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Basque Cultural Landscapes of the Western French Pyrenees

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Abstract

Results are presented on the co-evolution of agropastoralism and soils in the western Pyrenees Mountains (>800 masl) over the course of the Holocene conducted in the ethnically Basque commune of Larrau, France. Larrau presents a unique opportunity to examine the structural legacies and biotic factor in soil evolution across millennia. Multi-proxy evidence from geoarchives, archaeology, history and ethnography is analyzed to evaluate the relation between land management practices, soil characteristics and chronostratigraphy in the study

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area. Research indicates that the landscape of Larrau has been subject to intense human transformation through agropastoral use since at least the early Bronze age, yet there are no signs of significant degradation of the soil mantle. The place-based approach followed in this research provides the means for evaluating modal human behaviors and decision-making within a complex adaptive system. It details how the present is connected to the past and how contemporary land systems can contribute to a sustainable future.

Nel corso della ricerca effettuata nel comune etnicamente basco di Larrau (Francia) abbiamo indagato tracce multi-proxy per esaminare le forme di domesticazione dei paesaggi montani (> 800 m slm) dei Pirenei occidentali, nel corso dell'Olocene. I nostri dati suggeriscono che in quest'area le foreste originarie sono state trasformate in pascoli diverse migliaia di anni fa, senza che questo abbia comportato un degrado significativo del paesaggio e dei suoli. Il patrimonio dei paesaggi agropastorali di Larrau offre una rara opportunità per esaminare un doppio sistema in lento cambiamento, nel quale, attraverso millenni, le attività di gestione umana hanno strutturato un paesaggio scenografico, creando un sistema di produzione agropastorale resiliente e durevole, e hanno reindirizzato i sottostanti percorsi e meccanismi di pedogenesi. Se i sistemi terrestri contemporanei mirano a raggiungere un desiderabile futuro sostenibile, la situazione attuale deve essere continuamente e fortemente collegata al suo passato.

Introduction

The prime-mover explanations once favored for the expansion of domestication in Europe[1] are yielding to evidence that the Neolithic transition involved elements of demic diffusion, local adoption, and independent domestication[2]. The change in viewpoint stems from new methods for determining plant and animal domestication, systematic examination of high-resolution post-depositional environments, and extensive use of chronometric dating[3]. Such research was initially concentrated in highly evolved, low-gradient riverine environments[4], but the procedures are increasingly used in high-gradient mountain settings including the Pyrenees[5]. At the human scale, agropastoralism subsumes numerous activities that in combination contribute to shaping mountain landscapes over time. Interpreting the human capacity to transform earth processes over the Holocene by reference to a single activity such as grazing using a single fossil archive such as pollen can lead to simplistic

1 Ammerman, Cavalli-Sforza 1984; Dearing 2008.
2 Crubézy et al. 2006; Rowley-Conwy 2011; Zeder 2008.
3 Berger 2011; Dotterweich 2008; Galop et al. 2013; Rowley-Conwy 2011; van Mourik, Jansen 2013; Zeder 2008.
4 Berger 2011; Dotterweich 2008; Hoffmann *et al.* 2008; Holliday 1985.
5 Cunill *et al.* 2012; Ejarque *et al.* 2010; Kaal *et al.* 2008.

and deterministic accounts that are no different than earlier prime-mover explanations[6].

Agropastoralism is the primary means by which humans modified European mountain landscapes over the course of the Holocene[7], but the geomorphic, topographic, climatic and vegetative heterogeneity of these landscapes means that results obtained in one region may not be valid for interpreting mountain landscapes elsewhere[8]. More importantly, land degradation may not be the inevitable consequence of agropastoral practices. Whether such practices set in motion a degradation cycle can only be evaluated by ensuring the resolution of proxy indicators matches the human scale of land use activities[9]. The scale most suitable for analyzing human-environment interactions, particularly in mountain areas, is the local[10]. Accumulating evidence furthermore indicates that human land use over the Holocene in mountain landscapes was largely decoupled from climatic/temperature gradients[11]. Therefore adding additional weight to the need for avoiding simplistic and deterministic physical explanations of human land use in mountain settings[12].

Numerous studies confirm that mountain landscapes are the result of climatic and anthropic pressures exerted and interrelated in a variable manner over the course of the Holocene[13]. Examining the dynamics of this long-time series is key to identifying the existence of thresholds, alternative steady states, adaptation, contingency, and feedback in the anthropization of European mountain landscapes. It is equally important to explaining their contemporary biodiversity, landscape fragmentation, and habitat fragility[14]. Not only is environmental history relevant to an understanding of the past, it may be equally important to the future protection, management and promotion of the natural and cultural heritage of mountain landscapes.

In light of these observations, we are examining the co-evolution of agropastoralism and soils in the ethnically Basque commune of Larrau (Départment de Pyrénées Atlantiques, France) using multi-proxy evidence from geoarchives, archaeology, history and ethnography. While it complements previous work in the western Pyrenees[15] on the agropastoral transformation of mid-elevation (800-2000 masl) mountain landscapes, our approach is place-based and premised on the idea that factors of change cannot be separated from

6 Cunill *et al.* 2013; Ejarque *et al.* 2011; Moe *et al.* 2007.
7 Bal *et al.* 2015; Cunill *et al.* 2013; Ejarque *et al.* 2011; Moe *et al.* 2007.
8 Ejarque *et al.* 2011; Mazier *et al.* 2009; Brun 2011.
9 McGovern *et al.* 2007; Sandweiss, Kelley 2012.
10 Davis, Stevenson 2007; Dearing *et al.* 2010.
11 Cunill *et al.* 2013; Ejarque *et al.* 2011; Ejarque *et al.* 2010.
12 Cunill *et al.* 2013; Ejarque *et al.* 2011; Ejarque *et al.* 2010.
13 Bal *et al.* 2011; Ejarque *et al.* 2010; Pelachs *et al.* 2011; Vannière *et al.* 2001.
14 Bal *et al.* 2015.
15 Galop 2006; Mazier *et al.* 2009.

factors of location, duration and intensity[16]. Cultural landscapes such as those in Larrau provide a rare opportunity to examine the origin of structural legacies and isolate the biotic factor in soil evolution over the course of the Holocene[17].

Our results are organized to address 1) cultural management practices linked to soil fertility; 2) persistent conversion of forests to pastures leading to distinct chemical and physical soil profiles; and, 3) chronostratigraphy of small watersheds in relation to land clearing, pasture maintenance and reforestation across time. The conjunction of structural (long-cycle) and signal (short-cycle) processes in Larrau links the past to the present and provides the basis for evaluating modal human behaviors that transform earth processes. It also makes it possible to examine the response diversity of human decision-making about desired environmental end-states within a complex adaptive system[18]. As such, it clarifies how the present must be continuously and strongly connected to its past if contemporary land systems are to achieve a desirable and sustainable future.

