

Chronology and pedogenic effects of mid- to late-Holocene conversion of forests to pastures in the French western Pyrenees

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with 6 figures and 3 tables

Abstract. This paper presents a place-based examination of the timing and long-term pedogenic effects of human-induced forest to pasture conversion in the French western Pyrenees Mountains, Basque commune of Larrau. We analyzed colluvial stratigraphic sections to derive the chronology of landscape change using radiocarbon dating, charcoal concentrations, magnetic susceptibility, and *n*-alkanes to reveal when forests were replaced by pastures (largely by intentional use of fire). In addition, we compared properties of native forest soils to those of adjacent long-term pastures using a paired t-test approach. Results indicate that intense burning and clearing occurred in the late Holocene, starting at about 4,000 cal yr BP, but limited fires occurred on the landscape during the early and middle Holocene. After 4,000 cal yr BP the sedimentation rates significantly increased, constituting “legacy” sediment, but post-4,000 cal yr BP sedimentation rates remain well within a range typical for forested hillsides ($< 1 \text{ mm yr}^{-1}$). Thus, erosional degradation is not apparent. Our paired analysis of old-growth forests compared to long-term pastures reveals that soils of millennial pastures are building up by additions of organic matter and phytoliths, as well as by decreases in bulk density of topsoils. The pastured A horizons are triple the thickness of those in forests, and pastures have significantly lower bulk densities, resulting in much more rapid water infiltration capacities. Although the concentrations of some inorganic nutrients in the pastured soils are significantly lower than in forested soils (mg kg^{-1} basis), the overall result is that the soils in pastures are of higher quality than those in forests. Melanization of the pastured profiles is an indirect anthropogenic process that has built-up the A horizons through time, which testifies to the importance of human agency in long-term soil evolution. The agropastoral uplands of Larrau stand in contrast to conventional degradation narratives of millennially grazed landscapes. The apparent sustainability of this landscape suggests that over the long term, agropastoral land use actually can result in changes to soils and landscapes that facilitate conservation.

Keywords: soil, pedogenesis, agropastoral, phytoliths, melanization, radiocarbon, Anthropocene

1 Introduction

Since the Neolithic onset of agriculture and animal husbandry, European landscapes have been transformed by diverse processes including deforestation (often involving fire), cultivation and grazing on slopes, as well as the construction of terraces, lynchets, headlands and field boundaries. The western Pyrenees Mountains, where agriculture and animal husbandry first appear ca. 7,500 BP (GALOP 2006, MAZIER et al. 2009), are no exception. Indeed, during the middle to late Holocene it is difficult to define a single period anywhere in Europe when geomorphological and pedological conditions remained exclusive of human intervention (DOTTERWEICH et al. 2013). It is known from pollen, charcoal, and microfossil records that fire was extensively used by people across the length of the Pyrenees Mountains to clear native forests and to maintain pastures

throughout much of the Holocene (BAL et al. 2010, 2011, MAZIER et al. 2009, RIUS et al. 2009). However, this knowledge is coarse and general for the region as it derives from a few widely scattered wetland bogs, some of which are in the piedmont rather than the mountains. As an alternative approach, our research targets the examination of place-based or localized effects of human-induced landscape transformation from native forests to pastures and the pedological effects that result from maintaining these pastures for thousands of years with intentional use of fire. We focus on the co-evolution of agropastoralism, biomes, and soils in the ethnically Basque commune of Larrau (12.7 km²) along the international drainage divide between southwestern France and northern Spain (Fig. 1). We report initial findings from our reconnaissance that: (1) establish the timing of localized forest to pasture conversion based on charcoal, magnetic susceptibility, *n*-alkanes, and sedimentation rates measured in colluvium derived from hillslopes of zero-order hollows; and (2) identify morphological and chemical changes within the soil matrix that appear to be byproducts of long-term management of pastures that were long ago converted from native forests.

Documenting pedogenic changes resulting from the conversion of forests to pastures is not new research, but the vast majority of previous research is in the tropics, only considers *decadal* timescales (e.g. DANIELS et al. 1983, FEARNSIDE et al. 1998, ELLINGSON et al. 2000, CHACÓN et al. 2009, BRAZ et al. 2013, ZUCCA et al. 2010, HAMER et al. 2013, GOUDIE 2013), and is largely focused on *degradation* of physical, chemical, and biological properties (i.e. erosion, compaction, nutrient and organism depletions). GOUDIE (2013) summarizes a variety of negative impacts that result from deforestation and conversion to grazing lands, and ZUCCA et al. (2010, p. 46) provide a succinct literature review of specific types of soil degradation resulting from such landscape transformations. Studies that consider centennial to millennial timescales of pastoral soil development following deforestation are virtually unknown in the literature. Research in the high Andes of Ecuador (CHACON et al. 2009) and elsewhere may inherently include centennial to millennial pastures, but age control is uncertain. Our study area is in the heart of the ethnically Basque cultural region where agropastoralism (largely sheep herding) has been practiced for thousands of years (GALOP et al. 2013, MAZIER et al. 2009), and it provides an ideal opportunity to evaluate millennial-scale effects of pastoral land use. Our results indicate relatively beneficial outcomes, such as improved soil structure and soil hydrology, and thickening of A horizons, rather than the more conventionally cited negative outcomes of prolonged degradation.

2 Study Area

The commune of Larrau (Basque Province of Soule, Department of Pyrénées Atlantiques, France) abuts the treeless international drainage-divide between France and Spain (Fig. 1). The bedrock of this area consists of well stratified Mesozoic mudstone, shale, dolostone, and limestone that is steeply tilted and folded (MOORES & FAIRBRIDGE 1997). Bedrock is capped by a thin mantle of noncalcareous silty to clayey yellowish-brown residuum that ranges from 0 to about 2 m thick. Native soils under forests are podzolic and would classify as Alfisols (hapludalfs) under the USDA soil taxonomy (SOIL SURVEY 1999), and they commonly exhibit an A, E, Bt, C, R horizon sequence. In contrast, soils under pastures typically lack an E horizon

