1). The MS profiles are expressed by volume (S.I.)

Figure 4. Factor loadings of the analysed elements on the principal components obtained by PCA analysis. High and moderate loadings are marked in bold.

Figure 5. Thermomagnetic curves of representative samples from the studied cores: a) Core AIZ2, Unit 1a sediment sample. The curve jump around 300ºC (dashed interval) indicates that sediments did not reach this temperature before. b) Core AIZ2, Unit 2 sediment sample. The absence of curve jump around 300ºC indicates that sediments reached this temperature in the past.

Figure 6. Summary of the obtained factor scores for the obtained PCs indicating the most relevant chemical elements (down) and processes (up) that controlled the geochemical

variations through time in the studied cores. Note that even being some kilometres away, both cores show similar geochemical variations through time (depth).

Figure 7. a) General view of Aizarna and Akoa in 1956-1957: traditional polyculture. b) Present-day general view of Aizarna and Akoa: grasslands. Data source: *GeoEuskadi*. c) Aizarna completely covered in maize fields, 1914. Photo: Indalecio Ojanguren (GAG/1). d) Preparation of ferns for manufacture of manure in Aizarna, first half of the 20th century. Photo: Indalecio Ojanguren (GAG/2). e) Spreading lime on a field, 2005. Photo: Asier Olazabal-Uzkudun. f) Mechanised slurry spreading in Aizarna, 2005. Photo: Asier Olazabal-Uzkudun.

Figure 8. Summary of the main changes in agricultural practice observed in Aizarna and Akoa. Demographic evolution of the municipality of Zestoa (squares) and the Gipuzkoa province (dots) is included for reference.

Highlights

- Farming is a key element of human ecology and landscape modelling in the long term.
- Physicochemical proxies show dynamic rural societies with flexible farming strategies.
- Agricultural practice is defined by biogeographic, social and economic constraints.
- Rural landscapes are currently facing degradation caused by deep Modern changes.
- The paper studies long-term landscape dynamics in a case study from the Basque Country.