Background

Methodological, theoretical and conceptual advances are leading to a reassessment of the relation between human land use and pedogenesis. Soils are complex open process-response systems that are continually adjusting by various degrees, scales and rates to changing external and internal forces – all soils have a polygenic origin[19]. Human agropastoral land use, however, has often been examined as disrupting the 'natural equilibrium' of the soil system by accelerating erosion and degrading soil potential, ultimately leading to the extinction of the society dependent on the soil[20]. While agropastoral landscapes are constantly evolving over time and across geographical scales in response to both physical forces as well as human activities, notorious cases such as Easter Island[21] are not proof of the inevitable collapse of all human land systems. There have been numerous expansions and regressions of agricultural activity in Europe over the course of the Holocene[22], and the path from onset to the present is far from linear or deterministic.

From an evolutionary standpoint, the mere endurance of Basque agropastoralism across millennia hints at the existence of positive, not only

16 Russell 1998.
17 Bain *et al.* 2012; Yaalon 1975; Jenny 1958.
18 Antrop 2005; Leslie, McCabe 2013; Valsecchi *et al.* 2010; Willis, Birks 2006.
19 Beckman 1984; Johnson, Watson-Stegner 1987.
20 Harris 2012; van Andel *et al.* 1990.
21 Dearing *et al.* 2010; Harris 2012.
22 Dotterweich 2013.

negative feedback mechanisms. Slow processes that unfold over decades or centuries such as the evolution of low-country Plaggen soil by manuring to increase nutrient supply and water retention[23] or the evolution of stem families to manage household labor and landesque (i.e., permanent landscape modifications through the construction of terraces, lynchets, headlands and field boundaries)[24] lie beyond the reach of observational and instrumental data. The challenge is to understand the options and constraints the world presents people, the choices people make, and how their choices alter the world[25]. In effect, there is a need to ground concepts in observations and analyses that are place-based, comparative, and long-duration[26].

Our research problem centers on how long-term Basque agropastoralism in the western north-facing Pyrenees redirects pedogenic pathways and products detectable over centennial to millennial timescales. This problem includes factors and processes that interact across geographic space and give rise to a variable soilscape that can be characterized in time yet preserves signatures from its transformation over time as illustrated in the conceptual framework for our research (fig. 1). Jenny's[27] factorial pedogenic model can explain the geographical variation of soils in Larrau, Alfisols (Typic Hapludalfs) under forest and mollic Alfisols (Mollic Hapludalfs) under pasture. However, our evidence and that of others in the Pyrenees[28] indicates that human forest-to-pasture conversion and manipulation of the organic factor over the Holocene represents human action distinct from the other factors within Jenny's model (e.g., climate, topography, parent material).

Beyond Jenny's factors, pedogenesis is also understood as a function of additions, removals, translocations and transformations of materials within soil horizons[29]. In Larrau, for example, pastured soil profiles lack an eluvial (E) horizon that many of the forested soils contain. There is thus evidence of both progressive (i.e., up-building of the pastured A horizon) versus regressive (i.e., obliterating original forest A, AB and B horizons) pathways in the soilscape, not merely changes within a soil horizon[30]. In Larrau, the build-up of organics and structural improvement in pastured soils exemplify a "progressive pathway" while the loss of forest-soil horizonation exemplifies a "regressive pathway". At the scale of a landscape, agropastoral land use involves specific activities restricted to particular types of sites, but examined at a moment in time. A resulting problem is disentangling whether certain vegetative species primarily

23 Chiti *et al.* 2009; Dercon *et al.* 2005; van Mourik *et al.* 2011.
24 Arrizabalaga 1997; Kirch 2007; Olsson *et al.* 2000; Sabean 1990.
25 Smith 2012.
26 Carpenter *et al.* 2009; Collins *et al.* 2011; Dearing *et al.* 2010.
27 Jenny 1941; Jenny 1958.
28 e.g., Ejarque *et al.* 2011.
29 Simonson 1959.
30 i.e., Johnson, Watson-Stegner 1987.

occur in areas because of their contemporary environmental conditions, because of the activities that humans carry out at these locations in the present, or because of the legacy of past human and non-human disturbances at these locations[31].

The agropastoral transformation of the north-facing, western Pyrenees remains poorly documented and has not been subject to the same level of research carried out in the south-facing western Pyrenees or the eastern Pyrenees, north- or south-facing[32] Few sites have been excavated, and even fewer have been published[33]. There has also been a tendency to focus on monumental remains (tumuli, stone circles)[34] so that little is known about the use of habitat or resources. Most of what is known about the anthropization and neolithization of the north-facing western Pyrenees is due to the research by Galop and his associates[35]. The composite Holocene history of the western Pyrenees that emerges from their research provides ample evidence that the "natural" vegetation of this region results from the coupling of edaphic conditions in response to climatic oscillations and human agropastoral activities (tab. 1).

The first pollen evidence for agro-pastoral activities in the Basque country dates to the Early Neolithic (7500-7200 cal yr BP)[36]. Since its occurrence at elevation predates its appearance in the Lourdes Basin (6800-6500 cal yr BP)[37] it has been inferred that domesticates arrived in the Basque country from the Mediterranean basin via the Ebro valley[38]. Grazing activities extend to the western Pyrenees during the Middle-to-Late Neolithic (6500-4300 cal yr BP)[39] simultaneous with increasing signs of agriculture and human occupation in the piedmont[40] and the south-facing slopes of the western Pyrenees[41]. Fire episodes are synchronous with the occurrence of Cerealia-type pollen suggesting large, but temporary impacts from burning[42].

Although Cerealia-type pollen increases ca. 4100 BP suggesting the growing importance of agriculture, clearings remain small as inferred from the low fire frequency during the Bronze Age (4300-2300 BP). Increased deforestation is inferred from an increase in API (Anthropogenic Pollen Indicators:

31 Dambrine *et al.* 2007; Dupouey *et al.* 2002; Foster, Aber 2004; Hooke 1985; Lemon 1974.
32 e.g., Bal *et al.* 2011; Bal *et al.* 2010; Cunill *et al.* 2012; Ejarque *et al.* 2011; Lopez Saez *et al.* 2008; Pérez-Díaz *et al.* 2015; Vannière *et al.* 2001.
33 Marticorena 2014.
34 Blot 2014.
35 Carozza *et al.* 2005; Cugny *et al.* 2010; Mazier *et al.* 2009; Monna *et al.* 2004.
36 Galop 2006.
37 Rielle, Andrieu 1995; Rius *et al.* 2012.
38 Berger, Guilaine 2009; Peña-Chocarro *et al.* 2005.
39 Galop 2006.
40 Rius *et al.* 2009.
41 Pérez-Díaz *et al.* 2015.
42 Rius *et al.* 2012.