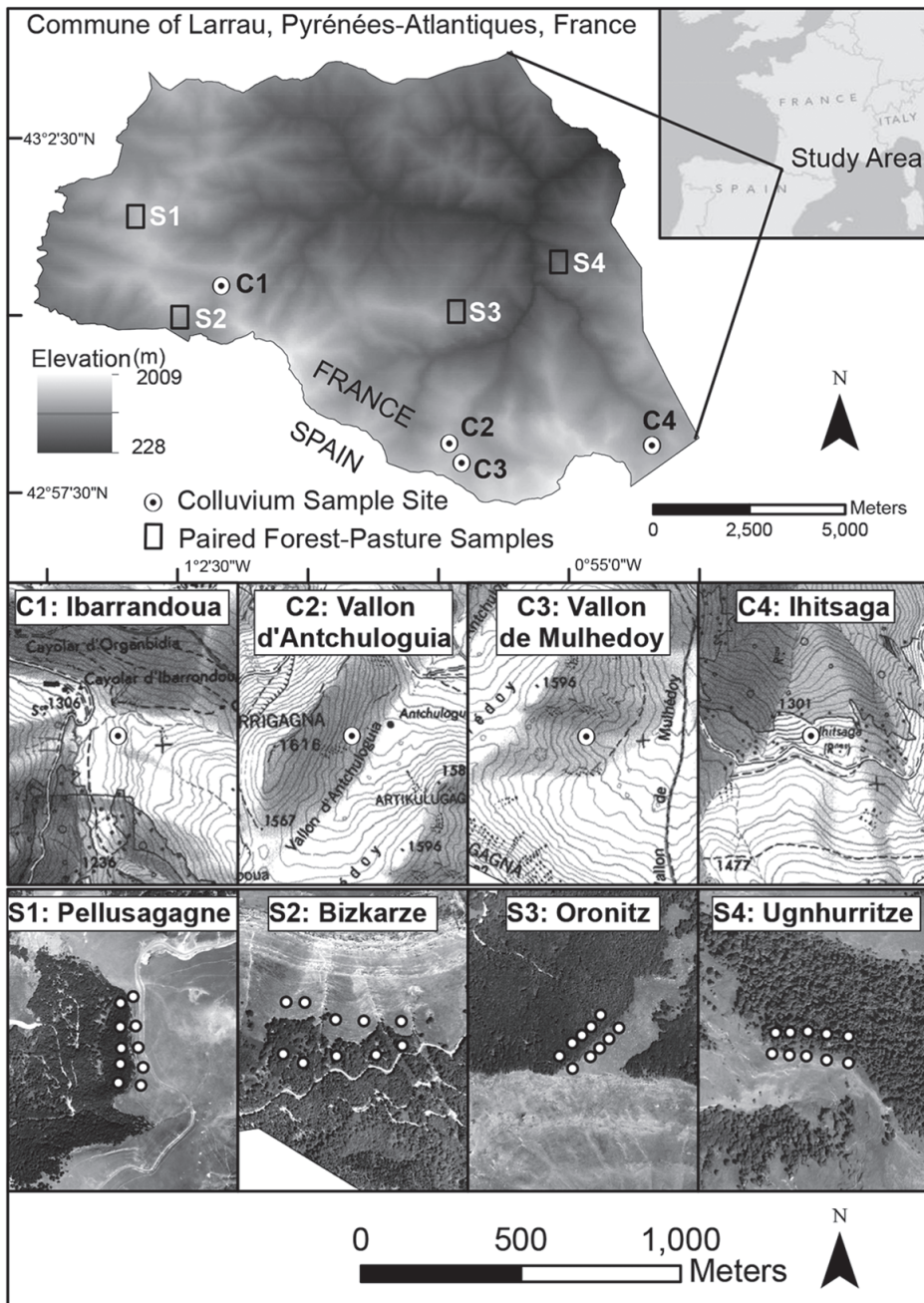


Fig. 1. Site location. Topographic map cells with "C" labels (colluvial sites) are from the 1:25,000 Carte Topographique Top 25 series of the French Institut Geographic National (IGN), map numbers 1346ET and 1446ET. The contour interval is 10 m. The aerial photographic cells with "S" labels (paired soil profile sites) are from digital images of the IGN 2000, as orthographically corrected aerial photos.

and have been organically enriched so that the A horizon is thicker than forested counterparts. They resemble Mollisols, except that they lack high enough base status and pH to be classified as such.

The climate of Larrau is humid oceanic (i.e., Atlantic) on the north-facing side of the French Pyrenees. The long-term (AD 1956–2010) mean annual precipitation is around 1,700 mm while the mean annual temperature is ca. 13 °C (range: 7–20 °C), which supports mesophyllous vegetation. Our research targets the elevation range from 800–1,700 m (above mean sea level at Marseille, France). Native woodlands are currently dominated by beech (*Fagus silvatica*), the single most important tree in the western Pyrenees, but is often intermingled with fir (*Abies pectinata*) and oak (*Quercus* sp.). The majority of south facing slopes and virtually all summits are covered with grasses and herbs, mostly bentgrass (*Agrostis* spp.), fescue (*Festuca* spp.), nard (*Nardus stricta*), and bluegrass (*Poa* spp.) that are intermingled with various sedges (Family *Cyperaceas*) and legumes (e.g., *Trifolium alpinum*). In fact, no trees currently exist above ca. 1,700 m, but the ecotone of the natural treeline would actually be around 2,200–2,300 m and has ranged up to ca. 2,400 m during portions of the Holocene (CUNILL et al. 2012). Pic d’Ohry is the highest point in Larrau (2,017 m) on the drainage divide between France and Spain. This international drainage divide is the spine of the western Pyrenees, and this interfluvium is entirely treeless throughout Larrau and adjacent parts of Basque communes both in Spain and France, largely functioning as pastures. The grassy south facing slopes and summits are regularly maintained by intentional burning (COUGHLAN 2013), and would revert to woodlands without such human intervention, while north facing slopes are largely forested.

As of 2003, approximately 49.7% of the land cover was grassland or pasture, 44.3% forest, 4.8% hay meadow, and 1.1% urban land or roads based on tabulations from orthophotos. Land use practices are characterized by transhumant agropastoralism, with sheep and cattle grazing in upland “outfields” during the summer months. The village center and satellite farmsteads are located on the bottomlands, terraces, and lower hillslopes amidst more intensively managed “infields”. Historically, infields were reserved for the cultivation of corn (*maize*), wheat (*Triticum* sp.), and other crops, or were mown for hay and bracken fern (*Pteridium* sp.) to provide winter fodder and animal bedding, respectively. Today, farmers continue to mow hay, and to a lesser extent bracken fern, from some infield hillslopes but crop cultivation is no longer practiced. Despite these changes in land use, less than 12% of the area underwent land cover conversion between 1830 and 2003, and most change occurred in the infield zone (COUGHLAN 2014). Traditional woodland use and management also has ceased, but timber harvest is practiced throughout the managed forests, mainly using selective cutting of the largest trees.

3 Methods and Rationale

3.1 Colluvial stratigraphic columns

Colluvial depositional sites were identified on small flats or hillslope benches, toeslopes, or depressions immediately beneath zero-order hollows on pastured hillslopes draining few to several hectares (Fig. 1, C1–C4). These sites were chosen to maximize likelihood of spatially uniform

and temporally steady sedimentation (primarily by slopewash). We hypothesized that these colluvial deposits retain sedimentary records of the transition from native forest to pasture, which is expressed by greater concentrations of charcoal, more rapid sedimentation rates, and higher levels of magnetic susceptibility during and following the intentional use of fire to initially clear and maintain the pastures within the zero-order catchments. A 7.6 cm diameter bucket auger was used to retrieve complete stratigraphic columns of unconsolidated colluvial sediment in contiguous 10 cm sample increments that were bagged and saved for laboratory analyses.