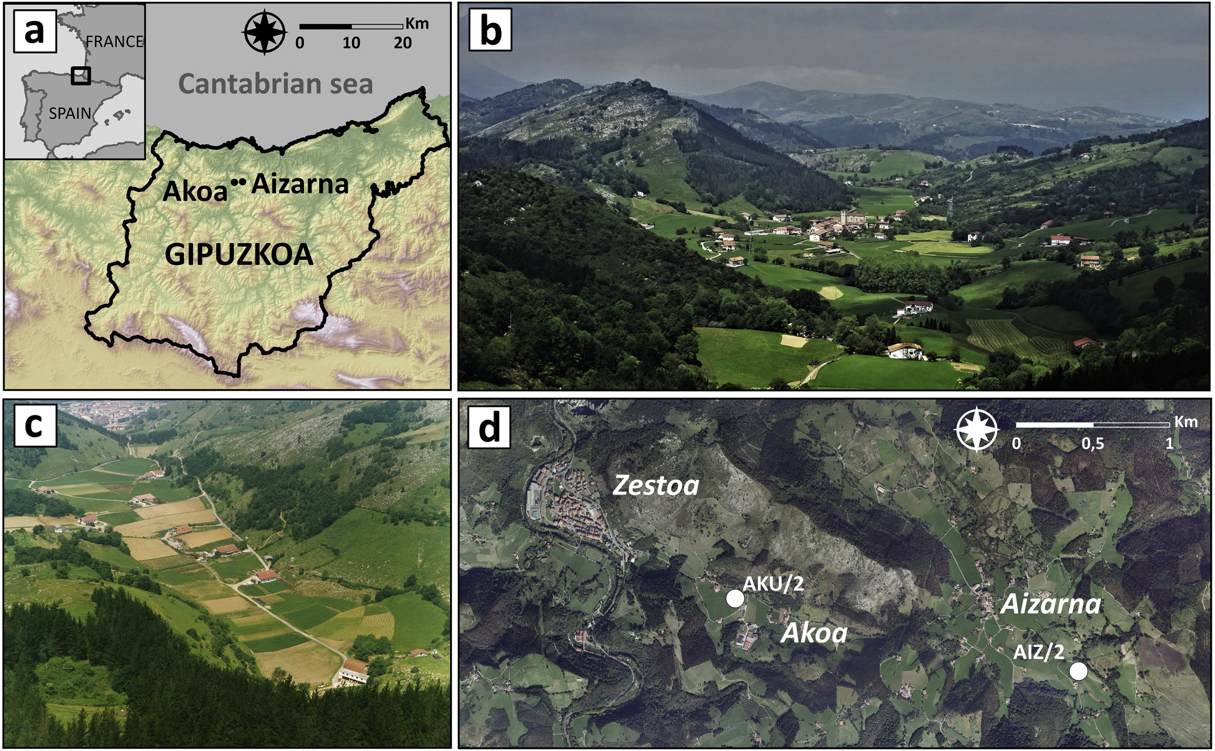

a
FRANCE
SPAIN
Km
0
10
20
Cantabrian sea
Akoa
Aizarna
GIPUZKOA
b
c
d
Km
0
0,5
1
Zestoa
AKU/2
Akoa
Aizarna
AIZ/2

Figure 1

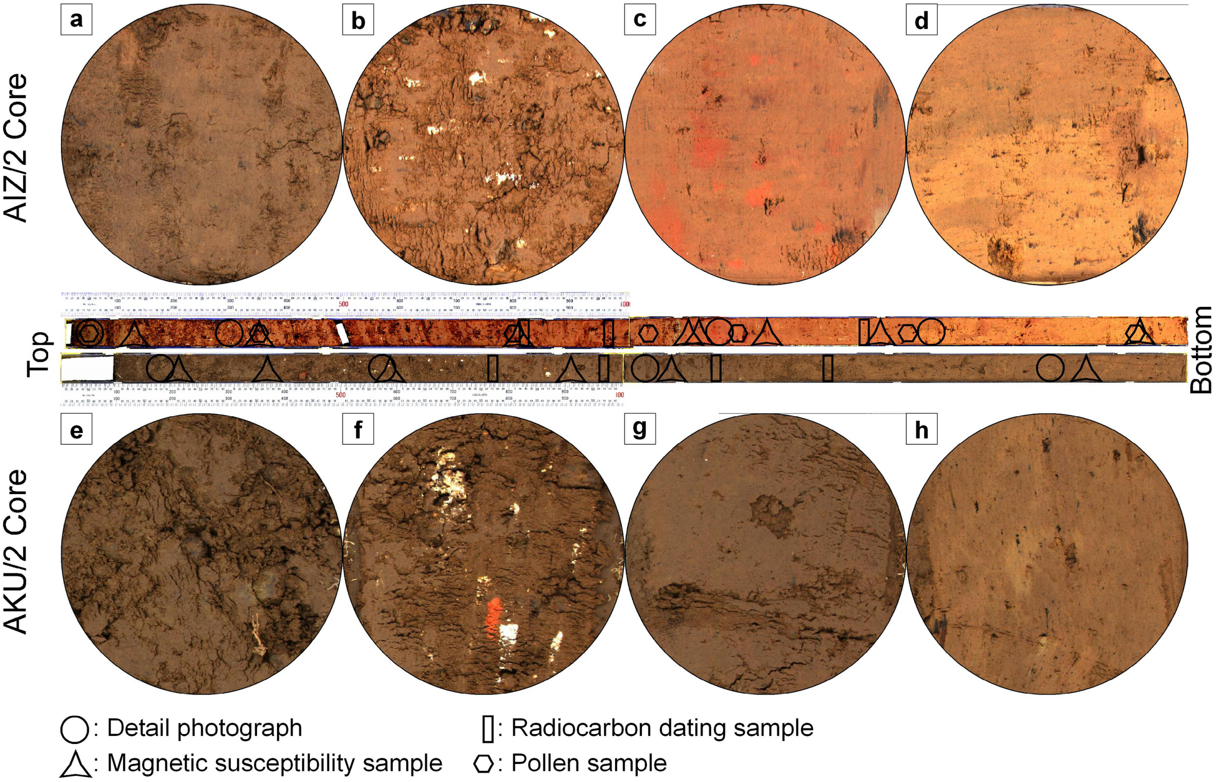

AIZ/2 Core
a
b
c
d
Top
Bottom
e
f
g
h
AKU/2 Core
○: Detail photograph
△: Magnetic susceptibility sample
▯: Radiocarbon dating sample
⬡: Pollen sample