Plantago, Artemisisa, Asteroideae, Brassicaceae, Centaurea, Chenopodiaceae, Cichoriodeae, Polygonum, Rubiaceae, Rumex, Trifolium, Urtica) ca. 3300 BP, although the use of several of these apophytes for determining human disturbance is increasingly questioned[43]. The absence of fire has been interpreted as the transition from an agro-sylvo pastoral system (e.g., slash-&-burn with forest fallows) to an agropastoral system[44] coincident with increased grazing activity above 500 m.

Regular and frequent fires characterize the Iron Age (2300-2000 cal yr BP). Along with the increased percentages of Poaceae-type pollen, an abrupt increase in API, and a decrease in arboreal pollen leads to the inference that grazing dominates during this period. There is also a rapid development of mining and smelting activities assumed to be associated with increased deforestation[45]. These trends continue into Antiquity (2000-1500 cal yr BP), with Roman and Basque mining activities expanding to include exploitation of iron, copper, silver further driving deforestation[46]. The low counts of arboreal pollen and high counts of API, Poacea-type, and nitrophilous taxa suggest relatively open vegetation dominated by herb communities with grasses. It has been suggested that fires are used as a "cleaning tool"[47] during this period.

API remain high and arboreal pollen low during the Middle Ages (1500-500 cal yr BP), with an abrupt drop off in beech (*Fagus*) after 700 BP. Fire occurrence is regular and high. There is diversification in crops with the addition of rye (*Secale*) between 1500-1300 cal yr BP[48], followed by expansion of cropping activity between 1300-1100 cal yr BP[49]. There is further intensification of agropastoral and mining activities between 1000-800 cal yr BP corresponding to the medieval population boom[50]. Land intensification have been inferred from the abrupt drop in arboreal pollen leading to the assumption that the area was extensively deforested between 1500-1000 BP, including the most sheltered north-facing slopes[51]. Similar patterns have been recorded in the eastern Pyrenees and elsewhere in Europe[52]. This was followed by a decrease in agro-pastoral activities during the Medieval Crisis (700-600 cal yr BP) associated with human demographic collapse[53].

Modern (500-0 cal yr BP) is characterized by progressive economic and demographic recovery, with an increase in fire occurrence (ca. 3.5+ fires/500

43 e.g., Ejarque *et al.* 2011.
44 Galop 2006.
45 Monna *et al.* 2004.
46 *Ibidem*; Rius *et al.* 2009.
47 Rius *et al.* 2009.
48 Galop 2000.
49 Rius *et al.* 2012.
50 i.e., Bonnassie 1989.
51 Cugny *et al.* 2010; Mazier *et al.* 2009; Monna *et al.* 2004; Rius *et al.* 2012.
52 Cunill *et al.* 2013; Valsecchi *et al.* 2010; Vanniere *et al.* 2011.
53 Berthe 1984.

yr). There is a noticeable slump in forest taxa used for charcoal production associated with the intense metalwork production in the 17-18th centuries[54] that collapses in the 19th century. Grazing pressure increases AD 1900-2000, but the increasing rural exodus of the 20th century leads to land abandonment and reforestation[55].

Socio-Ecological Dynamics in the Western Pyrenees

The commune of Larrau is part of Soule, the smallest of the seven Basque Provinces centered on the Saison River in the French department of Pyrénées-Atlantiques. The commune (a town and surrounding land with recognized political and economic authority) of Larrau abuts the Spanish border (fig. 2) and covers 12,680 ha. During the 1860s, there were over 100 households in Larrau engaged in agropastoralism and a population of ca.1600. Today, the commune has about 25 farming households and a population of ca. 200 residing either in the town of Larrau or one of six low-density neighborhoods (FR: *quartier*). Agropastoralism remains important economically as well as for reasons of identity.

Larrau residents self-identify as Souletin Basque and speak Souletin which is one of several dialects of Basque, a non-Indo-European language[56]. While multiple genetic sources point to the Basque as having locally differentiated within their present territory ca. 18,000 years ago[57], much of our understanding of the Basque and the valleys perpendicular to the axis of the Pyrenees Mountains as oligarchic republics[58], including the Soule, post-dates AD 1000. Cohesion in these republics was achieved by complementary and seasonal use of highland and lowland grazing areas by villages along the length of a valley. Market exchanges took place in a central valley town (i.e., Tardets in Soule), yet were tied to a macroregional exchange network that included piedmont towns north (e.g., Pau) and south (e.g., Pamplona) of the Pyrenees[59].

The climate is humid oceanic (i.e., Atlantic) on the north-facing Pyrenees where Larrau is located, with a long-term (AD 1956-2010) mean annual precipitation of ca. 1700 mm and a mean annual temperature ca. 13°C (range: 7-20°C). The area lies floristically within the Basque-Cantabrian district of the Cantabrian-Pyrenean sector[60], which is a transitional ecotone between the

54 Galop 2001.
55 Galop *et al.* 2011.
56 Gómez-Ibáñez 1975; Vyerin 2011.
57 Bauduer *et al.* 2005.
58 Cursent 1998; Gómez-Ibáñez 1975; Lefebvre 1963.
59 Lefèbvre 1933; Zink 1997.
60 Moreno Saiz *et al.* 2013.

Eurosiberian and the Mediterranean biogeographic regions[61]. Flora in Soule at present includes the Pyrenean oak (*Quercus pyrenaica*) dominates between 300-800 masl and is often associated with pedunculate (*Q. robur* L.) and sessil oak (*Q. sessiliflora*) traditionally pollarded to obtain firewood and animal bedding[62]. These species punctuate the intermediate zone used for rough grazing that is otherwise characterized by heath (*Erica vagans*, *E. ciliaris*, *E. cinerea*), gorse (*Ulex europaeus* and *U. minor* – both tend to diminish above 500 m), bracken (*Pteris aquilina*), ling (*Calluna vulgaris*), and broom (*Sarothamnus scoparius*).

