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Transhumance and long-term deforestation in the subalpine belt of the central Spanish Pyrenees: An interdisciplinary approach

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ABSTRACT

A key problem in explaining the mountain landscapes of the Mediterranean region is the relationship between the development of transhumance (seasonal movement of livestock over long distances) and deforestation of the subalpine and upper montane belts at 1350–2200 m above sea level (m a.s.l.). We examined this relationship in the Central Southern Pyrenees using information from multiple proxies—archaeology, pollen analysis, lacustrine sedimentation patterns, historical documents, and geomorphology. Although there is evidence of forest clearing since the Neolithic, and we can infer the presence of shepherds and livestock in mountain areas based on archaeological sites and pollen analysis in some lacustrine records, there is no strong evidence for transhumance between the Ebro Depression and the Pyrenees during the Prehistory. Instead, we found evidence of transterminance (seasonal movement of livestock over short distances) during this time. Growth of human populations and the establishment of large-scale markets favored longer livestock movements during the Roman period, although we only have indirect information on this for other areas of the Iberian Peninsula and the Mediterranean region. A few documents indicate the occurrence of transhumance during the Early Middle Ages, whereas all other proxies indicate a general expansion of livestock and transhumance during the 12th and 13th centuries. This coincides with the Christian conquest of the Central Ebro Depression by the Aragon Kingdom, the organization of large wool markets in Western Europe, and the exemptions conferred by the kings of Aragon to herders in the city of Saragossa. This led to rapid deforestation, in that forests were rapidly logged or burned to expand the summer grasslands. During this period, written documents indicate many conflicts between people in the villages and valleys for control of summer grasslands, pollen analyses show a rapid decline of arboreal pollen, and geomorphology studies indicate greatly increased sedimentation rates following deforestation, suggesting intense erosion. Transhumance has declined since the end of the 18th century, and particularly throughout the 20th century, and this has led to tree re-colonization of less accessible and marginal areas. The hydrological and geomorphological consequences of these recent events are important topics for future studies.

1. Introduction

Mountain areas are mainly defined by their altitude and slope gradients and by the presence of distinct altitudinal geoecological belts (Troll, 1972, 1973; García-Ruiz et al., 2015). Alexander von Humboldt first described these geoecological belts at Mount Teide in the Canary Islands and in South America during the early 1800s (Wulf, 2016). With the exception of mountains in the Arctic and Antarctic, a mountain must have at least two altitudinal belts to be considered an authentic mountain (Byers et al., 2013). Mountains thus have several altitudinal belts of vegetation, such as montane, subalpine, and alpine.

Since Neolithic times, land management of mountains has been

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based on the knowledge of (i) the diverse opportunities that altitudinal belts provide for obtaining a range of resources; (ii) the topographic and topoclimatic variability of the slopes according to insolation, gradient, redistribution of soil fertility, and water circulation (García-Ruiz and Lasanta, 2018); and (iii) complementarity of distinct altitudinal belts for optimizing grazing management and livestock cycles (Puigdefábregas and Fillat, 1986; Rodríguez Pascual, 2010; Fernández-Giménez and Fillat Estaque, 2012; Oteros-Rozas et al., 2013).

For centuries, one of the most characteristic features of mountains of the temperate zone was transhumance—the seasonal movement of livestock (mainly sheep and goats, occasionally also cows and horses) to high elevations during summer and low elevations during winter (Berezowski, 1971). This represented a holistic interpretation of vegetation complementarity between grasslands and scrublands in the lowlands (usually grazed from October to May) and the upper montane, subalpine, and alpine belts (which reach maximum grassland productivity from late spring to late summer) (Ruiz and Ruiz, 1986; Puigdefábregas and Fillat, 1986). Transhumance usually implies a long movement of livestock, in some cases hundreds of kilometers, along routes that link highlands with areas far outside the mountains. Stockbreeders from the mountains and the lowlands have traditionally practiced transhumance (Puigdefábregas and Balcells, 1966; Costello and Svensson, 2018). The term "transterminance", or "valley transhumance" (Fernández Mier et al., 2013), refers to local livestock movements within a mountain, in which there is no exploitation of grasslands outside the mountain. In this case, livestock remains in the valley bottom around villages and hamlets during the cold season and moves about 10–25 km to the high mountain region during summer, so that all management occurs within the same mountain (Fernández Mier and Tente, 2018; Fernández Lozano and Cabero Diéguez, 2017). Antolín et al. (2018) noted there is confusion in use of the terms "transhumance" and "transterminance" because the literature does not provide clear definitions and because there are multiple interpretations of transhumance (Costello and Svensson, 2018). In any case, Antolín et al. (2018) propose that "transhumance" should be used restrictively to refer to long-distance movements of herds. In both transhumance and transterminance, the subalpine belt is a key resource for the movement of large livestock herds. These movements of thousands of sheep, goats, cows, and horses have occurred in the Pyrenees for hundreds of years, and they still occur, although at a declining level (O'Flanagan et al., 2011).

Transhumance and transterminance were the reason for the enlargement of the area occupied by subalpine grasslands, due to an imbalance in the extent of winter and summer grasslands (Fig. 1). The subalpine and montane belts were forested since the beginning of the Holocene (González-Sampériz et al., 2017), although they have undergone progressive deforestation historically. Most of the Pyrenean subalpine and upper montane belts are currently covered with grasslands, isolated trees, and forest patches, with evidence of the extensive previous occupation by conifers (*Pinus uncinata, Abies alba*, *P. sylvestris*) and deciduous trees (*Fagus sylvatica*) (Montserrat, 1971, 1988). These human-induced deforested areas, used as grazing areas from May to October, are the object of this study.

The upper limit of the subalpine and montane belt is at approximately 2200 m above sea level (m a.s.l.), where more extreme climatic conditions indicate a transition to the alpine belt. The lower limit is highly variable, depending on topographic accessibility for grazing, and the pressures of local shepherds. Usually, the lower limit of the summer grasslands is at approximately 1600 m a.s.l. (Montserrat, 1971, 1988), although it can be as low as 1500 m a.s.l., and in exceptional cases at 1300 m a.s.l., coinciding with the bottoms of U-shaped valleys. For this reason we use the term "subalpine grasslands" or "subalpine belt" for areas that also include parts of the upper- and mid-montane belts that were deforested for summer grazing. This radical change in plant cover has had major hydrological and geomorphological consequences, including changes in snowmelt processes and overland flow

Fig. 1. The subalpine belt in the Acherito Valley, a tributary of the Aragón Subordán River, as an example of the current landscape after centuries of livestock management. The bottoms and hillslopes of glacial U-shaped valleys have been the preferred landscapes for summer grazing because of accessibility, topoclimatic variability and biodiversity for the distinct types of livestock. The subalpine belt of the Pyrenees and other Mediterranean mountains was deforested to enlarge the area of summer grasslands and thereby balance the winter resources (lowlands) and summer resources (highlands).

(Puigdefábregas and Alvera, 1986; Lana-Renault et al., 2011; López-Moreno et al., 2012), and activation of certain geomorphic processes, particularly shallow landslides (García-Ruiz and Puigdefábregas, 1982; García-Ruiz et al., 2010), soil erosion, creeping, rilling, and solifluction (Höllermann, 1985).