Figure 2

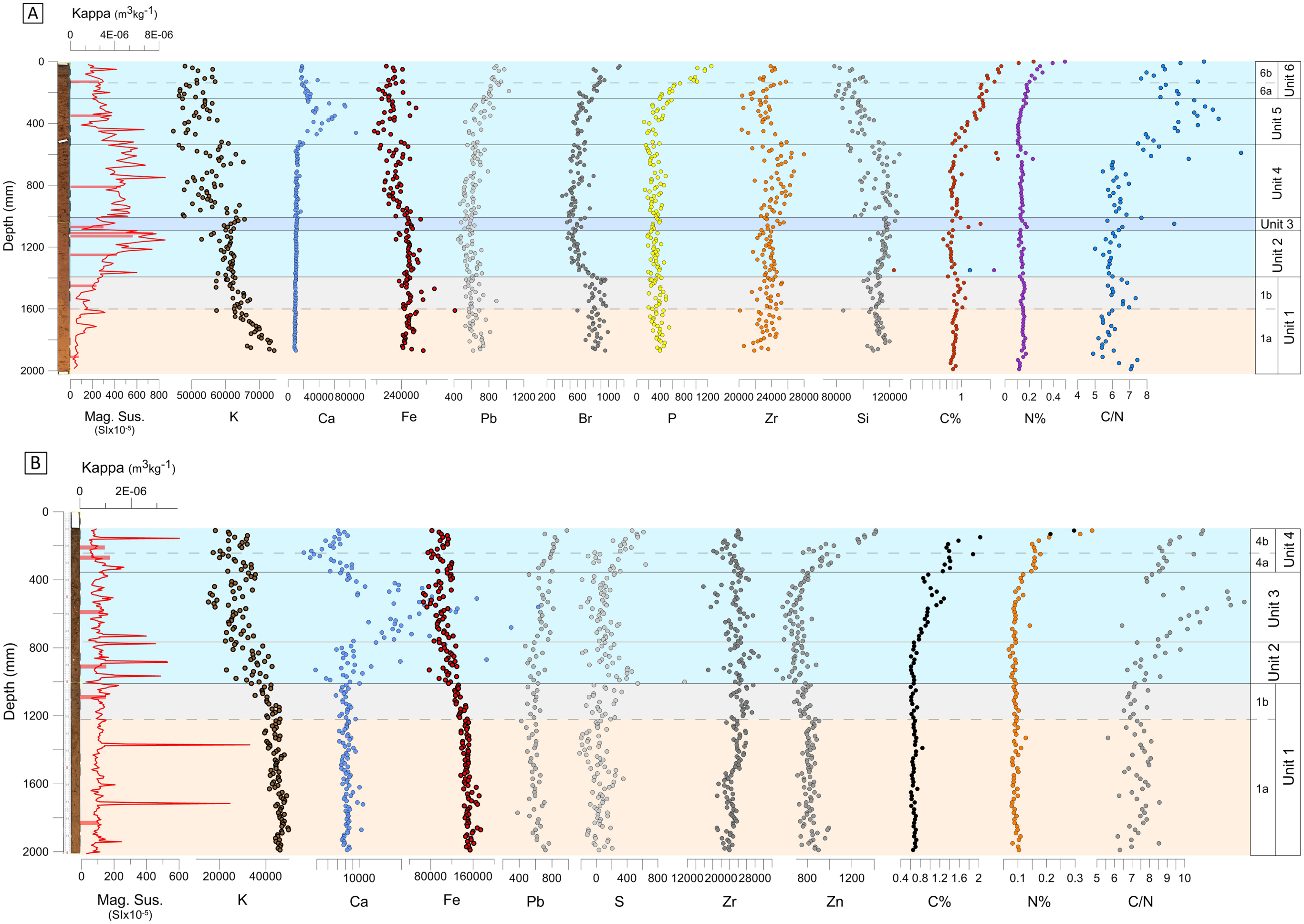
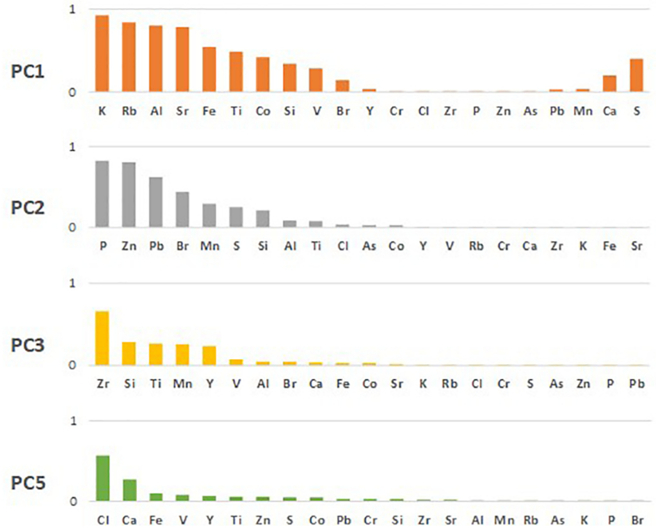