Between 800-1100 masl, pedunculate oak gives way to beech (*Fagus silvatica*) often intermingled with fir (*Abies pectinata*) and chestnut (*Castanea sp.*) first introduced to the area ca. 2000 BP based on pollen and other records[63]. Through the middle of the 20th century, nuts from beech and chestnut were used as wild-forage for livestock and to produce flour for making flat cakes, while the wood was used to make diverse farm implements. Beech and fir disappear ca.1550 masl giving way to a "grazing-climax" of grasses that begin to appear ca. 1285 masl[64]. The most common species in this complex are bentgrass (*Agrostis spp.*), fescue (*Festuca spp.*), nard (*Nardus stricta*), and bluegrass (*Poa spp.*) intermingled with various sedges (Family Cyperaceas) and legumes (*e.g.*, *Trifolium alpinum*). No trees currently grow above ca. 1700 masl; the natural treeline, however, would be around 2200-2300 masl and ranged to ca. 2400 masl during portions of the Holocene[65].

Methods & Materials

In partnership with French colleagues we have carried out ethnographic, historic and most recently archaeological and geomorphic investigations detailing many aspects of agropastoralism in the upper Soul[66]. In parallel with these investigations we developed a database of fiscal land records for the commune from 1830 to the present that contains 1) parcel profiles (e.g., taxable use – plowed field, pasture, etc., taxable value produced by the use, and owner) linked to 2) an ESRI GeoDatabase with polygon and topology values for each parcel and the structural footprints of houses, barns, cabins, mills, canals, roads, etc. We have used Bayesian Weights of Evidence and

61 Nogués-Bravo, Martínez 2004.
62 Fenley 1951; Lefèbvre 1933.
63 Conedera *et al.* 2004; Huntley *et al.* 1989; Lindbladh *et al.* 2008; Pérez-Díaz *et al.* 2015.
64 Morellón *et al.* 2012; Ninot *et al.* 2007.
65 Cunill *et al.* 2012.
66 Coughlan 2013b; de Bortoli *et al.* 2004; Welch-Devine 2008.

Event History procedures[67] to assess parcel use and management by individual households, predict the location and occurrence of fire events given spatially explicit evidence layers, as well as the processes of parcel extensification and household abandonment[68].

We combined results with aerial photography, contour maps and a preliminary archaeological inventory to guide a systematic pedestrian survey of the commune in 2012, 2013 and 2014. We have so far located and fully described over 100 prehistoric/early historic sites[69]. The survey has allowed us to verify and validate ethnographic and archival evidence on parcel-level settlement in addition to locating historic and prehistoric places previously only recorded by *lieu-dit* (a small geographic area with a traditional name) and in several instances never recorded. Eleven sites were selected to carry out a ground penetrating radar survey, limited subsurface testing using a 10 cm diameter bucket auger and recover datable material to establish the correspondence between surface and buried features[70]. Two of these sites were excavated in 2014 by French colleagues[71].

During the survey we identified four hillslope sites where large pastures occur immediately adjacent to forests with similar bedrock, aspect, and morphology. We excavated five paired soil pits at each site (n=40 profiles) well into the B horizon and in several cases to the contact with bedrock. Genetic soil horizons were described and soil horizons were sampled according to their boundary lines[72]. Also during the survey we identified colluvial depositional sites on small flats, benches, toeslopes or depressions immediately beneath zero-order hollows located on pastured hillslopes with known histories draining <10 hectares. Sites were selected to maximize the likelihood of spatially uniform and temporally steady slopewash sedimentation. A 7.6 cm diameter bucket auger was used to retrieve a complete stratigraphic column of unconsolidated colluvial sediment in contiguous 10 cm sample increments that were bagged in the field for subsequent laboratory analyses[73].

Particle size analysis of all samples followed the hydrometer and sieve method[74] using a known volume of soil extracted from the uppermost 7.5 cm of each A horizon. Subsamples were dried, weighed, and weight fractions of gravel, sand, silt, and clay were quantified with respective size breaks at 2000, 63, and 2 µm. Hydrogen icon concentration (pH) of a 1:2 soil-water paste was measured with a Corning® pH meter 443i; plant-available nutrients were determined by the

67 Blossfeld *et al.* 2007; Link, Barker 2010.
68 Coughlan, Gragson n.d; Coughlan 2013a.
69 Champagne, Le Couédic 2012; Le Couédic, Champagne 2013; Champagne *et al.* 2015.
70 Gaffney, Gater 2003; Stein 1986; Thompson *et al.* 2011.
71 Champagne *et al.* 2015.
72 Soil Survey 1993.
73 Leigh *et al.* 2015a; Leigh *et al.* 2015b.
74 Gee, Bauder 1986.

double-acid technique; and dry bulk density was based on the weight of mineral topsoil excluding the O horizon[75]. Macro-charcoal fragments recovered from the auger cuttings in the colluvial samples were cleaned and leached of possible carbonates with an acid-alkali-acid pretreatment[76] then radiocarbon (14C) dated by the accelerator mass spectrometry (AMS) method at the University of Georgia's Center for Applied Isotope Studies. Bulk sediment material was dated following ultrasonic dispersion and sieving through 125 µm mesh then cleaned with 1N HCl to remove possible carbonates. Calendar year calibrations were calculated using CLAM[77] based on the IntCal09 calibration curve[78]; calendar years before present (cal BP) reference A.D. 1950 as "present".

Colluvial subsamples were crushed to pass a 1 mm mesh. The resulting material was then placed in 2 cm3 cylindrical plastic containers and their mass-specific magnetic susceptibility (χfd) was measured using the low frequency setting on a dual-frequency Bartington™ MS3 magnetic susceptibility meter. Fires with soil temperatures >400 °C can produce significant amounts of secondary magnetic minerals that allow the ascription of sediment to past forest fires[79]. In addition, subsamples of 10-15 g of the <8 mm fraction were gently dispersed in a 100 g/L solution of sodium hexametasphosphate, then wet-sieved to pass a 125 µm mesh. The >125 µm residue (sand + organic matter) was bathed in a 5 percent solution of hydrogen peroxide (to destroy/bleach non-charcoal organics), oven-dried at 105 °C then gently salted into a plastic vial containing liquid sodium polytungstate with a density of 1.75 g cm-3. The floating fraction containing charcoal was removed by freezing the sample then rinsing the floated surface material on to Whatman #1 filter paper using a vacuum filtration funnel and flask. The residue on the filter was photographed at 10 µm pixel resolution, and the area of uniquely black charcoal fragments quantified using Sigma Scan Pro 5. The area of charcoal is normalized to a cubic centimeter based on an average dry bulk density of 1.5 g cm-3. It has been demonstrated[80] that charcoal >125 µm derives from local fires, while charcoal recovered in colluvium from small hollows produces a reliable record of past fires.