Historically, trees were harvested from some mountain areas for use as commercial timber, or production of resin and charcoal (Bielza de Ory et al., 1986; Palet et al., 2010; Tomás-Faci and Laliena, 2016), although most authors attribute deforestation to the increasing need for summer grasslands, which dates back to Neolithic times in some cases. In fact, the presence of megalithic monuments, which are particularly numerous in the mid-montane and subalpine belts, are evidence of early seasonal livestock movements (Blondel, 2006; Montes et al., 2016b, 2016a; Rojo Guerra et al., 2013; Tornero et al., 2016). Similarly, research suggests that remnants of charcoal fragments in subalpine soils and in lacustrine sediments are due to manmade fires designed to open up the forest during the Neolithic and the Bronze Ages (Connor et al., 2019). These activities occurred in the Pyrenees (Bal et al., 2011; Gassiot et al., 2014), other ranges of the Iberian Peninsula such as the Urbión Massif in the Iberian Range (García-Ruiz et al., 2016), and in the Cantabrian Mountains (Carracedo et al., 2017; Pérez-Díaz et al., 2018). However, other researchers emphasized that these fires could have had mainly a natural origin, and that deforestation had minor effect prior to the Middle Ages (González-Sampériz et al., 2019).

In spite of the importance of landscape changes in the subalpine belt, some crucial questions remain. First, we do not know exactly how deforestation progressed, nor the most critical times of deforestation, because it is extremely difficult to reconstruct the landscape and extent of deforestation in prehistoric times. A second question is the origin of transhumance. At present, information on the origin of transhumance seems to be fragmentary, based on historical documents, and published in national or regional historical journals and books that are mostly inaccessible to environmentalists, despite the extreme importance of transhumance as a global factor that changes landscapes.

Studies of changes in plant cover and its relationship with transhumance are important to specialists in multiple fields, including geographers, geologists, paleoenvironmentalists, pre-historians, and historians. Unfortunately, over-specialization of researchers may cause them to overlook useful information from similar or related fields.

Environmental studies currently use an interdisciplinary approach, and consider information from a variety of sciences, in the belief that science mainly advances at the frontiers between disciplines. For this reason, a multidisciplinary group of scientists collaborated in the present study to provide a global perspective about the evolution of deforestation and the advance of grasslands in the subalpine belt, and the relationship of these processes with the origin and development of livestock management and transhumant movements.

We reviewed publications that examined different historical periods (ancient, medieval, modern, and contemporary) and from different disciplines (geology, ecology, and geography). Many of these publications used proxy measurements (pollen analysis; micro-charcoal content and sedimentology from paleolakes, lakes and peat bogs; geomorphological mapping; charcoal dating from soils affected by shallow landslides; data from archaeological sites) and historical documents. Our diverse backgrounds allowed us to synthesize this complex and varied information to examine the relationship between livestock management—particularly the development of transhumance—and deforestation of the subalpine belt.

2. Study area

The study area is the Central Spanish Pyrenees, in the region between the Veral Valley (to the west) and the Noguera Ribagorzana Valley (to the east), and between the French border (to the north) and the contact between the Pre-Pyrenees and the Central Ebro Depression (to the south). The subalpine belt (1600–2200 m) within this region is the main focus (Fig. 2). To simplify the terminology, we use the term "Central Pyrenees" (or "Aragon Pyrenees") for the study area; "Eastern Pyrenees" for land east of the Noguera Ribagorzana Valley (or "Catalonia Pyrenees"); and "Western Pyrenees" for land west of the Ansó Valley (or "Navarre Pyrenees").

Broadly speaking, the subalpine belt spreads over a large variety of geological environments including Paleozoic quartzite, limestone and shale outcrops, and Mesozoic/Cenozoic limestone, sandstone and flysch. Nevertheless, subalpine grasslands are particularly located in slopes of relatively gentle or moderate gradient and are almost excluded from rocky, steep outcrops. Glacial U-shaped valleys, tills, deep-seated landslides and old erosion surfaces with deep soils have generally been the best valued areas for summer grazing.

The Mediterranean and Atlantic regions influence the climate of this region, with increasing continentality and Mediterranean influence east of the Gállego Valley. After removal of elevation effects (0.55 °C per 100 m a.s.l.; Navarro-Serrano et al., 2018), average annual temperature follows two gradients, one increasing from west to east and the other increasing from north to south; precipitation clearly decreases from north to south (in parallel with altitude), and ranges from 700 to 800 mm at 800 m a.s.l. to approximately 2000 mm at 2000 m a.s.l., and slightly less above 2000 m a.s.l. (Del Barrio et al., 1990). Snowfalls are common from November to May or even June, with remarkable snow accumulation above 1650 m a.s.l., and rapid snowmelt during April, May, and June (López-Moreno and García-Ruiz, 2004). Five elevational belts distinguish the Central-Western Pyrenees (Montserrat, 1988; Benito Alonso, 2018). The basal or hilly belt, also called the meso-