Small fragments of charcoal were removed from the auger cuttings and radiocarbon (^{14}C) dated by the accelerator mass spectrometry (AMS) method at the University of Georgia's Center for Applied Isotope Studies. The charcoal was cleaned and leached of possible carbonates with an acid-alkali-acid pretreatment prior to ^{14}C dating. Bulk soil material also was dated following ultrasonic dispersion and sieving through 125 μm mesh and cleaning with 1N HCl to remove possible carbonates. Calendar year calibrations were calculated using the program CLAM (BLAAUW 2010) based on the IntCal09 calibration curve (REIMER et al. 2009) and $\delta^{13}\text{C}$ corrected ^{14}C ages. The calendar years before present (cal BP) reference AD. 1950 as "present". Sedimentation rates were calculated by linear interpolation with the program CLAM (BLAAUW 2010), which considers the probability distributions of the separate radiocarbon dates in 10,000 iterations to produce the most probable match to interpolate between the two samples. We recognize and acknowledge that charcoal may be detritus and thus can produce erroneous ages for the actual time of sedimentation. However, we are careful to selectively date the largest angular fragments of charcoal that exhibit minimal traits of abrasion and rounding, and our radiocarbon chronology is bolstered by several bulk soil dates that are compatible with dates from charcoal.

Samples from the Vallon de Mulhedoy site (Fig. 1) were oven-dried at 105 °C and gently disaggregated to pass an 8 mm mesh. Subsamples were subjected to particle size, magnetic susceptibility, charcoal, and *n*-alkane analyses. Particle size analysis followed the hydrometer and sieve method (GEE & BAUDER 1986) to quantify the weight fractions of gravel, sand, silt, and clay with respective size breaks at 2,000, 63, and 2 microns.

Subsamples crushed to pass a 1 mm mesh were measured for volume-specific magnetic susceptibility in 8 cm³ cubical plastic containers 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 (e.g. BLAKE et al. 2006, GEDYE et al. 2000, OLDFIELD & CROWTHER 2007). We thus hypothesize that fire used in the initial conversion of forests to pastures, and subsequently to maintain pastures, will be reflected in the magnetic traits of colluvial stratigraphic profiles.

Subsamples of 50 g were gently dispersed in a solution of sodium metaphosphate (50 g/L), sieved to pass a 125 μm mesh, and > 125 μm particles of charcoal were tallied into categories of 125–250 μm , 250–500 μm , 500–1,000 μm , 1,000–2,000 μm and > 2,000 μm using a binocular microscope at 40x magnification. Charcoal > 125 μm derives from local fires as opposed to wind-blown charcoal from distant sources (CLARKE 1988, CLARKE & ROYALL 1995, 1996). HIGUERA et al. (2005) and BAL et al. (2010) demonstrate that > 125 μm charcoal in colluvium from small hollows produces a reliable record of past fires.

3.2 Experimentation with *n*-alkanes

We explored the utility of *n*-alkane hydrocarbon chains as biomarkers to evaluate the forest-to-pasture conversion using one pair of A horizon samples at the Oronitz site and two samples within the Vallon de Mulhedoy stratigraphic section, including one sample from presumed forested colluvium and another from presumed grassland colluvium. Our focus was on shifts in the ratio of C31/C27 carbon chains, which are known to be suitable for reconstructing shifts in vegetation groups (SCHWARK et al. 2002, ZECH et al. 2009, VAN MOURIK & JANSEN 2013). A toluene extract of the soil 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. The C31/C27 ratio simply represents the ratio of measured abundance of the two masses.

3.3 Paired forest/pasture soil properties

Four hillslope sites where large pastures occur immediately adjacent to forests with similar bedrock, aspect, and morphology were selected for paired analysis of soil properties (Fig. 1, S1–S4). We analyzed five pairs of soil profiles (pasture vs. forest) from each of the four hillslope sites (total of 40 soil profiles). Matched pairs at each of the four sites consisted of five pairs along the length of the forest/pasture boundary (Fig. 1), where we excavated the soil profile well into the B horizon and in many cases through the B and C horizons to bedrock. The mature beech (*Fagus*) forests commonly contain trees with ages of 200–300 years, based on dendrochronology from cores of the largest trees, but we suspect that the forested landscape may have been much older.

Measurements of soil properties include diagnostic soil horizon thickness and morphology (SOIL SURVEY STAFF 1993), hydrogen ion concentration (pH) of a 1:2 soil-water paste measured with a Corning® pH meter 443i, plant-available nutrients by the double-acid or Mehlich-1 technique (MEHLICH 1953, ISSAC 1983), amorphous silica concentrations (i.e. phytoliths) by the 0.05 M NaOH leaching method of JONES (1969) and SACCONI (2007), and dry bulk density based on the weight of mineral topsoil (excluding the O horizon) obtained with a 7.6 cm diameter by 7.6 cm long piston corer. Dry bulk density was measured on all 20 pairs of samples, whereas pH and chemical tests were restricted to 10 sample pairs derived from the Bizkarze and Oronitz sites. We measured saturated hydraulic conductivity (Ksat) of the upper 25 cm of soil at one site (Pellusagagne) with a compact constant head permeameter (AMOOZEGAR 1989), taking the geometric mean of three observations at one pastured locality and at one forested locality.

Soil phytoliths were separated from the > 2 µm fraction by elutriation, sieving, and gravity separation in sodium polytungstate at a density of 2.35 g cm⁻³ (MADELLA 1998). Charcoal and other light matter were separated from the phytoliths by a secondary heavy liquid flotation (1.7 g cm⁻³) to isolate the phytoliths. Plant phytolith content was gravimetrically measured by burning dry leaves at 550 °C for 3 hours in a muffle furnace, dissolution of non-silica ash with weak 1N HCl, and weighing the silica residue.

4 Results

4.1 Colluvial sedimentation

The uppermost colluvial stratigraphic unit at all four sites is uniformly a yellowish-brown (10YR 5/5) to light olive-brown (2.5Y 5/4) non-calcareous silt loam to silty clay loam with occasional granules and rarely pebbles that ranges up to about three meters thick. Slight pedogenic alteration features (weak ped structure) is apparent throughout the upper unit, but it lacks any evidence of buried topsoils or any other indicators of episodic sedimentation. At Ihitsaga the top of a buried paleosol was noted at 2.90 m depth that is developed in a lower silty stratigraphic unit that is darker than the upper unit (olive brown, 2.5Y 4/4) and extends to 4.5 m. At Vallon de Mulhedoy a silty dark greyish-brown (2.5Y 4/2) paleosol that is about 30 cm thick underlies the upper colluvial unit and abruptly overlies bedrock. Radiocarbon dates (Table 1) from all four colluvial sections indicate that the base of the uppermost colluvial unit ascribes to the early Holocene, whereas a late Pleistocene age was determined for the basal paleosol at Vallon de Mulhedoy (17,779–18,514 cal yr BP). The radiocarbon chronology (Table 1), stratigraphy, and sedimentology, generally indicate that the uppermost colluvial unit represents continuous and steady sedimentation throughout the Holocene, and that older stratigraphic units may exist at some sites.