We explored the utility of n-alkane hydrocarbon chains as biomarkers to evaluate the forest-to-pasture conversion[81]. We used two sample pairs from the hillslope forest-pasture soil profiles, and one sample each from a presumed forested colluvium and a presumed grassland colluvium. We only considered the shift in the ratio of C31/C27 carbon chains known as suitable

[75] Klute 1986; Singer, Janitzky 1986; Soil Survey Laboratory 1992.
[76] Kurth *et al.* 2006.
[77] Blaauw 2010.
[78] Reimer *et al.* 2009.
[79] Blake *et al.* 2006; Gedye *et al.* 2000; Oldfield, Crowther 2007.
[80] Higuera *et al.* 2005; Clark, Royall 1995.
[81] Gocke *et al.* 2013; Zech, Glaser 2008; Zech *et al.* 2009.

for reconstructing shifts in vegetation groups[82]. A toluene extract of each soil sample was subjected to analysis by gas chromatography coupled with mass spectrometry. The abundance of the straight chain aliphatic hydrocarbons having 31 and 27 carbon atoms (i.e. C31 and C27) were measured using the selected ion monitoring mode (SIM) of the mass spectrometer, with the C31/C27 ratio represents the ratio of measured abundance of the two masses.

The detailed presentation on the soil profiles and the correlation with proxy curves and radiocarbon dates are contained in another publication[83]. It should be clarified that the dates reported here and originally presented in this other paper[84] were obtained using a curve published in 2009[85], since the 2013 calibration curve[86] had not yet been published. While we have not re-run the dates presented here, we have re-run other dates from comparable sites that we are investigating in the Larrau area that are contained in an article published on line[87]. We have determined the difference in the dates using the 2009 vs. the 2013 curves are on the order of 0-5 years for the 2-sigma range over the course of the Holocene. This has absolutely no impact on the interpretation of results as presented here. Furthermore, as with any point date, the actual value can vary in function of the number of dates used to calculate the calibration curve so as more dates are used individual pin-point dates are likely to vary as the accuracy of the curve increases.

Results

Management Practices

Private lands are located in flat, low-lying alluvial plains and used intensively for crop cultivation. Intermediate slopes are a mosaic of private and communal fields, woodlands, and grazing pastures from which kindling and timber are harvested. Communal lands are above the intermediate zone (>800 masl) to the high drainage divide with Spain and include the zero-order basins where much of the reported research has taken place. Cadastral and other records indicate that the landscape of Larrau has been organized into private-communal lands across the three noted physiographic zones since at least ca. AD 1200. The organization is furthermore relatively stable – less than 12% of the commune

82 van Mourik, Jansen 2013; Zech *et al.* 2009.
83 Leigh *et al.* 2015a.
84 *Ibidem*.
85 Reimer *et al.* 2009.
86 Reimer *et al.* 2013.
87 Leigh *et al.* 2015b.

surface area changed in use between 1830-2003[88]. During certain periods (notably the 12th-13th and 17th-18th centuries), disinherited sons left their natal farm, enclosed a piece of the common in the intermediate zone to grow crops, and turned the family barn into a house thus establishing a new farmstead. Many farms in the intermediate zone today include as part of their name the word "borda" attesting to this infilling of the landscape.

Herders traditionally occupied the communal lands above 800 masl from mid-May to mid-August residing in dry-stone huts (*olha*) keeping their sheep in a corral next to the cabin at night[89]. Communal lands are not open access, but subdivided into 50 to 500 ha districts with grazing areas, forestland, building ensembles, and use rights for groups of 1 to 12 herders. This place-based institution – called an *olhatia* in Basque, a contraction of *olha* ('cabin') and *altia* ('surroundings') – typically goes back several hundred years. Each building ensemble within the *olhatia* has a proper name and minimally contains a cabin and a corral, sheltered hollow or bench for keeping the sheep at night. Building ensembles are located along the elevation gradient and designated the 'lower' (BA: *pekoa*) and the 'upper' (BA: *gagne*) *olha*. Users traditionally based themselves out of the lower *olha* at the beginning of the herding season and out of the upper *olha* later in the season[90]. The lower *olha* are often associated with 1 to 2 artificial mounds (ca. 12 m^3 each) called *tertres* (FR), while upper *olha* are associated with 3 to 20+ such mounds. While many *olha* are not associated with mounds, our pedestrian survey indicates that when mounds do occur they are geographically linked to *olha* and *olhatia*. Their internal structure as revealed by our GPR survey along with evidence collected in the surrounding area indicates they were probably built during a single construction event, but we have not yet carried out a thorough evaluation of them.

Private and communal lands across the commune of Larrau (and the Pyrenees in general[91]) have been maintained by fire for centuries. North-facing slopes are typically forested below 1285 masl while south-facing slopes and nearly all slopes above 1400 masl have been cleared of forest and serve as summer grazing lands. While most pastureland is communally owned, households carry the responsibility to appropriately manage the lands they use and this includes pasture burning. *Olhatia* members burn their *olha* territory by dividing the territory amongst them to more efficiently place ignitions across the landscape. Observation, interview, and survey results[92] indicate that pastures are burned annually, although herders recognize that altitude, aspect, exposure, vegetation type, and grazing pressure contribute to variability in fire frequency. Most respondents state that pastures would become unsuitable for grazing after

88 Coughlan 2013b.
89 Lassure 2006 [1993]; Ott 1993.
90 Lassure 2006 [1993]; Ott 1993; Welch-Devine 2008.
91 Métailié 1981.
92 Coughlan 2013a.

three to five years without fire due to the encroachment of woody vegetation, and that a fire free interval between 20 to 100 years would be problematic for grazing. For this reason, most pastures are regularly burned at present even if not currently in use. Fire return intervals for burned parcels vary by location, but below 1400 masl they are effectively <5 years.

Fires are set between the months of January and May. While winter weather in the western Pyrenees is typically cool and humid with frequent fog, light rain, and snow at higher elevations dry, southerly, downslope winds periodically bring clear, sunny skies with low humidity. Three to 10 days of such low-humidity days are ideal for setting a fire as long as low wind speeds prevail. Herders understand fuel moisture thresholds to contain their fires in pastures, and time the burn so that fires do not spread to hay meadows, hedgerows, or forests. Informants furthermore state that after 10 days of drying, fires could burn too hot or escape. Fire management thus consists of constraining fire by relying on higher fuel moistures in non-pasture vegetation, allowing streams, ridgelines, and livestock trails to function as firebreaks, and when necessary setting additional ignitions to both back-burn as well as facilitate spread of fire to additional pastureland.