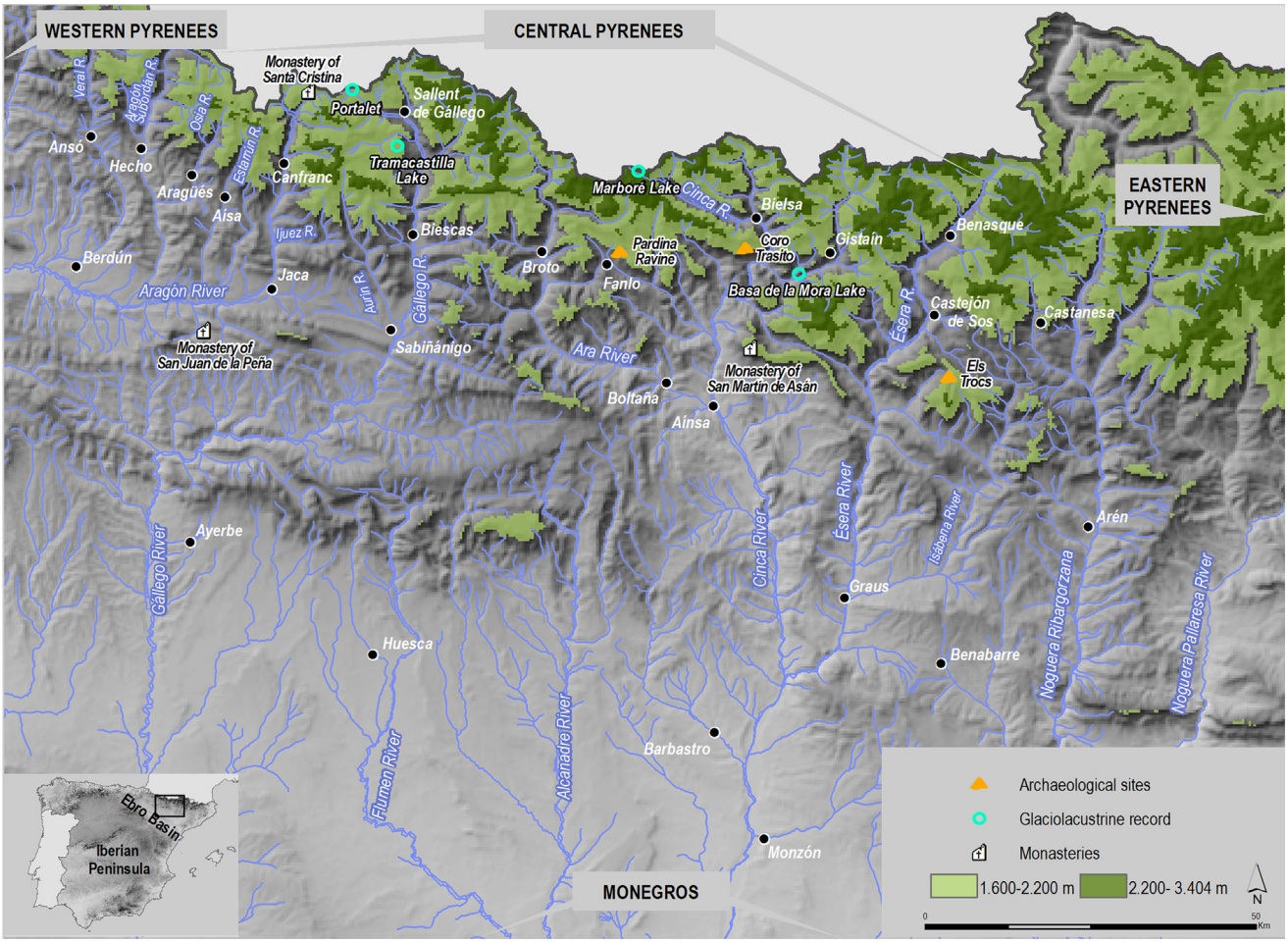

Fig. 2. The study area. The location of main rivers and villages is included, as well as the extent of the upper montane and subalpine belts (in light green) and the alpine and nival belts (in dark green). Valleys, settlements, archaeological sites, glaciolacustrine deposits, and monasteries cited in the text are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mediterranean belt (800–1000 m a.s.l.), is dominated by cultivated fields, *Quercus* gr. *faginea* forests, and sub-Mediterranean shrubs. The montane (or supra-Mediterranean) belt (up to 1650 m a.s.l.) is dominated by abandoned fields on south-facing slopes, extensive *Pinus sylvestris* forests in north- and south-facing slopes, and *Fagus sylvatica* forest in north-facing (particularly concave) slopes. The subalpine (or oro-Mediterranean) belt (up to 2200 m a.s.l.) was originally covered with *Pinus uncinata* forests, but is now almost completely deforested and consists of extensive grasslands. The alpine (or cryo-Mediterranean) belt (2200–2900 m a.s.l.) has grasslands alternating with large rocky areas. The nival belt has prevailing rock outcrops and scree accumulations. Notably, the lower limit of the subalpine belt roughly coincides with the location of the 0 °C winter isotherm, which is approximately the lower limit of the permanent cold season snow cover (Del Barrio et al., 1990).

3. Changes in the subalpine belt of the Pyrenees in relation with livestock management

3.1. Livestock management and landscape transformation during prehistory

Knowledge of the presence of humans and landscape changes in Mediterranean mountains has increased rapidly during recent decades (Palet et al., 2010), mainly studies in archaeology, palynology, and paleolimnology. In particular, studies of the Pyrenees have examined the Eastern region (Riera et al., 2004; Pèlachs et al., 2007; Ejarque et al., 2010; Bal et al., 2011; Cunill et al., 2012; Catalán et al., 2013; Gassiot et al., 2014; Orengo et al., 2014; Palet et al., 2014; Garcés-Pastor et al., 2017), the Central region (Montserrat, 1992; González-Sampériz et al., 2006, 2017; Morellón et al., 2009; Pérez-Sanz et al., 2013; Leunda et al., 2017, 2019), and the northern face (Galop, 1998, 2016; Aubert et al., 2004; Rius et al., 2012; Le Couédic et al., 2016; Rendu et al., 2016).

Archaeological evidence demonstrated that some pastoral activity was present in the subalpine and mid-montane belts since the early Neolithic (ArchaeoGLOBE Project, 2019). In the Eastern Pyrenees, archaeologists have identified and dated shelters, shepherd huts, enclosures, ovens, charcoal kilns, and megalithic monuments in the Andorran valleys (Palet et al., 2014), even above 2000 m a.s.l. Miras et al. (2010) found evidence of human impact in this region from 5300 to 4900 cal BCE, and of a previous occupation at 5544 ± 69 cal BCE, in which the percentage of pine pollen declined. There was also increased human presence from 4350 to 3500 cal BCE (Orengo et al., 2014), based on the presence of coprophilous fungal spores and ruderal species, suggesting forest clearance related to grazing activity. At 3500 cal BCE, Ejarque et al. (2010) reported a decline in the elevation of the upper forest limit (timberline) in the same valleys. Notably, forest clearing only occurred in small areas, most likely because of the small sizes of the sheep and goat herds, and open forest areas for grazing alternated with woodland recovery (Ejarque et al., 2010). In the Central Pyrenees, archaeologists have clearly confirmed early human activity in sites such as the Pardina ravine (Ordesa and Monte Perdido National Park; Laborda et al. 2017), based on excavation of several rock shelters with archaeological remnants corresponding to the late Neolithic and Chalcolithic eras or earlier. Some studies suggested that grazing and deforestation during the Neolithic and Bronze Age affected the mid-montane belt and the upper forest limit at its contact with the alpine belt. For example, Palet et al. (2010) found two huts and a livestock enclosure located at 2500 m a.s.l. dated at 2400–2160 cal BCE. In the French Pyrenees, Galop (1998) noted early altitudinal declines of the upper forest limit at approximately 2900 BCE (4850 BP). Parallel studies in the Central Pyrenees at the archaeological sites of Els Trocs in the Isábena valley (Rojo Guerra et al, 2014, 2018) and Coro Trasito in the Cinca valley (Clemente et al., 2014, 2016; Obea Gómez, 2014) indicated the presence of intermediate or transitional grazing areas at approximately 1500 m a.s.l., between the valley bottoms (700–900 m a.s.l.) and the highest grassland areas. These intermediate areas would be mostly grazed during May, June, and October, in parallel with seasonal livestock movements.

Palynological analyses of glaciolacustrine deposits are less conclusive. For instance, Montserrat (1992) dated charcoal in the Tramacastilla Lake (Upper Gállego Valley) to 4000 cal BP, although recovery of the forest was rapid, indicating little human impact. In the Basa de la Mora Lake (Cinqueta Valley; Pérez-Sanz et al., 2013), the landscape was densely forested, as well as the area around the El Portalet peat bog (Upper Gállego Valley), at least until 5000 cal BP (González-Sampériz et al., 2006). A similar situation can be inferred at a regional scale from the Marboré Lake record (Leunda et al., 2017). Nevertheless, fire activity increased at ca. 3700 cal BP, indicating a reinforcement of human activities and forest clearing (Leunda et al., 2020).

In any case, most studies considered the changes in plant cover to have been limited, in that there were only small forest clearings that changed location due to recolonization and creation of new clearings. The impact progressively increased during the Bronze Age and the beginning of the Iron Age (Galop, 1998, 2016; Le Couédic et al., 2016; Rendu et al., 2016), as in the Swiss Alps (Colombaroli et al., 2010).

What was the significance of seasonal livestock grazing in the subalpine belt? It is difficult to provide a definitive answer. Some researchers have repeatedly used the term “transhumance” (Higgs, 1976; Blondel, 2006; Rojo Guerra et al., 2013; Tornero et al., 2016), but others have consistently rejected this term (Chapman, 1979). Davidson (1980) suggested that the presence of Neolithic and Bronze Age lithic manufacturing along the transhumant pathways must be interpreted with caution. Fairén Jiménez et al. (2006) prefer the use of “transterminance” (short-distance displacements from a valley bottom to a subalpine grassland), and reject the occurrence of long-distance livestock movements because this would require regulations among different territories.

It is generally accepted that deforestation is intimately linked to transhumance and transterminance, although large wild herbivores would have been able to partially open the forest during the Holocene (Vera, 2000; Montserrat-Martí and Gómez-García, 2019). The main problem is that most information on primitive livestock cycles and deforestation is indirect and fragmentary, making it difficult to infer the details of livestock management during the Neolithic and the Bronze and Iron ages. We know that shepherds with their herds of sheep and goats were present in the subalpine belt of the Pyrenees during summer. The large number of dolmens and stone circles is evidence of the seasonal importance of the subalpine belt for these local shepherds, as they show an interest in demonstrating to others ownership of the space (e.g. Domínguez and Calvo, 1990; Andrés Rupérez, 2000; Fernández Mier et al., 2013, for the Cantabrian Mountains), because people do not typically bury their dead in a strange territory. Some authors conclude that the presence of these structures supports the presence of large seasonal livestock movements (Rojo Guerra et al., 2013; Tornero et al., 2016) from the lowlands to the highlands—the initiation of transhumance.