Radiocarbon dates were obtained at all four sites from samples near the base of the stratigraphic zone most enriched in macroscopic charcoal recognized during field examination of auger cuttings (Table 1, grey shaded rows). Together, these four dates fall within a 2-sigma range of 1,019–3,971 cal yr BP and indicate the late Holocene was distinctly characterized by fires at the sites.

Three or more dated samples (including radiocarbon dates and the modern soil surface) were obtained within each of the four stratigraphic sections to facilitate calculation of age-depth curves and long-term-average sedimentation rates over the span of the terminal Pleistocene and Holocene (Table 1, Fig. 2). At each of these sites the fastest sedimentation rates were registered within and above the zones with the most charcoal, and these sedimentation rates were significantly higher than those earlier Holocene strata underlying the maximum influx of macroscopic charcoal. The radiocarbon chronologies at Vallon d'Antchuloguia and Vallon de Mulhedoy, and Ihitsaga indicate that sedimentation rates increased tremendously (100 to 1000 percent) following the first major influx of macroscopic charcoal, while Ibarrandoua only increased a modest 23 percent (Table 1, Fig 2). The most well dated chronology at Ihitsaga indicates that sedimentation rates fell nearly back down to pre-charcoal-influx background levels during the last 2,000 years within levels above the zone with most macroscopic charcoal (Fig. 2).

The Vallon de Mulhedoy stratigraphic section was subjected to further tests of particle size, charcoal tabulation, magnetic susceptibility, and *n*-alkane analyses (Fig. 3). These tests distinguish the basal paleosol/stratigraphic unit at 155–185 cm, which consists of a very dark greyish-brown (2.5Y 3/2) silt loam that abruptly overlies bedrock and has a buried A horizon at the top. Overlying this buried soil is relatively uniformly textured yellowish-brown (10YR 5/5) silt loam that exhibits a significant increase in charcoal concentrations and magnetic susceptibility values at the beginning of the Holocene, immediately above the buried A horizon at 155 cm. Both charcoal and magnetic susceptibility gradually increase from 155 cm upward into the midst of

Table 1. Dates and sedimentation rates from colluvial deposits.

Site/Sample	C ¹⁴ Depth Interval (cm)	Material Dated	δ ¹³ C ‰	Geologic Material	UGA C ¹⁴ Lab #	C ¹⁴ yr BP	+/- 1 stdv.	2-Sigma Min. Cal yr BP	Best Interpol. Cal yr BP	2-Sigma Max. Cal yr BP	Interpol. ^{**} Sedimentation Rate mm yr ⁻¹
Ihitsaga-1	0	none	n.a.	surface	n.a.	n.a.	n.a.	n.a.	-63	n.a.	n.a.
Ihitsaga-1	65	charcoal	-26.4	colluvium	15487	2140	25	2010	2140	2299	0.29
Ihitsaga-1*	180-190	charcoal	-25.3	colluvium	15033	3090	30	3225	3311	3379	1.02
Ihitsaga-1	280-290	soil	-24.3	colluvium	15488	7430	40	8180	8260	8343	0.20
V. Antechuloguia	0	none	n.a.	surface	n.a.	n.a.	n.a.	n.a.	-63	n.a.	n.a.
V. Antechuloguia*	85	charcoal	-26.9	colluvium	11776	1180	20	1019	1108	1173	0.73
V. Antechuloguia	140-145	soil	-23.4	colluvium	17407	8330	30	9273	9358	9445	0.07
V. Mulhedoy-1a	0	none	n.a.	surface	n.a.	n.a.	n.a.	n.a.	-63	n.a.	n.a.
V. Mulhedoy-1a*	85-90	charcoal	-26.5	colluvium	11775	3600	20	3845	3907	3971	0.22
V. Mulhedoy-1b	150-155	soil	-24.4	colluvium	15489	8980	30	9939	10157	10231	0.10
V. Mulhedoy-1b	180-182	soil	-23.4	colluvium	15034	14850	40	17782	18165	18514	0.04
Ibarrandoua	0	none	n.a.	surface	n.a.	n.a.	n.a.	n.a.	-63	n.a.	n.a.
Ibarrandoua*	95	charcoal	-26.2	colluvium	15031	2380	25	2342	2407	2481	0.38
Ibarrandoua	260-265	soil	-25.0	colluvium	17409	7000	30	7756	7846	7932	0.31

notes:

* grey shaded samples are near the base of the zone of maximum charcoal based on field examination of auger cuttings
** interpolated rates assume ground surface at -63 cal yr BP is A.D. 1950, and rate computations according to BLAAUW 2010

the stratigraphic section. Magnetic susceptibility steadily increases upward through the section to a maximum value at 100–110 cm, which is matched by an initial peak in amounts of $> 125 \mu\text{m}$ charcoal particles. The volume of charcoal exhibits a distinct peak at 80–90 cm that corresponds to the beginning of a plateau in the > 125 charcoal counts. The distinct peak in the charcoal volume ($\text{mm}^3 \text{ kg}^{-10}$, Fig. 3) at 80–90 cm owes to a unique spike in 1–2 mm and 2–4 mm charcoal grains that corresponds to a radiocarbon date of 3,845–3,972 cal yr BP obtained at 85–90 cm. Both charcoal and magnetic susceptibility diminish off of their plateaus from 20 cm depth toward the top of the section, which is matched by a shift to slightly siltier sediment.

4.2 Pasture versus forest soil properties

The most significant difference observed between the pastured versus forested soil was the dry bulk density of the mineral soil surface (Table 2), with a mean value of 0.66 g cm^{-3} for pastures versus 0.93 g cm^{-3} for forests. The bulk density of pastures was less than forests in 19 out of the 20 pairs, with the Oronitz site showing the least difference and the Pellusagagne site showing the greatest difference between sample pairs (Fig. 4). Organic matter and total carbon contents for those 10 sample pairs from the Oronitz and Bizkarze sites are not significantly different (Table 2), so it appears that structural differences probably explain the contrasts in bulk density. Indeed the A horizons in pas-