Soil Profile Evolution

The uppermost colluvial stratigraphic unit at all sites is a yellowish-brown (10YR 5/5) to light olive-brown (2.5Y 5/4) non-calcareous silt loam to silty clay loam that can reach a depth of ca. 3 m. Slight pedogenic alteration features are apparent throughout the upper unit, but there is no evidence of buried topsoils or other indicators of episodic sedimentation[93]. The most significant difference observed between the pastured versus forested soil is the bulk density of the mineral soil surface, with a mean value of 0.66 g cm-3 for pastures versus 0.93 g cm-3 for forests (bulk density of pastures was less than forests in 19 out of 20 cases). Organic matter and total carbon content are not significantly different indicating that structural differences likely explain the contrasts in bulk density. The A horizons in pastures consistently exhibit strong medium to fine granular structure, whereas those in forests exhibit moderate medium to coarse subangular blocky structure. Grass rootlets are much finer and more abundant than coarse roots in the forested sites.

The average thickness of the whole A horizon (A1+A2+AB) is more than three times in pastures versus forests soils (18.4 vs. 4.7 cm). Even when the E and EB horizons from the forested epipedons are included, the pastured sites still have epipedons that are more than twice as thick as those in the forests (19.5 vs. 9.3 cm). The uppermost A horizon (A1) is also more than twice as

93 Leigh *et al.* 2015a.

thick in pasture vs. forest soils (12.2 vs. 4.7 cm). It appears that the A horizons of pastures are building up through time due to decreases in bulk density and by melanization of the once forested E and B horizons (pastures no longer exhibit an E horizon). Thus, the forest to pasture conversion results in significant pedogenic reorganization of the soil profile, which is largely expressed by reduction of bulk density, melanization, and build-up of the A horizons[94].

Chronostratigraphy of Landscape Change

Colluvial cores all exhibit distinct zones of charcoal macrofossils in their middle portions that we used to establish a paleoenvironmental chronology. The counts of >125 μm charcoal and magnetic susceptibility from our two best-dated stratigraphic sections to date (Sakia and Vallon Mulhedoy) indicate that limited burning occurred as early as 10,000 cal yr BP, a situation also recorded in the east-central Pyrenees[95]. Although some authors[96] have suggested such fires may indicate human activity in the mountains during the earliest Holocene, we have discovered no archaeological remains in the area from this period and other evidence[97] indicates environmental and edaphic conditions at the beginning of the Holocene may have favored more natural fires than during the late Pleistocene.

Our magnetic susceptibility and charcoal volume (mm3/kg) results further indicate that the forest-to-pasture transition occurred ca. 4000 to 3200 cal yr BP. There is considerable evidence this period was characterized by relatively wet conditions poorly suited to natural fires at least in central Europe[98] a condition that is locally indicated by the influx of beech (*Fagus*)[99]. While we have not yet identified any habitation sites from this period, the concentration of tumuli and stone circles in saddles and overlooks in Larrau exhaustively inventoried by Blot[100] indicates human activity in the zone. The dates for these sites lie between 3200-2000 BP, with the greatest number (92%) dating between ca. 3000-2500 BP. We furthermore determined that the sedimentation rates from sampled colluvial hollows at least doubled after the onset of widespread burning at these sites. Four of our five post-4k BP rates fall within a 0.01 to 1.00 mm/yr range, and our highest rate is 1.01 mm/yr. Finally, the n-alkane C31/C27 ratio for the A horizon of the two modern forest samples was 0.14 and 0.19, while that of two modern pasture samples was 0.05 and 0.04. A sample from above the

94 *Ibidem*.
95 Cunill *et al.* 2013.
96 Riera, Turu 2011.
97 Cunill *et al.* 2013.
98 Dotterweich 2008.
99 Pérez-Díaz *et al.* 2015; Rius *et al.* 2009.
100 Blot 2014.

first incidence of intense burning (40-50 cm) presumed to be grassland yielded a C31/C27 ratio of 0.11, while the sample from below the first incidence of intense burning yielded a C31/C27 ratio of 0.68 (130-140 cm)[101].

Discussion

The stem family (BA: *etxe*, FR: *famille souche*) household has been the fundamental decision-making unit in the Pyrenees Mountains for farm-level production since at least the medieval period[102]. Individual households were structurally linked to other houses through institutionalized commodity and non-commodity relations[103]. The boundaries between households were permeable and continually changing as people and property were redistributed between them[104]. However, the household also involved the day-to-day ordering of power relations within the family – oligarchy was the organizing principal for valleys in the western Pyrenees as well as households. The eldest child (male or female) inherited the entire estate along with the right to form a family, while younger siblings who remained with the house were subject to the decisions and labor demands of the inheritor[105]. The land estate of individual houses consisted of numerous private parcels widely distributed across low and intermediate zones of the commune. For example, the Arbide neighborhood in Larrau contained 40 households that in 1830 owned a total of 769 land parcels or an estate of ca. 19 parcels/household[106].

The stem family grew out of the need to maintain the integrity across time (i.e., impartibility) of a family's estate, most notably land and buildings[107]. Membership in a household was not only the basis for management practices on private lands it was also the basis for usufruct rights to communal lands and the management practices occurring on them, e.g., the *olhatia*[108]. The parcel is a persistent atomic unit of analysis discernible in historic documents and detectable from physical evidence on the ground that provides a fundamental behavioral unit for managing scale in this coupled human-natural system. The division of the Larrau landscape into private and communal lands is thus the nexus between the scalar organization of society into households, neighborhoods and commune, and the discrete management practices at particular kinds of

101 Leigh *et al.* 2015a.
102 Cursent 1998; Lefèbvre 1933; Zink 1997; Le Play 1871.
103 Fauve-Chamoux 1984; Ott 1993; Sabean 1990.
104 Cursent 1998; Jenkins 2010; Sabean 1990.
105 Arrizabalaga 2005; Gómez-Ibáñez 1975.
106 Coughlan 2013b.
107 Arrizabalaga 1997; Olsson *et al.* 2000; Sabean 1990.
108 Cavaillès 1931; Gómez-Ibáñez 1975; Ott 1993.

sites capable of influencing and directing pedogenic processes.

It is currently unknown when this characteristic organization of valleys across the Pyrenees into oligarchic republics was established, although some authors[109] argue for an ancestry far beyond any records to substantiate its existence. The earliest historic record for Larrau[110] describes how in June 1174 Arnaud de Laginge, his wife Marie Bertrande, his sons Guillaume Arnaud and Raimond gifted to Gerar, Abbot of Sauvelade, the place of Saint Jean Baptiste de Larrau to serve as a monastic church (*prieuré*). Significantly, the gift included the right to graze (*paître*) animals on the surrounding lands. In addition to the value of the territory for pasturage, it had strategic value in giving the Abbey of Sauvelade control over the crossing of the Pyrenees at the Port of Larrau, as well as access to routes into Navarra and various destinations (i.e., Pamplona, Isaba, Jaca, Huesca and Saragosa) for sale of merchandise. Saint Jean Baptiste de Larrau also served as a monastic guesthouse (*prieuré-hôpital*) for pilgrims[111].