To identify the origins of transhumance, it is essential to know the reasons why people would want to develop this system. Transhumance is a difficult and strenuous activity that requires significant personal and familial sacrifices, exposes individuals to many dangers, and can only occur under certain conditions. Besides, we must consider that because the movement of large herds affects many people it must be profitable. For this reason transhumance is only possible when there is: (i) a period of population growth and relative prosperity that allows establishment of increasingly important regional and national markets; and (ii) political stability and the substitution of territorial fragmentation by more complex forms of organization with a supra-regional political regulation that ensures the movement of shepherds and livestock, or a network of alliances that is continually renewed (Galán Domingo and Ruiz Gálvez, 2001; Fairén Jiménez et al., 2006). Instead, transterminance, short-distance livestock movements between the valley

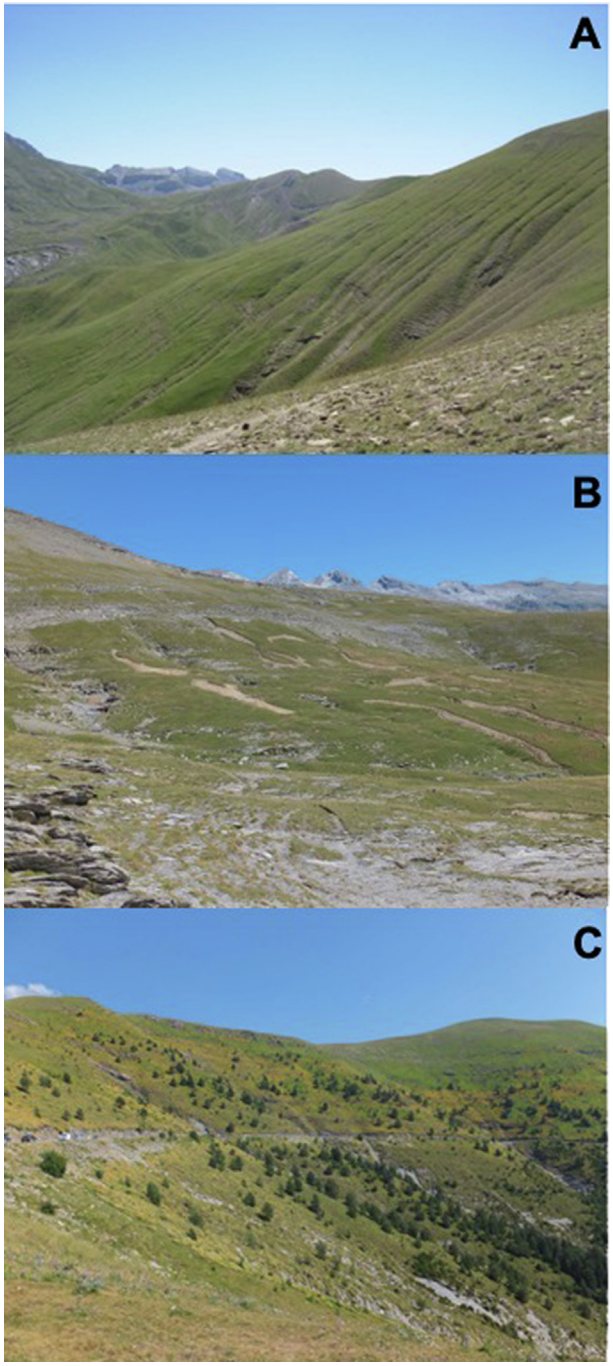

Fig. 3. A: Parallel rills/gullies in the Agüerri Valley, a tributary of the Aragón Subordán Valley. These erosion landforms suggest the occurrence of local deforestation in steep slopes prior to the Middle Ages, given the deep incision into flysch bedrock, although the exact time of their occurrence is uncertain. B: Shallow landslides in a deforested area of the Añisclo Valley, close to the Plana Canal Mountain Pass, Ordesa, and Monte Perdido National Park. Deforestation of the subalpine belt led to development of shallow landslides that affected deep soils in slopes with gradients over 15° (García-Ruiz et al., 2010). C: Many summer grasslands were abandoned following depopulation and the transhumance crisis in the Mediterranean mountains. In the Central Pyrenees, the livestock decline led to a rapid recovery of the hillslopes with *Echinospartum horridum* (indicating the recurrent use of fires). At present, young pines (*Pinus sylvestris*) have naturally established as a new forest colonization front.

bottom and subalpine belt of the same mountain, was common. This is supported by the presence of megalithic monuments and limited deforestation in the subalpine belt. Nevertheless, it is possible there were some occasional long-distance movements of herds prior to the Roman period in other parts of the Iberian Peninsula, as suggested by the presence of cinnabar in the bones of domestic animals in the Iberian Range (Logemann et al., 1995; Gómez-Pantoja, 2001), some hundreds of kilometres away of the Alcudia Valley (Southern Spain), where mercury mines were present.

Nevertheless, there is a remaining unsolved geomorphic problem that is most likely related to deforestation. Some slopes in the subalpine belt are affected by intense rilling and gullying, with a dense network of parallel incisions that, in their lower stretches, are up to 3 m deep in the flysch. Such extreme degradation of this relatively hard bedrock must have occurred over a long time in a deforested environment. Were these slopes deforested during the Neolithic and Bronze Age? This is a pending question suggesting that some slopes would have been deforested early, experienced strong erosion and faced difficulties for forest recovery (Fig. 3A).

As suggested by archaeological structures in the subalpine belt and evidence of agriculture in the valley bottoms, farmers would migrate in late spring with their small herds to the intermediate-altitude grasslands. They then moved in summer to the highest grasslands, close to the timberline, and activities there caused a progressive, although initially limited, decline of the upper forest limit. In October, the herds returned to the valley bottoms, and they grazed in the surroundings of small hamlets. The absence of regional or national markets and cities, and the absence of a consistent political organization exclude the possibility of transhumant herds coming from more than 100 km.

3.2. Evidence of livestock management during the Roman period (2nd century BCE to 5th century BCE) and the Early Middle Ages (5th to 9/10th centuries)

Little is known about the occurrence of seasonal livestock movements during the Roman period, although some indirect evidence suggests an increasing importance of grazing along with a general increase of human activities (Diarte-Blasco, 2018). In general, the Roman conquest of *Hispania* led to significant changes in the social, cultural, and economic life of the Iberian Peninsula (Santos Yanguas and Cruz Andreotti, 2012). This coincided with the “Warm Roman Period”, from 250 BCE to 450 CE (Desprat et al., 2003), which also increased land productivity. The Roman occupation was associated with increased deforestation due to military activities and the need for fuel and materials for building and transport (Hughes, 1994; Aranbarri et al., 2014) and with intensive cultivation, particularly in the lowlands.