A
Kappa (m3kg-1)
0
4E-06
8E-06
Depth (mm)
0
400
800
1200
1600
2000
Mag. Sus. (SIx10-5)
K
Ca
Fe
Pb
Br
P
Zr
Si
C%
N%
C/N
6b
6a
Unit 6
Unit 5
Unit 4
Unit 3
Unit 2
1b
1a
Unit 1
B
Kappa (m3kg-1)
0
2E-06
Depth (mm)
Mag. Sus. (SIx10-5)
K
Ca
Fe
Pb
S
Zr
Zn
C%
N%
C/N
4b
4a
Unit 4
Unit 3
Unit 2
1b
1a
Unit 1

Figure 3

AIZ/2

	PC1	PC2	PC3	PC4	PC5	PC6
K	**0,96049069**	-0,0503314	0,10806128	-0,0383746	0,05938662	-0,008851
Rb	**0,91453825**	0,08139396	-0,0902306	-0,1448543	-0,0692756	-0,2448341
Al	**0,8936503**	-0,3084786	0,22403584	-0,0098812	0,105346	0,01852865
Sr	**0,88283593**	-0,0105746	-0,1289667	-0,1307619	-0,1341019	-0,2516602
Fe	**0,74055821**	0,02215743	-0,1645489	0,23843831	0,31221641	0,33246582
Ti	**0,70167855**	-0,2834565	0,51545436	0,10944446	0,2492879	0,12572082
Co	**0,64562957**	0,16974907	-0,1537038	0,3388356	0,22628336	0,27314935
Si	**0,58606638**	-0,4612354	**0,53421748**	0,11099048	0,16723431	0,0727436
V	**0,54011458**	-0,1275268	0,27731608	0,16483581	0,2919409	0,21957089
Br	0,38060715	**0,66214543**	-0,219207	-0,2612887	-0,0188912	-0,2269327
Y	0,1956985	0,13224738	**0,485215**	**0,49153536**	-0,2586601	-0,2668433
Cr	0,02531103	-0,0807559	-0,0788778	-0,0214787	-0,1712991	**0,80641933**
Cl	0,00772559	-0,2122028	0,08594354	0,00341491	**0,75348596**	-0,0855059
Zr	-0,0070997	-0,0598276	**0,81669097**	0,06556865	0,13429236	-0,127413
P	-0,0758895	**0,90735345**	0,02098952	0,14046917	-0,0501592	-0,0288578
Zn	-0,0995418	**0,89951207**	-0,0633415	0,00198505	-0,2391691	-0,0700464
As	-0,0995593	-0,1794643	0,07173898	**0,8879396**	0,06814243	0,02484424
Pb	-0,1883278	**0,79133247**	-0,0139907	-0,3299993	-0,1815403	0,07067233
Mn	-0,1943692	**0,54640787**	**0,50733551**	-0,1111876	0,08513288	0,33016844
Ca	**-0,4533328**	0,07298324	-0,1916026	-0,043405	**-0,5274961**	0,22664997
S	**-0,633913**	**0,50641338**	-0,0757388	0,1074811	0,22634914	-0,1341772