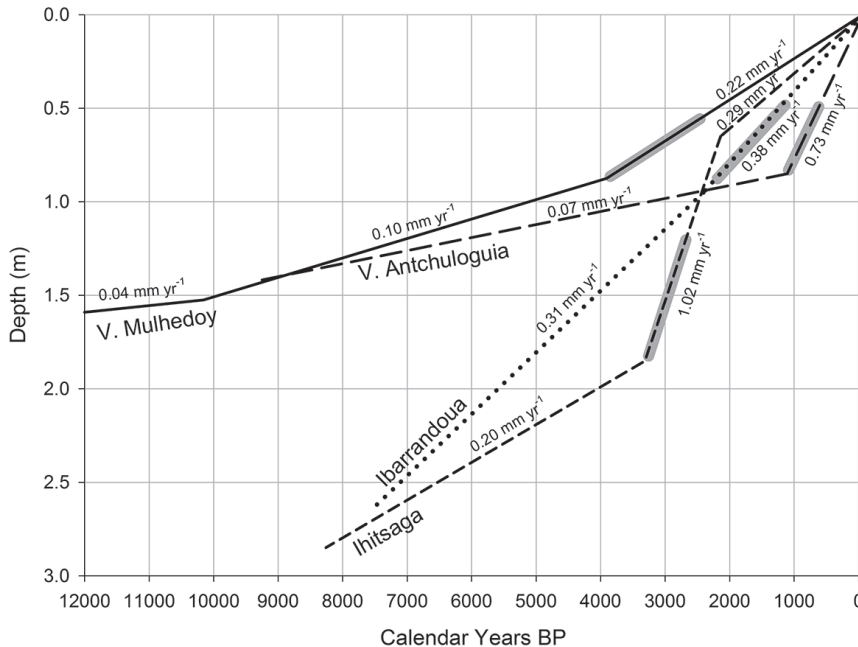


Fig. 2. Sedimentation rates at colluvial sites. Grey shaded areas represent zones of maximum charcoal concentration identified from field inspection of augured samples.

tures consistently exhibit strong medium to fine granular structure, whereas those in forests exhibit moderate medium to coarse subangular blocky structure. Also, grass rootlets are much finer and more abundant than coarse roots in the forested sites (Fig. 5). Thus, contrasts in ped structure and rootlet density probably explain the differences in bulk density. Such differences in bulk density clearly are expressed in the saturated hydraulic conductivity (K_{sat}) of a pasture/forest soil pair at Pellusagagne site 4. Here the pastured site (0.90 g cm^{-3}) has an average K_{sat} flow rate of 224 mm hr^{-1} , whereas the forested site (1.17 g cm^{-3}) has an average K_{sat} flow rate of only 36 mm hr^{-1} .

The thickness of the O horizon is the only one of the epipedon properties that is *not* significantly different (Table 2). In contrast, the average thickness of the whole A horizon ($A1+A2+AB$) is more than three times as thick in the pastures versus forests ($18.4 \text{ vs. } 4.7 \text{ cm}$, Fig. 6). 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 ($19.5 \text{ vs. } 9.3 \text{ cm}$). The uppermost A horizon ($A1$) also is more than twice as thick in the pastures than in the forests ($12.2 \text{ vs. } 4.7 \text{ cm}$).

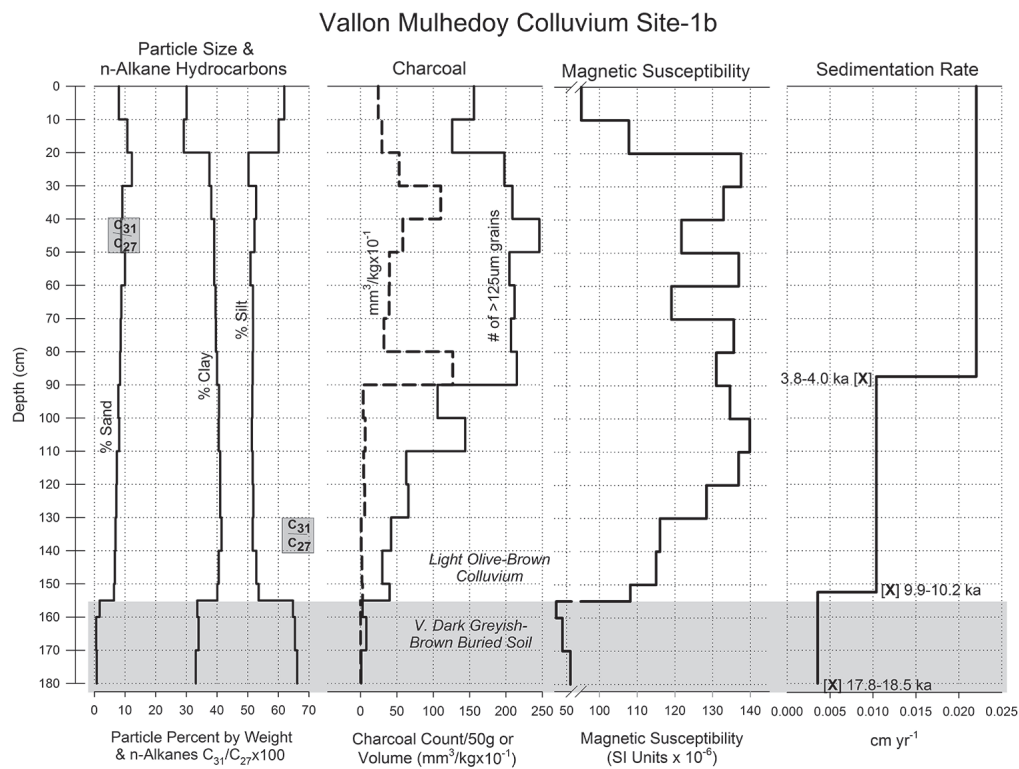


Fig. 3. Particle size, charcoal, n -alkane, magnetic susceptibility, and sedimentation rate data for the Vallon de Mulhedoy stratigraphic section of slopewash colluvium. The C₃₁/C₂₇ shaded boxes indicate the value of that ratio according to the center of the box. Radiocarbon dates on the sedimentation rate plot are averaged to the nearest century and expressed as thousands of years ago (ka).

Table 2. Mean values for properties of epipedon horizons in pastures versus adjacent forests, along with paired t-test values and significance levels (P) of their difference of means. Shading distinguishes significance levels (P-values) of < 0.05 and < 0.01. All chemical and LOI samples represent the upper 5 cm of the A horizon with n = 10 and other variables are self-explanatory with n = 20.