The mountain areas were also affected by mining, charcoal production, logging, and hunting (Palet et al., 2010; López-Sáez et al., 2014). According to Gómez-Pantoja (2001), sheep herds were the main livelihood for people living in the interior of the Iberian Peninsula. Nevertheless, it is difficult to establish the consequences of this extensive grazing and its dependence on long-distance seasonal displacements in search of the best grasslands. Unfortunately, most archaeological remnants (e.g., huts, watering places, stalls) have disappeared because they were only transitory structures or because they were only scarcely studied, except in the Eastern Pyrenees (Ejarque et al., 2010; Bal et al., 2011; Catalán et al., 2013; Gassiot et al., 2014; Palet et al., 2014), in the Pardina Ravine of the Central Pyrenees (Laborda et al., 2017), and in the Cantabrian Mountains (González-Álvarez et al., 2016, 2018; González-Álvarez, 2019). Another complication is that the Latin terminology is often confusing. For example, the *pastio agrestis* of Varron (*r.r.* 3, 2, 13) could be a type of transhumance or livestock displacement, although we cannot currently determine the distance and the travel time associated with this terminology. This was not unusual in other Mediterranean regions. For example, in the Italian Peninsula, Varron (*r.r.* 2 *praef.*) reported that large sheep and mare herds moved between Sabina and Apulia. Gómez-Pantoja (2001) noted that transhumant livestock was economically profitable in the Italian Peninsula, and concluded that this practice also developed in Roman

Hispania, given the adequate climate conditions and the many ancient literary references to the excellence of Hispanic livestock (fast horses, large herds of beef cattle, large pigs in Lusitania and other mountainous areas, and many sheep herds). In the closest *Gallia*, Pliny (*NH* 21, 57) reported that the *campi lapidei* of *Arelate* (currently Arlès), a grassland area of ca. 600 km^2 at the foot of the Alpilles massif, accommodated thousands of sheep every year.

Studies of the Iberian Peninsula provide no definitive information on the occurrence of transhumance between the lowlands and highlands, although some indirect evidence suggests there was seasonal movement of livestock to optimize the use of grasslands. Gómez-Pantoja (2016) stresses that there is no reliable written evidence of transhumance before late antiquity, although there is indirect evidence of livestock movements from the 1st and 2nd centuries CE based on inscriptions indicating strategic points for livestock movements. These inscriptions include points for counting of sheep going from the northern Iberian ranges to the winter grasslands of the Guadiana River, and mention of the regulation of grasslands. Besides, we must consider that Romanization entailed control of this territory and the organization of a complex administration supported by a powerful army. This meant the construction of a dense network of roads, increased security, and particularly the opportunity for increased relationships among distinct territories that previously were controlled by different authorities (Galán Domingo and Ruiz Gálvez, 2001). It is obvious that the existence of rules, norms, and laws, the writing of documents with permissions, and confirmation of property favored the spatial integration of land for the first time in *Hispania*. Besides, the foundation and growth of cities and the opening of larger markets provided opportunities for rural development (Alfaro Giner, 2001).

The flourishing of livestock during the Roman Period was confirmed at many sites. For instance, in the Aralar Sierra (Navarre), located between the western Pyrenees and the Cantabrian Mountains, Mujika Alustiza et al. (2013) documented many materials of Roman origin. These authors proposed two possible livestock management systems: seasonal local movements with short journeys, and long-distance transhumant movements. This second system was documented in other parts of the Roman Empire (Gabba and Pasquinucci, 1979), such as the transhumance of large sheep herds used for wool production (Leveau, 2016) since the 2nd century BCE (García Martín, 2001; Gómez-Pantoja, 2001). Nevertheless, even if the environmental conditions of the Iberian Peninsula could accommodate long-distance transhumance, Gómez-Pantoja (2001) confirmed that its occurrence is not easily documented because of the historical opacity of grazing activities, and the absence or rarity of vestiges.

In the Eastern Pyrenees, the Madriu, Perafita, and Claror valleys (Andorra), have evidence of increased pastoral activity from the middle of the 1st century to the middle of the 5th century CE at approximately 2200 m a.s.l. The greater livestock pressure on these subalpine and alpine grasslands is based on pollen analyses, which indicate a loss of forest and a greater floristic diversity (Ejarque et al., 2010). The presence of pines drastically declined, particularly during the 4th century CE (Palet et al., 2007). However, the need for more summer grasslands to feed the increasing number of livestock was not the only cause of deforestation and enlargement of subalpine grasslands; resin extraction, charcoal production, and metallurgic activities were also responsible. Ejarque et al. (2010) and Palet et al. (2010) identified a kiln used for resin extraction dated at about the 2nd century CE, and found many kilns at 2200–2350 m a.s.l. Catalán et al. (2013) reported an increase of archaeological sites in the National Park of Aigües Tortes and Sant Maurici during the Iberian-Roman period and the Roman Imperial Period (1st–4th/5th centuries), with evidence of livestock enclosures and exploitation of iron minerals. This practice would clearly reduce the extent and density of natural forests, making them more easily grazed henceforth. All of this information indicates there were significant enlargements of cleared areas during the Roman period, although most of the deforestation occurred in the upper subalpine belt (Ejarque et al., 2010) and the valley bottoms for agricultural purposes, in a similar way than in the Cantabrian Mountains (Fernández Mier and Tente, 2018).

On the French side of the Pyrenees, remnants of permanent structures in the subalpine belt, with evidence of Roman hand-made pottery, are very common in Aquitania (Southern France) and *Hispania Tarraconensis* (Northern and Middle Spain). The route between Bordeaux (*Burdigala*) and Saragossa (*Caesaraugusta*) could have had a remarkable influence in the development of some transhumance pathways, particularly in the Aspe and Ossau valleys. This is supported by the establishment of the city of *Beneharnum* (now Lescar) at the northern piedmont of the Pyrenees, which is related to agropastoral activities in the Entre-deux-Gaves area, including transhumance from the Landes of Gascony (now Aquitaine) to the summer grasslands in the Pyrenees (Callegarin et al., 2005; Réchin, 2000).

Summarizing, there are many indications suggesting transhumance during late protohistory or the Roman Period. These include: (i) the establishment of new forms of territorial administration and more complex political organization, developments that provided more security and facilitated interregional relationships; (ii) the increasing importance of cities, population growth, and the corresponding consolidation of local and regional markets; (iii) the progressive clearing of the forest in mountain areas, because of grazing, mining, metallurgy, and charcoal production; and (iv) indirect evidence from inscriptions and Roman writers that indicate livestock movements in distinct areas of the Iberian Peninsula and other similar areas in the Mediterranean region.

Based on our limited knowledge of seasonal livestock movements during the Roman period, it seems almost certain that some transhumance between the semi-arid lowland areas and the subalpine belt of the mountains occurred during the Imperial Roman Period, although we do not know its extent or significance. This, together with other activities, would explain the progressive, though limited, deforestation of mountainous areas at this time.

After the fall of the Roman Empire, the *Lex Visigothorum* (Law of the Visigoths) confirms the importance of large-scale livestock production. This law regulated free livestock movements (Butzer, 1988), and is a compilation of Roman Law and an up-date of the *Lex Agraria Epigraphica* (Agrarian Epigraphic Law) from the year 111 BCE (Gómez-Pantoja, 2016). A document dated at 551 CE from the Visigothic Monastery of San Martín de Asán (at the current Monastery of San Victorián, Cinca Valley, Central Pyrenees, according to archaeological vestiges), reports interest in having properties at the summer pastures of the Pyrenees, in the area of Sobrarbe, and in the dryland areas of the Central Ebro Depression, close to Caesaraugusta (Saragossa) and Ilerda (Lérida) (Fita, 1906; Fortacín, 1983; Tomás-Faci and Martín Iglesias, 2017). This is likely the first known document to indicate the complementarity of highlands and lowlands, and suggests the occurrence of seasonal livestock movements. Although the Arab conquest of the Iberian Peninsula at the beginning of the 8th century CE disrupted relationships between the Ebro Valley and the Pyrenees (the former dominated by the Arabs until the 11th and 12th centuries CE, and the latter by the Christians), there is evidence of continuing communication among the elites of both territories (Butzer, 1988). Thus, we cannot rule out that some movements of people and livestock could have survived the fragmentation of this territory. For instance, in the year 1023 CE the Muslim King Mundir of Saragossa allowed the Monastery of Sant Sadurni of Tavèrnoles (in the County of Urgell, Eastern Pyrenees) to access the Low Ribagorza, in the Central Ebro Depression, most likely for grazing during winter (Baraut, 1994–1995).