AKU/2

	PC1	PC2	PC3	PC4	PC5	PC6
K	**0,98488299**	-0,0301357	0,06157853	0,0278108	0,00341497	0,04451745
Fe	**0,98018752**	0,05443669	0,00620436	-0,011329	-0,0361375	-0,0027656
Al	**0,97274983**	-0,1053469	0,04317166	0,03360954	0,0268502	0,03477399
Ti	**0,9458425**	-0,0331002	0,18816551	0,09805032	0,0447717	0,1066134
Rb	**0,93827805**	0,14141846	0,04252641	-0,1356852	-0,0702277	-0,0351287
Si	**0,90207654**	-0,1525855	0,25018756	0,10396791	0,07451758	0,10201859
Sr	**0,81600399**	0,18231194	0,19201479	-0,3887393	-0,0237529	-0,0259178
V	**0,81252568**	0,01938696	0,19757627	0,1353048	-0,0019077	0,14316399
P	**0,71105739**	0,27622436	-0,0385948	0,35497422	-0,1319724	-0,0812848
Mn	**0,64777754**	0,13707036	0,10565654	0,00478951	0,59221027	-0,1423051
As	**0,60670356**	-0,1893622	-0,1370716	-0,1973247	-0,2122685	0,17341904
Y	0,31429922	0,23511133	**0,80567578**	-0,0775108	-0,0367394	-0,0072022
Ni	0,11963819	**0,46459922**	-0,3097688	-0,0392479	0,16438701	**0,58891712**
Zr	0,11584856	0,01142414	**0,8969872**	0,01428651	0,10142546	0,12066361
Cr	0,08128746	-0,0475925	0,19126308	0,10293096	-0,0212993	**0,70076311**
Zn	0,07951019	**0,82497638**	-0,0851317	0,27337425	-0,1472732	-0,0014378
Pb	0,0647991	**0,72876823**	0,18801261	0,20670681	0,39378226	-0,2479664
Cu	0,03817775	**0,65043513**	0,03615161	-0,0275777	0,02708719	**0,40153134**
Cl	-0,1485871	-0,1154715	0,01142484	0,01522206	**0,81414063**	0,09236634
Br	-0,1723292	**0,60603361**	0,24591999	-0,0341147	-0,1677737	-0,020197
S	-0,2993236	0,1439185	-0,1021558	**0,69908373**	0,22373336	0,06467596
Ca	-0,3211475	-0,1280761	-0,0596832	**-0,6770347**	0,13447951	-0,0590455