Our results clearly indicate that the pastured soil profiles have been building up organic matter and enhancing the structural quality of their epipedons for at least hundreds of years. The net effect is creation of a new soil profile that has significantly better hydraulic properties, and is able to infiltrate and store more water than native forest soils. This has important implications for certain aspects of watershed hydrology, such as maintaining baseflow, resisting droughts, and reducing flooding. We cannot yet make a direct link between post-AD 1000 practices in Larrau and processes over the last several millennial, but we can state that the human-induced landscape transformation in Larrau from native forest to pasture appear to be benign and in some cases environmentally beneficial. This contrasts sharply with the stereotypical view that degradation of landscapes is the inevitable outcome of human use, pastoral or otherwise[112].

While sedimentation rates double in colluvial hollows after the onset of widespread burning, they remain modest by comparison to Holocene background erosion and sedimentation levels in forested environments. Terminal Pleistocene and early Holocene sedimentation rates calculated from a forested zero-order hollow in southwestern Germany range between 0.30 and 0.60 mm/yr[113]. Prehistoric sedimentation rates calculated in zero-order hollows in the humid-temperate Southern Blue Ridge Mountains (southeastern U.S.A) average 0.23 mm/yr and range from 0.06 to 0.70 mm/yr[114], while colluvial footslope sedimentation rates range from 0.02 to 1.14 mm/yr, and average 0.41 mm/yr[115]. For comparison, historic (beginning ca. AD 1820) colluvial sedimentation rates

109 Vyerin 2011.
110 Besse 1910; Steunou 2008.
111 Urrutibéhéty 1982.
112 Otterman 1974; Goudie 2013.
113 Dotterweich 2013.
114 Hales *et al.* 2012
115 Leigh, Webb 2006.

in the same region range from 2.0 to 2.7 mm/yr and directly attributable to timber harvesting and road construction. It is thus reasonable to conclude that rates measured in Larrau fall within the two-order-of-magnitude range of 0.01 to 1.00 mm/yr recorded for "natural" rates of forested hillslope sedimentation without significant human impact. This slight increase in erosion rates may nevertheless represent the earliest recorded "legacy sediment"[116].

Conclusion

The pedosphere has been suggested as the "golden spike" for determining the onset of when human impact on the total environment surpassed natural forces[117]. Smith and Zeder[118] specifically suggest that the introduction of agriculture marks the beginning of the Anthropocene epoch[119]. The singular focus on the onset of agropastoralism, however, cannot match the insight into causal processes afforded by a place-based approach to the study of humans in relation to their biophysical environment. How systems progress and regress, how feedbacks link fast and slow processes, and how alternate steady states can co-exist are key elements to the sustainable management of human-dominated ecosystems. They are also central to understanding how agropastoralism in the north-facing western Pyrenees Mountains has shaped the present landscape and soils.

Mountains are increasingly viewed as the "backbone of Europe"[120] because they provision essential ecosystem goods and services to both mountain dwellers and those people living beyond them. The capacity of mountain ecosystems to provide these goods and services, however, is at risk from several sources and in particular the marginalization of agropastoral activities[121]. The visible expression of marginalization across Europe, including the north- and south-facing Pyrenees, is the emigration of economically active segments of society and the aging of the local population. This demographic shift has been abetted over the last two centuries by increasingly specialized land-use policies and sectoral regulations[122]. For example, pastoral fire use in France is interpreted by governing bodies and the general public as irresponsible land stewardship that inevitably leads to land degradation.

Our findings demonstrate that use of mountain pastures in Larrau over

116 James 2013.
117 Certini, Scalenghe 2011.
118 Smith, Zeder 2013.
119 Autin, Holbrook 2012; Zalasiewicz *et al.* 2010.
120 Hazeu *et al.* 2010.
121 Huber *et al.* 2013; Rounsevell *et al.* 2006; Welch-Devine 2008.
122 Cash *et al.* 2006; Eichhorn *et al.* 2006; MacDonald *et al.* 2000.

millennia including the regular application of fire has not resulted in obvious signs of land degradation. Indirect human agency in Larrau have altered pedogenic processes over the course of millennia, and the transformative processes are not limited to mechanical alterations and direct additions to soil. They include redirecting the pedogenic pathways and processes that sustain soil evolution[123]. Pasture-woodlands across Europe are highly valued landscapes – socially, economically, and biotically – although evidence increasingly indicates these "human-made" or cultural landscapes rapidly degrade once agropastoral use and management cease[124]. Research into the co-evolution of agropastoralism and soils in the western Pyrenees connects the present continuously and strongly to its past, and this information is necessary if we are to engage contemporary land systems and leverage knowledge and practice across multiple scales to achieve a more desirable and sustainable future[125].

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123 Johnson, Watson-Stegner 1987; Runge 1973; Simonson 1959.
124 Eichhorn *et al.* 2006; Mottet *et al.* 2006; Rounsevell *et al.* 2006.
125 Antrop 2005; Brand *et al.* 2013; Cash *et al.* 2006; Dearing *et al.* 2010.