3.3. The Late Middle Ages (10th to 15th centuries): A key period for deforestation and transhumance

There are methodological difficulties in using written documents of the Middle Ages to study transhumance at that time because of the

drastic changes in the characteristics of documentation between the 13th and the 14th centuries. This is because of the emergence of public notaries, the introduction and growth in the use of paper, and the beginning of administrative documentation during this period (Pascua Echegaray, 2012; Menant, 2015). Thus, apparent changes in deforestation, transhumance, and other factors could simply be due to changes in the way information was recorded and transferred. In general, documents prior 1300 CE provide information on the rights of land-use, the appropriation of territory or tax exemptions in grazing areas, above all in the case of monasteries or other ecclesiastical institutions, and to a lesser extent aristocratic people and town councils. These documents were preserved to record the rights of land use and management (Cursente, 2016).

Information on the use of pastoral resources is scarce before the 12th century suggesting that these resources had a limited importance (Tomás-Faci and Laliena, 2016). Interestingly, during the Early Middle Ages, socially prominent people of the Central Pyrenees had constant disputes regarding the control of agricultural resources (as inferred from monastic cartularies, from San Juan de la Peña to Alaón) (Ubieto, 1962–63; Corral, 1984). Since the second half of the 12th century, documents regarding the property and the use of the subalpine belt became more common (Pallaruelo, 1993). This is clear evidence of the increasing importance of livestock and transhumance between the highlands and lowlands. In fact, we can assume that if the competence for the property of a resource increases, an increasing use of such resource occurs. Most documents on this topic refer to ecclesiastic institutions, although the oligarchy of the city of Saragossa also succeeded in the fight for summer pastoral resources (see below). Utrilla et al. (2005) stressed the importance of Christian monasteries as major livestock owners and the existence of royal concessions granting herders the right to graze in summer grasslands. These authors thus confirm the occurrence of transhumance in the 10th century. Other document of the 12th century indicate that King Pedro I exempted the Monastery of San Juan de la Peña from paying taxes for its sheep herds at any place in the Kingdom of Aragon, where they used to graze during winter and summer (Utrilla et al., 2005).

The control of the subalpine belt had a major impact on the functional organization of the Pyrenean valleys during the 12th and the 13th centuries (Pascua Echegaray, 2012). Utrilla et al. (2005) emphasized the revaluation of summer grasslands in Pyrenean valleys after the end of the 12th century, and the interest of the great monasteries in obtaining royal exemptions that provided them free circulation and grazing rights in the whole Kingdom of Aragon. In the Ésera Valley, the most important and disputed area during the Early Middle Ages was the agricultural plain of Castejón de Sos, and subsequently the headwaters of the valley, where the Benasque locality controlled most of the summer grasslands. A similar process occurred in the Castanesa Valley, where the Castanesa locality, previously irrelevant, became one of the main settlements in Ribagorza County because of its summer pastoral resources (Tomás-Faci and Laliena, 2016).

In the Central Pyrenees, some valleys lost control of their mountains to others due to political circumstances. The best example is the Ansó Valley, which was favoured by King Jaime I to obtain control of the grasslands and forests in the headwaters of the neighboring Echo, Aragüés, and Aísa valleys, and thereby reinforce its border with Navarre and France (Tomás-Faci and Laliena, 2016). At the end of the Middle Ages, the competence for the subalpine pastoral resources increased extraordinarily (Martín de las Pueblas and Hidalgo, 1999). Conflicts between Ansó and Echo for control of the headwaters of the Aragon Subordán Valley led to many casualties, until there was a definitive resolution during the 15th century, which led to the shared use of some of these disputed areas (Tomás-Faci and Laliena, 2016). In other cases, the increasing numbers of livestock led to land use changes; for example, vineyards dominated the plain of Castejón de Sos during the 11th century, but meadows dominated after the 14th century (Tomás-Faci and Laliena, 2016).

Changes in the subalpine grasslands coincided with the southward advance of Christian kingdoms and the decline of Muslims domains, which led to occupation of the semi-arid lands of the Central Ebro Depression and made grazing in large steppes and open forests possible. The city of Saragossa had a notable role from the beginning of the 12th century. In 1118, King Alfonso I conquered Saragossa, the main city (then and now) in the Ebro Depression, and designated it as the capital of the Kingdom of Aragon. With the purpose of attracting a new Christian population, he conferred to all the stockbreeders who were established in Saragossa the right of “universal grazing”, allowing them to graze any place in the Kingdom of Aragon. In 1218, King Jaime I reinforced this privilege with the creation of the (still existing) *Casa de Ganaderos* (House of Stockbreeders), an institution devoted to the defence of Saragossa’s stockbreeders against the interests of other stockbreeders and municipalities in other parts of the Kingdom of Aragon. This institution had the right to punish people who caused harm to livestock or shepherds from Saragossa (Serrano Martínez, 1997). There were several important consequences of these actions. First, the number of large herds greatly increased in Saragossa (most of them from southern France, Navarre, the Basque Country, and the Aragon Pyrenees), stockbreeding became the main economic activity, and many related artisanal activities also developed (Serrano Martínez, 1997). Second, many conflicts arose between Saragossa’s stockbreeders and the local shepherds, particularly in the Western region of the Central Pyrenees (including the Ansó, Echo, Aragüés, Aísa, Canfranc, Gállego and Broto valleys), because of the increasing grazing pressures on the subalpine grasslands during summer (Canellas, 1988; Fernández Otal, 1993). These conflicts were slowly resolved during the mid-14th century, particularly in the Ansó Valley (Tomás-Faci and Laliena, 2016). Most of transhumance movements connected the Ebro Valley with the Pyrenees and the Iberian Range. In addition, there were other transhumant circuits that linked Aragon to other neighbouring kingdoms (i.e. towards the Mediterranean coast and the south of Castile: Pascua Echegaray, 2012). Political boundaries did not block cross-border transhumance, although they were determinant in their geographical shaping. It is also noteworthy that the organization of stockbreeding and transhumance was quite different in the kingdoms of Aragon and Castile: in the former it was controlled by urban and rural owners grouped in local associations (the most important, the *Casa de Ganaderos*, from Saragossa), whereas the latter developed a unique centralized institution, the Mesta, which rather represented the interests of large owners (Pascua Echegaray, 2012). In any case, both kingdoms established rules for the preservation of transhumant routes called *Cañadas Reales*.

These large-scale changes in the Pyrenean economy during the Middle Ages were intimately linked to social and economic changes in Western Europe (Bourin et al., 2011). First, there was rapid population growth since the beginning of the 11th century, so that the number of inhabitants by about 1300 was greater than at any other time before the 18th century (Sesma and Laliena, 2004). This population growth was accompanied by an increase in overall production and productivity, because of the increasing economic specialization and the development of efficient commercial networks (Britnell, 1996; Sesma and Laliena, 2009). Besides, there was a spectacular growth of the wool market in Europe, particularly in Catalonia, Genoa, and Venice, throughout the 13th century (Munro, 2001; Sesma and Laliena, 2004). In the Kingdom of Aragon, economic specialization was achieved in the production of raw materials such as saffron, olive oil, and especially wool (Sesma, 2013), leading to a “golden period” for transhumance in the Pyrenees and the Iberian Peninsula (Diago Hernando, 2002). Of course, the Aragon monarchy also benefited from these dramatic economic transformations and the related development of transhumance. Thus, at the middle of the 13th century, King Jaime I created a uniform system for the payment of taxes by stockbreeders as they moved to and from the Pyrenees (Moret Oliver and Tomás-Faci, 2014).