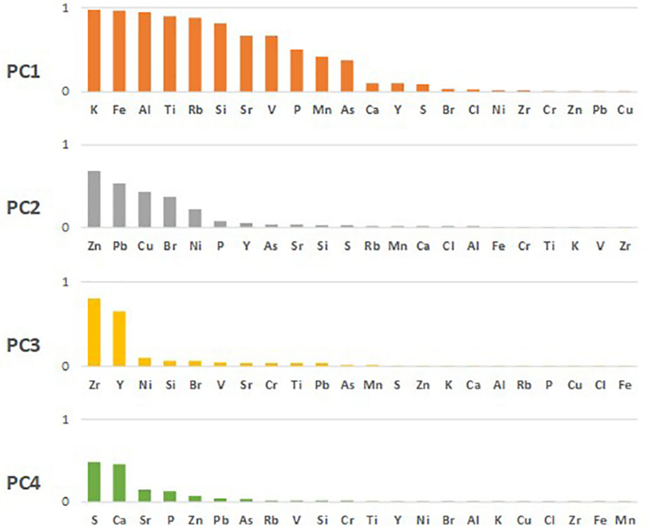


Figure 4

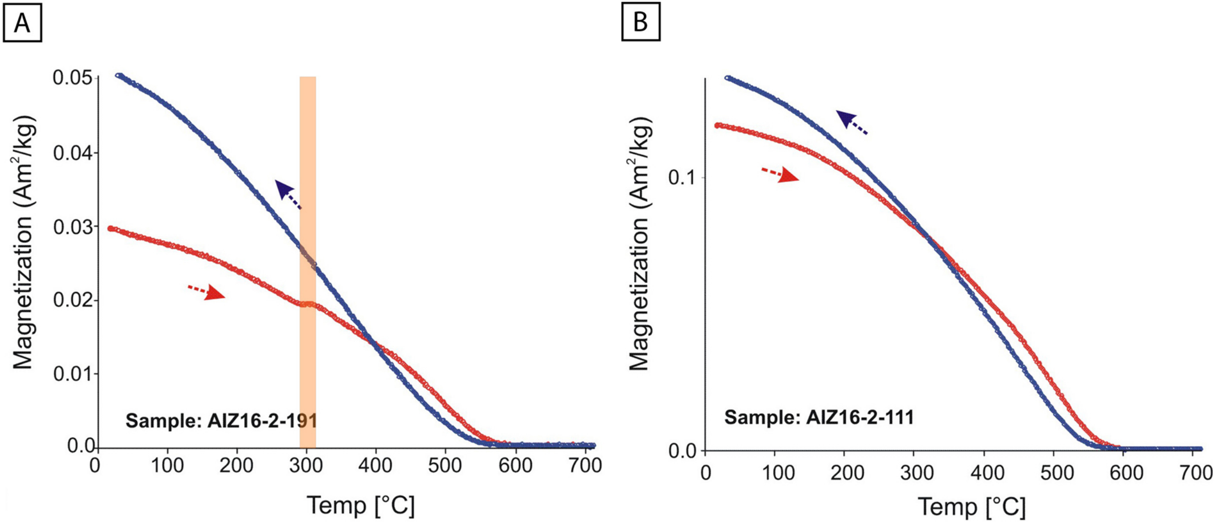

A
0.05
0.04
0.03
0.02
0.01
0.0
Magnetization (Am²/kg)
0
100
200
300
400
500
600
700
Temp [°C]
Sample: AIZ16-2-191
B
0.1
0.0
Magnetization (Am²/kg)
0
100
200
300
400
500
600
700
Temp [°C]
Sample: AIZ16-2-111