Variable (shaded values classify P-values < 0.01, <0.05, >0.05)	Pasture Mean	Forest Mean	t-Stat	P(T<=t) one-tail
Dry Bulk Density for 0-7.6 cm of soil (g cm ⁻¹)	0.66	0.93	-6.36	0.000002
A1 Thickness (cm)	12.2	4.7	5.51	0.000013
Total A (A1+A2+AB) Thickness (cm)	18.4	4.7	5.45	0.000015
Epipedon (A, E, AB, EB) Thickness (cm)	19.5	9.3	4.71	0.000076
Amorphous Silica Amount*	0.1	-0.3	3.73	0.002366
K (mg kg ⁻¹)	112.5	206.0	-3.12	0.006198
Mn (mg kg ⁻¹)	37.6	112.1	-2.95	0.008113
Ni (mg kg ⁻¹)	0.8	1.4	-2.61	0.014221
S (mg kg ⁻¹)	1206.3	1322.1	-2.24	0.026088
Si (mg kg ⁻¹)	13.2	9.7	1.96	0.040545
Zn (mg kg ⁻¹)	5.0	9.4	-1.96	0.040579
Mg (mg kg ⁻¹)	96.8	152.3	-1.88	0.046475
Al (mg kg ⁻¹)	693.9	553.9	1.71	0.060984
Ca (mg kg ⁻¹)	620.4	871.0	-1.65	0.066298
P (mg kg ⁻¹)	11.9	19.7	-1.56	0.076040
Cd (mg kg ⁻¹)	0.1	0.2	-1.29	0.115013
Fe (mg kg ⁻¹)	144.0	164.9	-0.94	0.185251
Total Nitrogen (mg kg ⁻¹)	0.9	1.0	-0.54	0.300261
Avg. pH 1:2 Soil:Water	4.3	4.2	0.50	0.315405
Cu (mg kg ⁻¹)	0.6	0.6	-0.44	0.334122
O horizon Thickness (cm)	2.2	2.5	-0.41	0.342740
Organic Matter as % LOI@420° C for 4 hrs	28.2	30.3	-0.28	0.391494
Total Carbon (mg kg ⁻¹)	14.8	15.7	-0.25	0.405540
Na (mg kg ⁻¹)	28.6	29.0	-0.10	0.460914
C/N Ratio	15.7	15.7	0.01	0.497551

* amorphous silica concentrations were regressed against % organic matter and residual values were subjected to the t-test.

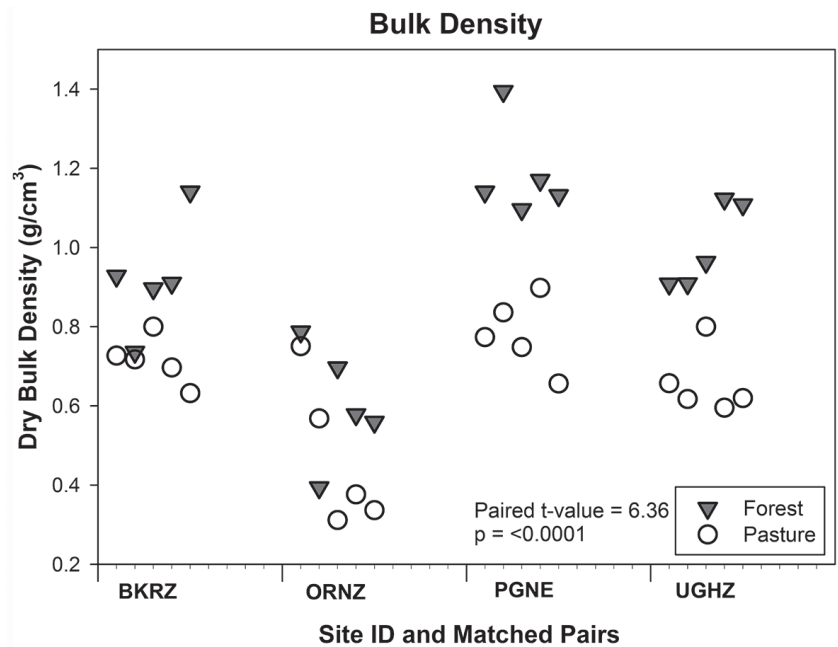


Fig. 4. Results of bulk density measurements from the uppermost mineral soil (top 7.6 cm) of paired soil samples (pasture vs. forest). Paired samples have the same x-axis value. Site names are abbreviated with acronyms BKRZ for Bizkarze, ORNZ for Oronitz, PGNE for Pellusagagne, and UGHZ for Ugnhurritze sites.

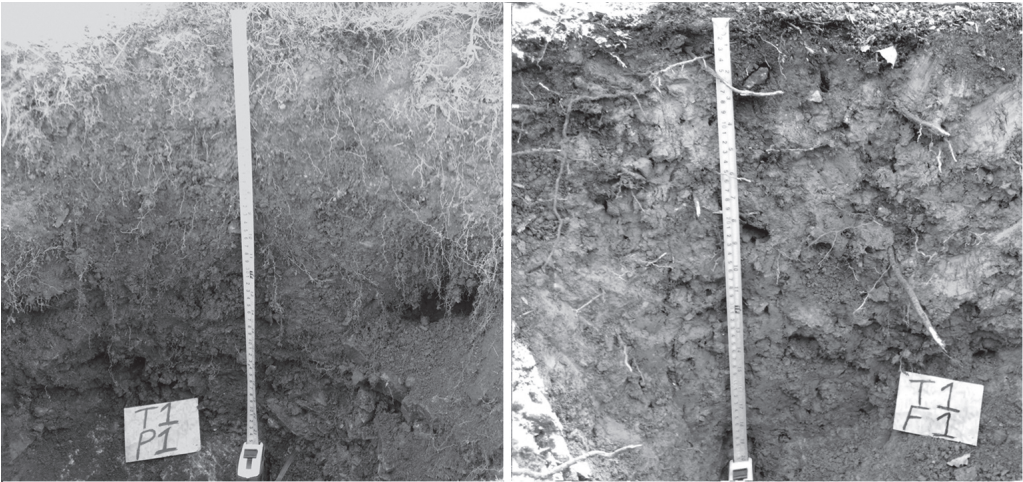


Fig. 5. Photographs of the pastured soil (left) versus the forested soil (right) at the Oronitz site #1. The length shown by the tape measure in both photos is 50 cm.

Thus, it appears that the A horizons of the 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 any E horizons). It is reasonable to surmise that the amount of time since the forest-to-pasture conversion is positively correlated with the average A horizon thickness, which would imply that the Bizkarze and Oronitz pastures are older than those of Pellusagagne and Ugnhurritze (Fig. 6), though this remains to be tested. In summary, the forest to pasture conversion results in very significant pedogenic reorganization of the soil profile, largely expressed by reduction of bulk density, melanization, and build-up of the A horizons.

Amorphous silica (SiO_2) contents in the pastured soils are significantly higher than those in the forested soils (Table 2). This stands to reason, because grasses produce far more biogenic silica (opal phytoliths) than trees (DIXON et al. 1977). Indeed, we gravimetrically measured the silica residue in grass and tree leaf samples from Larrau and found the percent-by-weight of silica residue in the grasses were 1.76–3.88 %, but only 0.05–0.21 % in the tree leaf samples (Table 3). Also, we separated phytoliths from the A horizon of two paired forest/pasture samples (at Bizkarze and Oronitz) and found that pastured A horizons contain 1.3 to 1.5 % of phytoliths while forested A horizons only contain 0.2 to 0.6 % of phytoliths (Table 3). Such pronounced differences in phytolith content may ultimately allow us to quantitatively estimate the age of forest to pasture conversion by selective radiocarbon dating of occluded carbon within the phytoliths in the A horizon and by measuring the total mass of phytoliths in the whole soil profile.