Studies of lacustrine sediments indicated that humans have had a

major impact in the lower slopes of the Central Pyrenees (Riera et al., 2004; Morellón et al., 2009) since the 8th century. This impact included the increasing cultivation of cereals, grapes (for wine), olive trees, and hemp. However, evidence from the subalpine belt indicates that large changes in plant cover and hydrology occurred beginning in the 12th century (González-Sampériz et al., 2017, 2019). One of the best studied sites is the Basa de la Mora Lake (1900 m a.s.l.), in the headwaters of the Cinqueta Valley. Pollen sequences indicate the presence of a forested landscape during the late Holocene, suggesting limited human impact, but an abrupt decline in the percentage of pine pollen beginning in about 950 CE (Pérez Sanz et al., 2011). The pollen series at Marboré Lake (2600 m a.s.l.), in the Upper Cinca Valley, indicates a decline in the percentage of arboreal pollen during the last 1300 years, with a remarkable increase of non-arboreal pollen (Leunda et al., 2017), even though this lake is very far from arboreal pollen sources.

Montserrat (1992) studied Tramacastilla Lake (1670 m a.s.l.), in the Upper Gállego Valley and found a layer with abundant charcoal remnants that was associated with critical changes in plant cover that was dated to approximately 1000 years BP. This indicates a general deforestation of pines and beech trees, and an increase of grasslands. This author attributed the rapid deforestation to the need for more summer grasslands as the conquest of the lowlands of the Ebro Depression advanced. Charcoal data from the Basa de la Mora and Marboré sequences from 1250 years BP, and especially during the last 300 years, indicated increasing fire activity during recent centuries (Leunda et al., 2020). In fact, it is impossible to explain the rapid expansion and consolidation of transhumance without a widespread deforestation of the subalpine and upper montane belts, and their transformation into large open landscapes dominated by grasslands.

This deforestation manifested as an abrupt increase in the sedimentation of Tramacastilla Lake, due to activation of geomorphological processes, mainly shallow landslides (Fig. 3B), rilling, and gullying (Del Barrio and Puigdefábregas, 1987; García-Ruiz et al., 2010), and an increase in sediment grain size, clear evidence of enhanced overland flow. The problems created by excessive logging (used to enlarge summer grasslands and for timber harvesting) obligated some municipalities to approve by-laws that regulated forest exploitation, particularly in Ansó, at least since the 17th century and probably before (Tomás-Faci and Laliena, 2016) and Bielsa (Bielza de Ory et al., 1986).

Other researchers also found evidence of a major period of deforestation in the subalpine belt of the Pyrenees. Thus, Cunill et al. (2012) attributed the greater number of fires in the Upper Noguera Ribagorzana Valley during the Middle Ages to the increase of transhumant livestock. In Burg Lake (1821 m a.s.l.), between the Noguera Ribagorzana and Noguera Pallaresa valleys, the subalpine belt became an open landscape, with a strong decline of *Pinus* since 1450 cal BP (Bal et al., 2011). Reviews of landscape evolution in the Eastern Pyrenees also indicated an expansion of grasslands in the subalpine belt of the Catalonia Pyrenees (Pèlachs et al., 2007; Palet et al., 2014), in accordance with the development of transhumance during the 11th and 12th centuries (Roigé Ventura et al., 1993). The species of the original forests, dominated by *Pinus sylvestris* and particularly *P. uncinata*, were rapidly relegated to rocky, steep areas, where they were subjected to long periods of snow cover, low temperatures, snow and rock avalanches, and thin soils. In general, the current timberline is at approximately 500 to 600 m below the natural treeline, i.e. about 1600 m a.s.l., and even lower in some exceptional cases such as the headwaters of the Ansó and Echo valleys (see also Ninot et al., 2008, and Cunill et al., 2012, for the Catalonia Pyrenees). Similar changes also occurred in the French Pyrenees (Galop, 1998; Mazier et al., 2009; Rendu et al., 2016), the Iberian Range in the northern Iberian Peninsula, especially in Urbión Sierra (García de Celis et al., 2008; García-Ruiz et al., 2016), and in other European mountains (Guiguet-Covex et al., 2011; Roepke and Krause, 2013; Dietre et al., 2014).

All available information points out to an exceptionally rapid development of transhumance during the Late Middle Ages. Although there are some examples of long-distance livestock movements during the Early Middle Ages, the long distance movement of herds was definitively established during the 12th and 13th centuries, as in other Iberian mountains, e.g. the Gredos Sierra in the Central Range (López-Sáez et al., 2014, 2018) and the western Cantabrian Mountains (Fernández Mier et al., 2013; Fernández Mier and Tente, 2018).

Summarizing, the enlargement of summer grasslands to feed the transhumant herds was only possible by a systematic deforestation of the subalpine belt of the Pyrenees. This changed the mountain landscape at the expense of the forests above 1600 m a.s.l. Summer grasslands became the most important natural resource for the high Pyrenean villages, and were the cause for many human conflicts (Tomás-Faci and Laliena, 2016). Most forests were logged or burnt and transformed into large grasslands, starting a period of increased erosion and geomorphic destabilization of the slopes, as deduced from lacustrine sedimentation (Montserrat, 1992; Pérez-Sanz et al., 2013). This led to some authors determining this period as the beginning of the Anthropocene era in the Pyrenees during the 12th and 13th centuries (González-Sampériz et al., 2019).

3.4. Modern (16th to the end of 18th centuries) and contemporary (since the beginning of the 19th century) ages: Consolidation and crisis of transhumance

From the 14th century to the beginning of the second half of the 20th century, there were no large landscape changes in the subalpine belt of the Central Pyrenees. Transhumance was a sustainable and successful system until the 18th or 19th centuries, in that it allowed an increasing number of animals to travel between the Pyrenees and the Central Ebro Depression. New deforestation events cannot be ruled out in the less accessible areas because mountain communities wanted to increase their incomes by renting summer grasslands. For instance, Pérez Sanz et al. (2011) recorded changes in the pollen sequence of the Basa de la Mora Lake, with a decline in the percentage of arboreal pollen during the 17th and 18th centuries. Similarly, the Marboré sequence shows an intense decline of *Pinus* and an increase of fire activity since the end of the 18th century, and especially during the 19th century (Leunda et al., 2020). Also, logging at the end of the 19th century altered the headwaters of the Ijuez River, coinciding with a great population increase, and resulting in the development of large debris flows and a braided fluvial channel that was partially the consequence of deforestation in the subalpine belt (Sanjuán et al., 2016). Unfortunately, sedimentary records from paleolakes at high altitudes in the Pyrenees are scarce and provide limited details of the changes in vegetation of the subalpine belt after the Middle Ages. In any case, the potential capacity of summer grasslands in some Pyrenean valleys record extremely high values in the last centuries: for instance, 152,399 sheep in the Ansó Valley, 80,925 in the Echo Valley, 115,869 in the Gállego Valley, and 54,380 in the Benasque Valley (O'Flanagan et al., 2011).