Figure 5

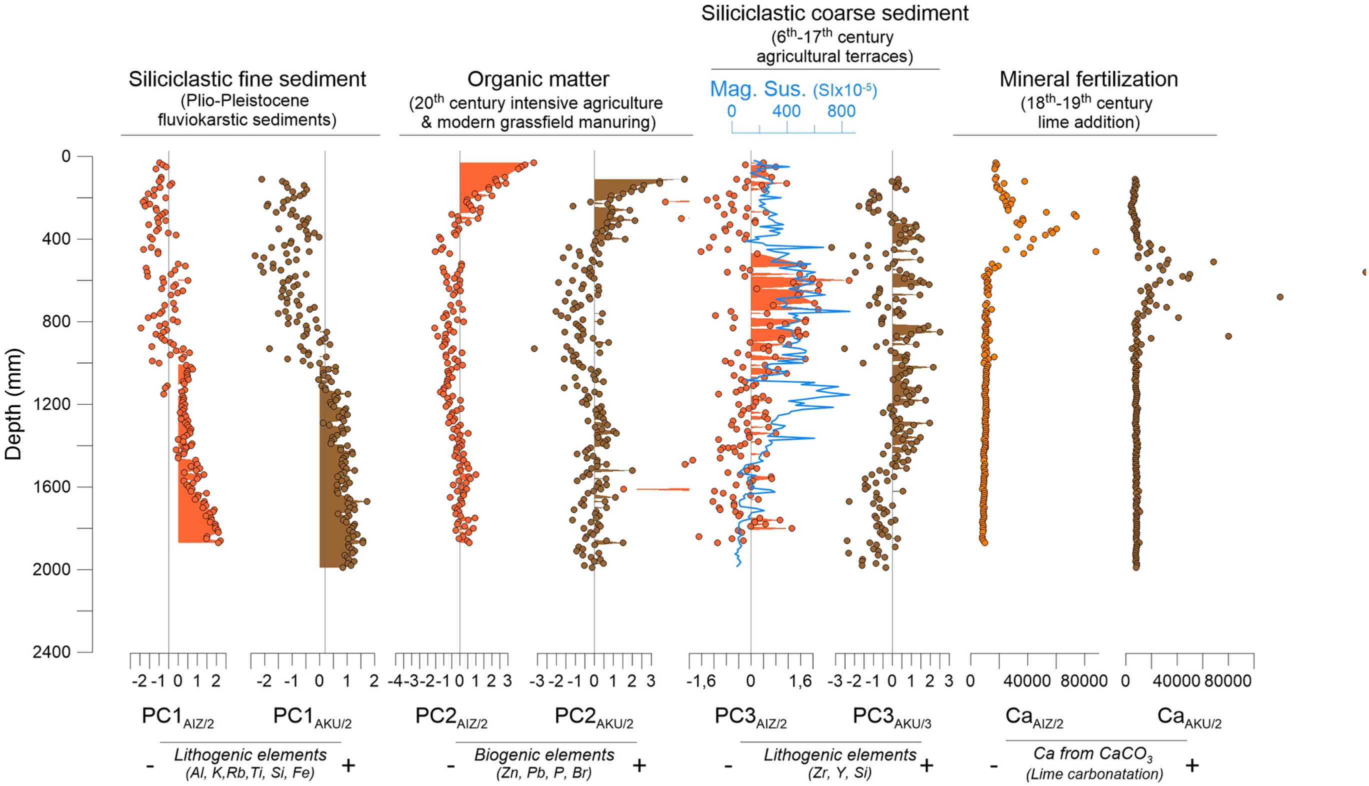

Siliciclastic fine sediment
(Plio-Pleistocene fluviokarstic sediments)
Organic matter
(20th century intensive agriculture & modern grassfield manuring)
Siliciclastic coarse sediment
(6th-17th century agricultural terraces)
Mag. Sus. (SIx10-5)
0
400
800
Mineral fertilization
(18th-19th century lime addition)
Depth (mm)
0
400
800
1200
1600
2000
2400
-2 -1 0 1 2
-2 -1 0 1 2
-4 -3 -2 -1 0 1 2 3
-3 -2 -1 0 1 2 3
-1,6 0 1,6
-3 -2 -1 0 1 2 3
0 40000 80000
0 40000 80000
PC1 AIZ/2
PC1 AKU/2
PC2 AIZ/2
PC2 AKU/2
PC3 AIZ/2
PC3 AKU/3
Ca AIZ/2
Ca AKU/2
- Lithogenic elements (Al, K, Rb, Ti, Si, Fe) +
- Biogenic elements (Zn, Pb, P, Br) +
- Lithogenic elements (Zr, Y, Si) +
- Ca from CaCO3 (Lime carbonatation) +