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Appendix

Period	Vegetation Dynamics	Charcoal (Fire) Record	Human Events
Modern 500-0 BP	*Open landscape*: Pine ↑; Oak ↓; Beech ↓; Hazel ↓; Chestnut ↑; API abrupt ↑ (<400 BP); Grass ↓	~0.1 $mm^2{*}cm^{-2}{*}y^{-1}$ (~4 f/500 y)	Corn introduced ~400 BP; Chestnut ↑ food and pannage; pastoralism abrupt ↑ 250-50 BP; mining/metallurgy and oak-to-charcoal abrupt ↑ 400-150 BP, then collapse.
Middle Ages 1500-500 BP	*Open landscape*: Oak ↓; Beech ↑ (north-facing slopes cleared); Hazel ↓; API abrupt ↑ (<1000 BP); Grass ↑	~0.2 $mm^2{*}cm^{-2}{*}y^{-1}$ (3-4 f/500 y), ↑ 1300-800 BP	Crop diversification, rye introduced ~1500 BP; extensive to intensive agropastoralism ~1300 BP; herd size ↑, shepherd huts at elevation; Roncevaux and Lyre abbeys compete for pannage. Mining peaks ~1400 BP then declines; pastoral activity ↓ 700-500 BP – Medieval demographic crisis.
Antiquity 2000-1500 BP	*Open landscape*: Oak ↓; Beech ↑; Hazel ↓; API ↑; Grass ↑	~0.1 $mm^2{*}cm^{-2}{*}y^{-1}$ (3-4 f/500 y), ↑ <1700 BP	Chestnut introduced ~2000 BP; moderate deforestation; grazing ↑, fire used as 'cleaning tool'; shepherd huts at altitude; mining ↑ iron, copper, silver and lead; numerous workshops; oak-to-charcoal for smelting.
Iron Age 2900-2000 BP	*Open landscape*: Beech ↑; Oak ↑; Hazel ↑: API abrupt ↑; Grass →	~0.2 $mm^2{*}cm^{-2}{*}y^{-1}$ (~3 f/500 y), peak at 2100 BP	Anthropogenic fire regime established: deforestation ↑, grazing ↑; abrupt ↑ mining, smelting and production bronze alloys and copper artifacts; stone/burial monuments.
Bronze Age 4300-2900 BP	*Beech-Oak forest established*: Beech ↑; Oak ↓; Birch ↓; API ↑ (<3000 BP)	~0.1 $mm^2{*}cm^{-2}{*}y^{-1}$ (~1 f/500 y), abrupt ↑ 3300 BP	Shifting cultivation of barley and wheat in small clearings; grazing above 500 masl ~3300 BP; stone/burial monuments.
Neolithic 7700-4300 BP	*Landscape closes*: Oak ↑; Hazel ↓; Grass ↑ (<7000 BP); Birch ↑ (<6700 BP); API ↑, peaks at 7500-7100, 5700-5500, 5000-4500 BP	~0.4 $mm^2{*}cm^{-2}{*}y^{-1}$ (3-4 f/500 y), abrupt ↑ peaks at 7700-7500 BP, 7000-6500 BP, 5800-5000 BP	1st barley/wheat ~7600 BP; 1st grazing >500 masl ~5500 BP; fire episodes synchronous with grains suggests temporary clearings; increase in API and decrease in grains until 4250 BP suggests grazing over cultivation.

Key sources: Conedera et al. (2004), Cugny et al. (2010), Galop (2006), Mazier et al. (2009), Monna et al. (2004), Morellón et al. (2012), Rius et al. (2012).

Symbols: Relative abundance – decrease ↓; no change →; increase ↑

API = Anthropogenic Pollen Indicator (includes): *Plantago, Artemisisa, Asteroideae, Brassicaceae, Centaurea, Chenopodiaceae, Cichoriodeae, Polygonum, Rubiaceae, Rumex, Trifolium, Urtica.*

Cultivated crops: Barley (*Cerealia* type); Chestnut (*Castanea silva*), Corn (*Zea mays*), Rye (*Secale* type), Wheat (*Triticum* type).

Vegetation: Beech (*Fagus*), Birch (*Betula*), Grass (*Poaceae*), Hazel (*Corylus*), Oak (*Quercus*), Pine (*Pinus*)

Tab. 1. Composite Holocene history of the Western Pyrenees (all dates are calibrated years before present)

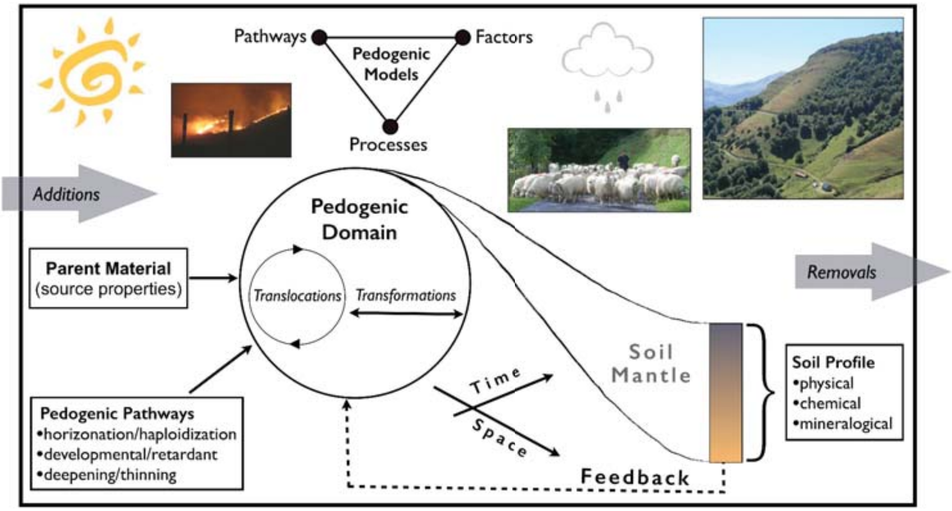

Fig. 1. Conceptual framework of pedogenic factors, processes and pathways related to the co-evolution of agropastoralism and soils in the Western Pyrenees over the Holocene (Principals sources: Jenny 1941; Simonson 1959; Johnson and Watson-Stegner 1987)

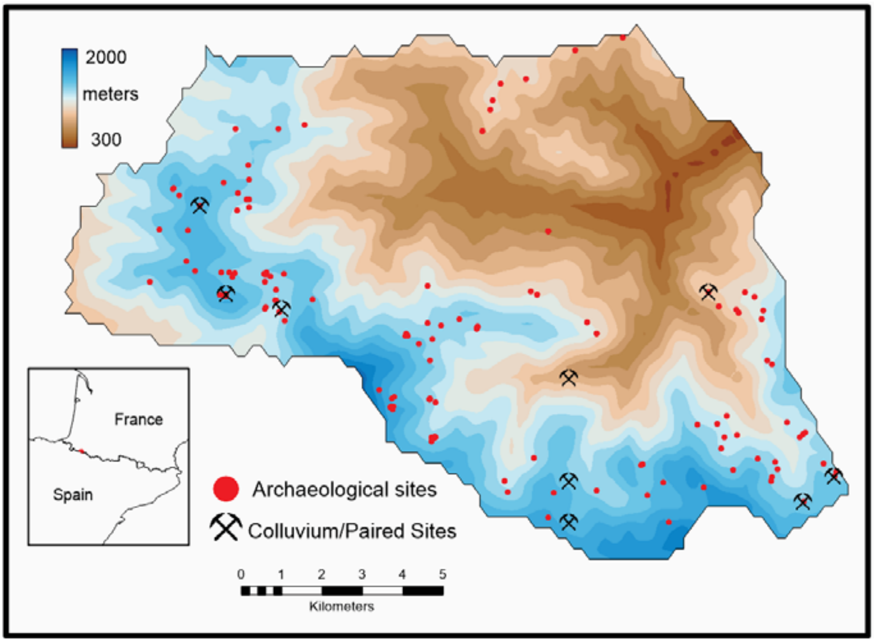

Fig. 2. Boundary map of the commune of Larrau showing location of sites and sedimentary archives recorded in 2012, 2013 and 2014

Saggi