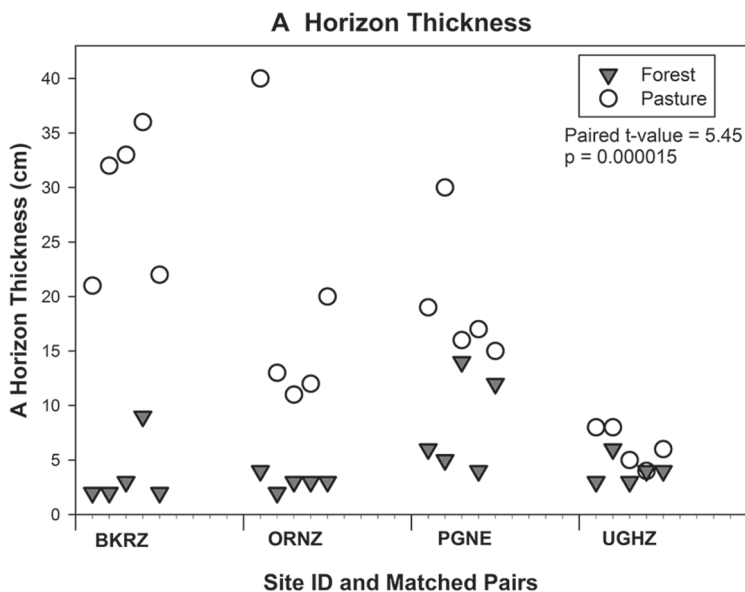


Fig. 6. Results of whole A horizon (A1+A2+AB) thickness measurements from paired pasture versus forest soil samples. Paired samples have the same x-axis value. Site names are abbreviated with acronyms BKRZ for Bizkarze, ORNZ for Oronitz, PHNE for Pellusegagne, and UGHZ for Ugnhurritze sites.

Table 3. Phytolith concentrations from the upper 5 cm of A horizons and various leaves.

Sample	Phytolith Content (% by wt.)
Bizkarze pasture site #1, A horizon soil	1.45
Oronitz pasture site #1, A horizon soil	1.33
Bizkarze forest site #1, A horizon soil	0.61
Oronitz forest #1, A horizon soil	0.21
Grass leaves 1	1.76
Grass leaves 2	3.88
Grass leaves 3	2.45
Beech leaves 1	0.05
Beech leaves 2	0.21
Fir leaves	0.10

The plant-available or “extractable” K and Mn are significantly different at the 0.01 level, and Mg, Ni, S, Si, and Zn are significantly different at the 0.01 to 0.05 levels, with the pasture soils having much lower concentrations in all cases, except for Si (Table 2). The higher Si content in pastures is consistent with the demonstration above showing that pastured soils contain more phytoliths.

5 Discussion and Conclusions

5.1 Chronicles from colluvial stratigraphic sections

Our results demonstrate that the forest-to-pasture transformation is clearly recognizable in colluvial stratigraphic sections that collect slopewash from zero-order hillside catchments, despite the rather coarse temporal resolution of our 10 cm thick samples. This is important because it facilitates fine spatial resolution (individual pastures) of place-based paleolandscape analysis that can be associated to nearby archaeological investigations and provide insight about past land use. Indeed, we currently are involved in efforts to link our results to ongoing archaeological investigations. Furthermore, we anticipate that finer temporal resolution will be possible by using thinner samples.

Results from our two most well dated stratigraphic sections (Ihitsaga and Vallon de Mulhedoy) indicate that the forest-to-pasture transition occurred at those sites by ca. 4,000 to 3,000 cal yr BP. This corresponds extremely well with the assertion by Galop et al. (2013: 21) that human-induced fires in “uplands” registered a very pronounced increase at ca. 4,200 to 3,000 cal yr BP during the Bronze Age. However, their graphed suggestion that “upland” human-induced fires began around 6,000 cal yr. BP is less well supported by our data at the Vallon de Mulhedoy site, because the magnetic susceptibility and charcoal indicate that some burning probably actually had begun perhaps as early as 10,000 cal yr BP. While it is intriguing to consider human-induced fires during the earliest Holocene, we cannot rule out the possibility that climate conditions at the beginning of the Holocene simply may have favored more fires than during the late Pleistocene. Similarly, we cannot completely rule out the possibility that changes in climate may have facilitated a higher frequency of fire at ca. 4,000–3,000 cal yr BP, but the argument for human-induced fires then is more compelling. There is considerable evidence that ca. 4,000–3,000 cal yr BP actually may have been a time of relatively wet conditions and poorly suited for natural fires in central Europe (Dotterweich 2008: 197), which is locally indicated by a major influx of beech (*Fagus*) trees that prefer moist conditions (Rius et al. 2009) ill-suited for natural fires. Moreover, several lines of evidence point toward human use of fire in association with agropastoral activities accelerating at 4,000–3,000 cal yr BP (Rius 2009, Galop 2006).

It is interesting that the maximum magnetic susceptibility values slightly precede the peak in charcoal concentrations in the Vallon de Mulhedoy section (Fig. 3). A possible explanation for this is that initial burning on the landscape prior to the peak in charcoal was sufficient to fully transform the iron-bearing minerals to their magnetically-enhanced condition. Alternatively, increasing fire activity during the middle Holocene may have shifted erosional processes from surficial sheetflow to rill erosion that entrained subsoil that had not been magnetically altered by heating of the ground surface.

Our data indicate that sedimentation rates commonly increased by twofold to an order-of-magnitude in colluvial hollows after the onset of widespread burning at the sites. Assuming that land use change (deforestation and conversion to pasture by burning and grazing) is the driver of the change in sedimentation rates, then we have identified the earliest “legacy sediment” (sensu JAMES 2013) in Larrau. This legacy sediment testifies to a slight increase in erosion rates on the hillsides within the zero-order hollows, and thus one could argue that human-induced land degradation was manifested during the middle Bronze Age at our sites. Despite these recognizable increases in sedimentation rates, even the maximum sedimentation rates are modest to low values when compared to background levels of Holocene erosion and sedimentation measured in comparable forested environments. Terminal Pleistocene to earliest Holocene sedimentation rates calculated from a forested zero-order hollow in southwestern Germany yield sedimentation rates ranging from about 0.30 to 0.60 mm yr⁻¹ (DOTTERWEICH et al. 2013: 47, Table 1). Prehistoric sedimentation rates calculated in zero-order hollows of the humid-temperate Southern Blue Ridge Mountains (southeastern U.S.A) average 0.23 mm yr⁻¹ and range from 0.06 to 0.70 mm yr⁻¹, based on two radiocarbon dated profiles of HALES et al. (2012: 126, Table 1, n = 11). They excluded the anomalously low and high radiocarbon dates and calculated that Holocene *erosion* rates (derived from sedimentation rates) on fully forested hillslopes must have ranged from 0.05–0.11 mm yr⁻¹,