Figure 6

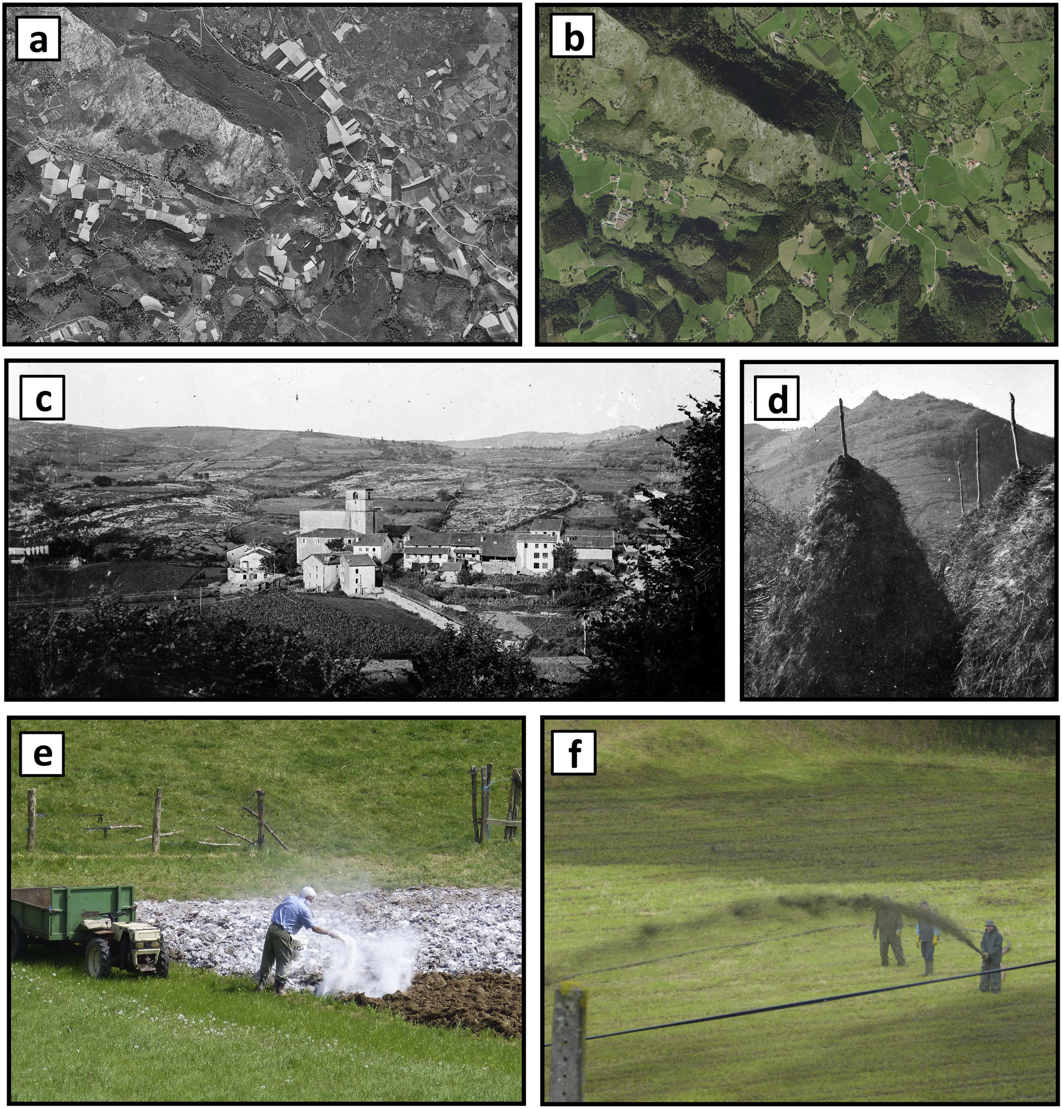


Figure 7

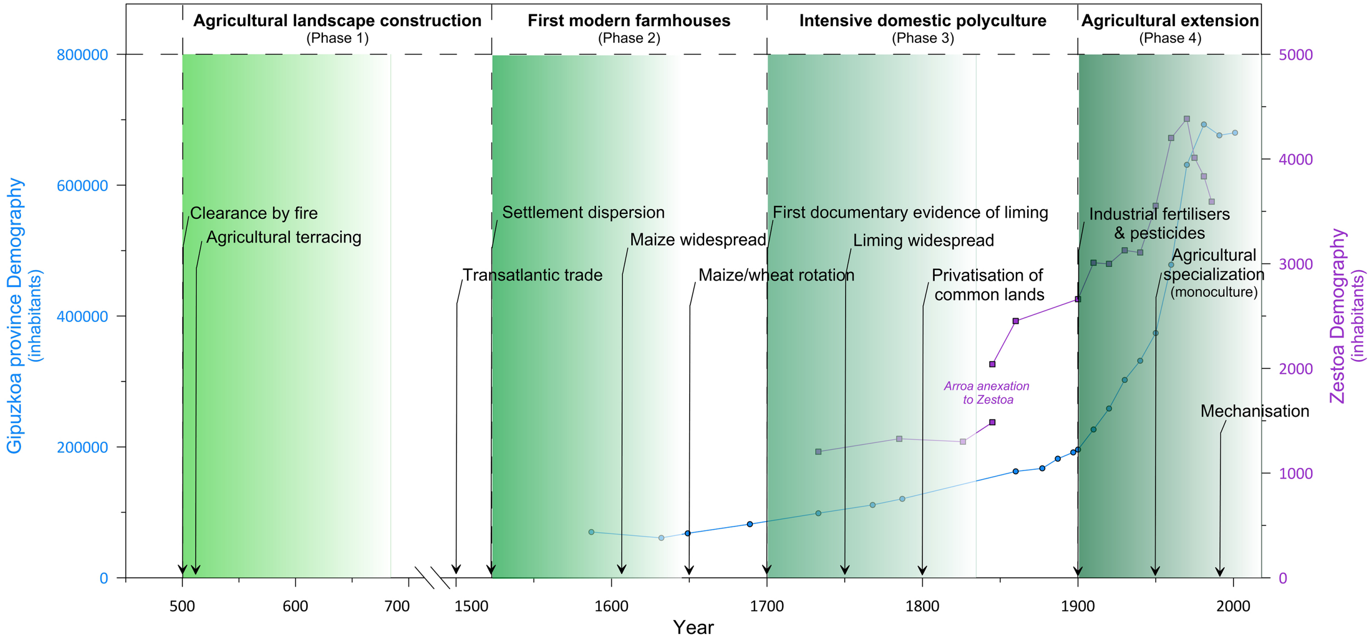

Agricultural landscape construction
(Phase 1)
First modern farmhouses
(Phase 2)
Intensive domestic polyculture
(Phase 3)
Agricultural extension
(Phase 4)
Gipuzkoa province Demography
(inhabitants)
Zestoa Demography
(inhabitants)
800000
600000
400000
200000
0
5000
4000
3000
2000
1000
0
Clearance by fire
Agricultural terracing
Transatlantic trade
Settlement dispersion
Maize widespread
Maize/wheat rotation
First documentary evidence of liming
Liming widespread
Privatisation of common lands
Industrial fertilisers & pesticides
Agricultural specialization
(monoculture)
Mechanisation
Arroa anexation to Zestoa
500
600
700
1500
1600
1700
1800
1900
2000
Year

Figure 8