which is attributed mostly to tree throw and soil creep. This rate is comparable to Neolithic erosion rates in Germany (DREIBRODT et al. 2010). At another site in the humid-temperate Southern Blue Ridge Mountains, LEIGH & WEBB (2006: 167, Table 2) document prehistoric colluvial foot-slope sedimentation rates during the Holocene within a range of 0.02 to 1.14 mm yr⁻¹, and averaging 0.41 mm yr⁻¹ (n = 5). In addition, LEIGH & WEBB (2006: 167, Table 2) report much higher historical or legacy colluvial sedimentation rates of 2.0 and 2.7 mm yr⁻¹ that are attributable to human activities such as timber harvest and road construction. In an estuary fed by steepplands in New Zealand, SHEFFIELD et al. (1995) found that pre-Polynesian sedimentation rates for native forests were 0.1 mm yr⁻¹. This rate climbed in Polynesian fern/shrublands to 0.3 mm yr⁻¹, while post-European rates shot up to 11 mm yr⁻¹. Broadly comparable results were found in a later study in another part of the North Island of New Zealand by PAGE & TRUSTRUM (1997). Thus, it is reasonable to conclude that “natural” rates of forested hillslope sedimentation (without significant human impact) fall within a two-order-of-magnitude range of about 0.01 to 1.00 mm yr⁻¹. Four of our five measured sedimentation rates that postdate the maximum influx of charcoal fall well within this range (Fig. 2), and only one barely exceeds it (1.02 mm yr⁻¹ at Ihitsaga). Thus, even the human-influenced sedimentation rates in Larrau are comparable with “natural” background rates. In summary, while we are able to document legacy sediment attributable to human actions in the Pyrenees, the landscape does not appear to have been significantly “degraded” in the sense of severe erosion and soil loss from the pastures.

5.2 Pastoral transformation of soils

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 and probably thousands 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 much more water than the predecessors of native forest soils. This has important implications for certain aspects of watershed hydrology, such as maintenance of baseflow, resistance to droughts, and minimization of flooding. In Larrau, the human-induced landscape transformation from native forest to pasture appears to have been *beneficial* and contrasts sharply with the more stereotypical outcome of landscape degradation.

The pastured soils appear to be slightly less fertile than the forested soils in terms of inorganic nutrients, and in this respect there may have been minor human-induced degradation. Four mechanisms possibly explain this depletion of inorganic nutrients in the pastures. First, the pastured soils lack deep roots to extract nutrients from the subsoil, unlike the forest soils that can replenish nutrients to the surface through transfers from deep roots (GOUDIE 2013: 114). Second, nutrients are being exported in the bones, tissue, fluids, and hair of sheep and other grazers, and this becomes especially noticeable over long periods of time. Third, several studies have concluded that frequent fires lead to decreased nutrients in soils by losses to erosion, to the atmosphere, and to enhanced leaching of ash compounds (MCINTOSH et al. 2005). Fourth, the inorganic nutrients are being “diluted” as the A horizon of the pastures builds up at the expense of precursor E and B horizons of the former forest soil, and those precursor soil horizons inherently had fewer nutri-

ents (i.e. were already leached) compared to the original A horizon. Indeed, all four processes are operating on the landscape in Larrau and contributing to the depleted inorganic nutrient status of the pastures, but it is difficult to determine the relative importance of each process.

In contrast to most of the inorganic nutrients, the other measured nutrient components of organic matter (% LOI), total carbon (C), total nitrogen (N), C/N ratio, and phosphorus (P) are not significantly different between the pastured and forested soils. In fact, much more carbon and nitrogen are being stored in the pasture soils because the concentrations of those elements are almost identical between forests and pastures (Table 1) while the average thickness of the A horizon in pastures is about three times that of forests. In this respect the transformation to pastures has been very beneficial. Phosphorus may not be significantly different because of geochemical pathways of plant available phosphorus that are enhanced by plant growth and animal excretions.

5.3 *Humans and long-term soil evolution*

Pedogenically, the soils in Larrau provide a fascinating example of indirect human agency altering pedogenic processes over millennial timescales. This timescale of human-impact on soil evolution is largely unknown in scientific literature. Earlier on, YAALON & YARON (1966) recognized human alteration of soils, and currently RICHTER (2007) argues for the recognition of humanity as a “sixth” factor of pedogenesis, but these calls for recognition of humanized soils focus on decadal timescales. Indeed, there is virtually no discussion of millennial-scale human alteration of pedogenic processes in textbooks (e.g. SHCAETZLE & ANDERSON 2006, BUOL et al. 2011). Recently, CERTINI & SCALENGHE (2011) recognized direct human impact on soil as a focal point for resolution of the Anthropocene (CRUTZEN 2002, ZALASIEWICZ 2011), but they merely suggest 2,000 cal yr BP as the turning point when humanity is registered within soil and focus primarily on mechanical alterations and direct additions to soil. Indeed the World Reference Base for Soil Resources (IUSS WORKING GROUP WRB 2006) includes “Anthrosols” of many sorts, but they are attributed to many types of direct additions, manipulations, and alterations of soils, rather than to redirection of pedogenic pathways and processes like we observe in Larrau. Thus, we believe that the long-term alteration of pastoral soils in Larrau contributes to a better understanding of shifting processes and pathways of soil evolution like those discussed by SIMONSON (1959), RUNGE (1973), and JOHNSON & WATSON-STEGNER (1987) by advancing the long-term human element into those models.

5.4 *Why are the pastured soils not more degraded?*

Our data suggest that native forests of the western Pyrenees were transformed to pastures several thousand years ago, probably involving frequent use of fire, yet the landscape and soils are not significantly degraded. Inorganic nutrients are slightly depleted in the pastures, but not to the point that it becomes a limiting factor for vigorous growth of grass in pastures. The erosion rates in the pastures are slightly greater than in the native forests, but only marginally, and not detrimentally so. Organic matter accumulation has resulted in much thicker A horizons and much

better structure in the pastured epipedons. Better structure has in turn significantly increased the hydraulic conductivity of the soil. These soil improvements (organic build-up and increased Ksat) have important implications for conservation and sustainability of pastoral landscapes, and one may ask: why and how have these pastures obtained and maintained their beneficial pedogenic and hydraulic qualities? Our observations suggest a simple answer: the pastoral landscape has not been overgrazed. Overgrazing appears to be a common cause of degradation in pasturelands (OTTERMAN 1974, GOUDIE 2013: 49, 121, 123, 187). Animals (mainly sheep) roam the pastures of Larrau only during the summer, and their densities do not appear to be very high. Thus, soil compaction and reduced rainfall infiltration is not a problem in Larrau, nor is reduced vegetation cover and erosion. In short, the agropastoral uplands of the French western Pyrenees, at least in Larrau, stand in contrast to conventional degradation narratives of millennially grazed landscapes. The apparent sustainability of this landscape suggests that over the long term, agropastoral land use actually can result in changes to soils and landscapes that facilitate conservation.

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