It is well known that transhumance progressively expanded in this region until the end of the 18th century, when the greatest numbers of transhumant sheep were recorded (Le Flem, 1972). Many large churches in the main villages of the Pyrenees were built during the 16th century (Tomás-Faci and Laliena, 2016), in the same places where small Romanic churches were built centuries earlier, confirming this was a period of prosperity and population growth that affected the whole Kingdom of Aragon and the rest of the Iberian Peninsula. This period of widespread transhumance extended until the end of the 18th century, when many large stockbreeders collapsed and the number of sheep declined (Diago Hernando, 2002). Consequently, the pressure of livestock on the subalpine grasslands was strong enough until the beginning of the 19th century to maintain the high quality of the summer pastures and prevent the re-colonization of trees. The transition between the 18th and the 19th centuries is also when Saragossa's *Casa de Ganaderos* experienced a marked decline in its power and when

pressure on summer grasslands started to decline (Serrano Martínez, 1997). The causes of the decline of transhumance and the numbers of large stockbreeders were the progressive decline of profits from livestock farming, a decline of wool prices, and the abrupt decline of Spanish wool exports during the first third of the 19th century, all of which were exacerbated by the Napoleonic wars in Spain (García Sanz, 1978). Besides, the price for renting the winter grasslands in the lowlands increased in parallel with the increased price of cereals, and this encouraged the cultivation of these grasslands (Pinilla Navarro, 1995; O'Flanagan et al., 2011).

The collapse of the transhumance system—the transhumance crisis—had remarkable effects on the Pyrenean landscape, as in other mountains of the Iberian Peninsula, such as the Iberian Range in La Rioja (Moreno Fernández, 1996). The transhumance crisis occurred during a period of significant demographic pressure and the decline of textile craftsmanship, thus obligating people to transform many marginal lands into cultivated fields. In some cases, marginal shifting agriculture was used, and this had dramatic adverse consequences on soil conservation (Lasanta et al., 2006) in the montane belt. This was similar to the process described by Gómez Urdáñez and Moreno Fernández (1997) for the Iberian Range.

We do not know how the transhumance crisis affected the subalpine belt of the Pyrenees in the 19th century. One of the most common types of cultivated fields in the Pyrenees are the *panares*, bench-terraced fields created in the upper limits of cultivated areas (1550–1700 m a.s.l.), often in contact with subalpine grasslands. Farmers mainly grew rye in the *panares,* which were mostly located in lateral moraines. Because of the high elevation, they grew rye in a 13-month cycle, with sowing in August and harvesting in September of the next year. Daumas (1976) suggested that *panares* date from the 19th century, because it was necessary to increase cereal production to feed the local population and to compensate the declining of the transhumance. However, some documents indicate the presence of *panares* at some sites of the Gistaín Valley since at least the 16th century (Fernández Piñar, 2019), with an increase during the last decades of the 19th century and the beginning of the 20th century. Surprisingly, we have no information on the consequences of the Little Ice Age (14th–19th centuries) on summer grazing (Bal et al., 2011).

Following the transhumance crisis, there was a depopulation of this region during the 20th century, a general decline in the number of sheep and goats that was not compensated by an increase in cattle, and a recent and obvious expansion of forest at higher elevations, also favoured by global warming (Camarero et al., 2015; García-Ruiz et al., 2015). The human population declined by approximately two-thirds in the main livestock villages in the Central Pyrenees during the last 150 years. This, together with the ageing of stockbreeders, led to the collapse of transhumance from the Pyrenees to the Central Ebro Depression during the 1960–1980s. A small flourishing has been noted in the last decades, thanks to European and Spanish subsidies and to changes in the livestock management, including the use of cattle trucks for livestock displacements (O'Flanagan et al., 2011). In any case, the transhumance crisis is major evidence of a social disruption that affected traditional agropastoral activity (García-Ruiz et al., 2015). As indicated above, the current upper forest limit is at approximately 1600–1700 m a.s.l., and even lower in the Ansó and Echo valleys. For centuries, the establishment of new trees and shrubs was prevented because of the strong livestock pressure, particularly horses and goats; sheep herds maintained the quality of the grasslands in the slopes, and cattle grazed in the valley bottoms and peat bogs (Montserrat, 1964, 2009), helping to stabilize the new landscape and impeding forest recovery. The abrupt declines in the numbers of sheep, goats, and horses and the spectacular expansion of cattle herds (Lasanta-Martínez et al., 2005) transformed the summer grasslands, with under-grazing of the slopes and overgrazing of the flat areas, thus causing changes in the floristic composition of this region (Montserrat, 2009). The major consequence is the rapid colonization by trees and shrubs at high elevations (Gartzia et al., 2014; García-Ruiz et al., 2015; Nadal-Romero et al., 2018) (Fig. 3C). Global warming has contributed to these changes, particularly in the timberline (Camarero et al., 2015). This phenomenon was also reported in the Eastern Pyrenees (Batllori and Gutiérrez, 2008), the northern sierras of the Iberian Range (Sanjuán et al., 2018), and other European ranges (e.g. Caviezel et al., 2014). Tree colonization is reducing the overall area of grasslands and is dividing them into smaller areas (Pueyo and Beguería, 2007; García-Ruiz et al., 2015). No doubt this process will have remarkable consequences from a geomorphological and hydrological point of view, because forest consume more water than grasslands, and canopy interception of rain will reduce the quantity of rainfall that reaches the soil (Llorens and Domingo, 2007). The presence of forests instead of grasslands in the subalpine belt will also alter snow accumulation and melting, the consequences of which are currently under study (López-Moreno and Latron, 2008; Sanmiguel-Vallelado et al., 2020).

4. Concluding remarks

We have reviewed the evolution of deforestation in the subalpine belt of the Pyrenees and its relationship with the development of livestock management, particularly transhumance, a system in which livestock rely upon grasslands in the mountains and the lowlands during different seasons. Transhumance, as well as transterminance (or valley transhumance), had a major impact on the landscape and social and economic organization in the Pyrenees and many other Mediterranean mountains. This explains the necessity for the progressive enlargement of grasslands needed for summer grazing, in contrast to grasslands and shrublands in the lowlands of the Ebro Depression, which have greater productivity between autumn and spring. Fig. 4 summarizes the main features of each historical period and their relationships with the evolution of transhumance and consequent deforestation. It provides a holistic perspective of changes that have accompanied the development of transhumance, and allow us to underline the most relevant conclusions of this study:

(i) The time when deforestation occurred in the subalpine belt is critical for understanding changes in plant cover in the Pyrenees and the multiple environmental effects of human activities. It is also critical for linking landscape changes with seasonal livestock movements, a key factor affecting biodiversity.
(ii) Changes in the landscape of the Pyrenean subalpine belt are the result of a long history of interactions between livestock management and deforestation related with market development, population growth and political issues.
(iii) The Neolithic/Chalcolithic period (7000–3700 BP) showed the seasonal presence of shepherds, according to the existence of a high number of megalithic monuments and structures from that period related with livestock management. The main consequences were the first forest clearings since around 4000 BP, the increase in the occurrence of forest fires and temporal soil erosion. This period was characterized by short seasonal livestock movements.
(iv) During the Bronze Age/Iron Age (3700–2200 BP) there was a light livestock pressure increase and the moderate clearing of the forest continued.
(v) The Roman Period (2nd century BCE to 5th century CE) brought a new territorial administration and complex political organization, together with population growth and the establishment and consolidation of regional markets. This constituted an adequate framework for the beginning of transhumant movements. Deforestation of the subalpine belt progressed.
(vi) During the Early Middle Ages (5th–9/10th centuries) the first written evidence of transhumance between the highlands (the subalpine belt of the Pyrenees) and the lowlands (the Central Ebro Depression) appeared. They explain new, although limited,

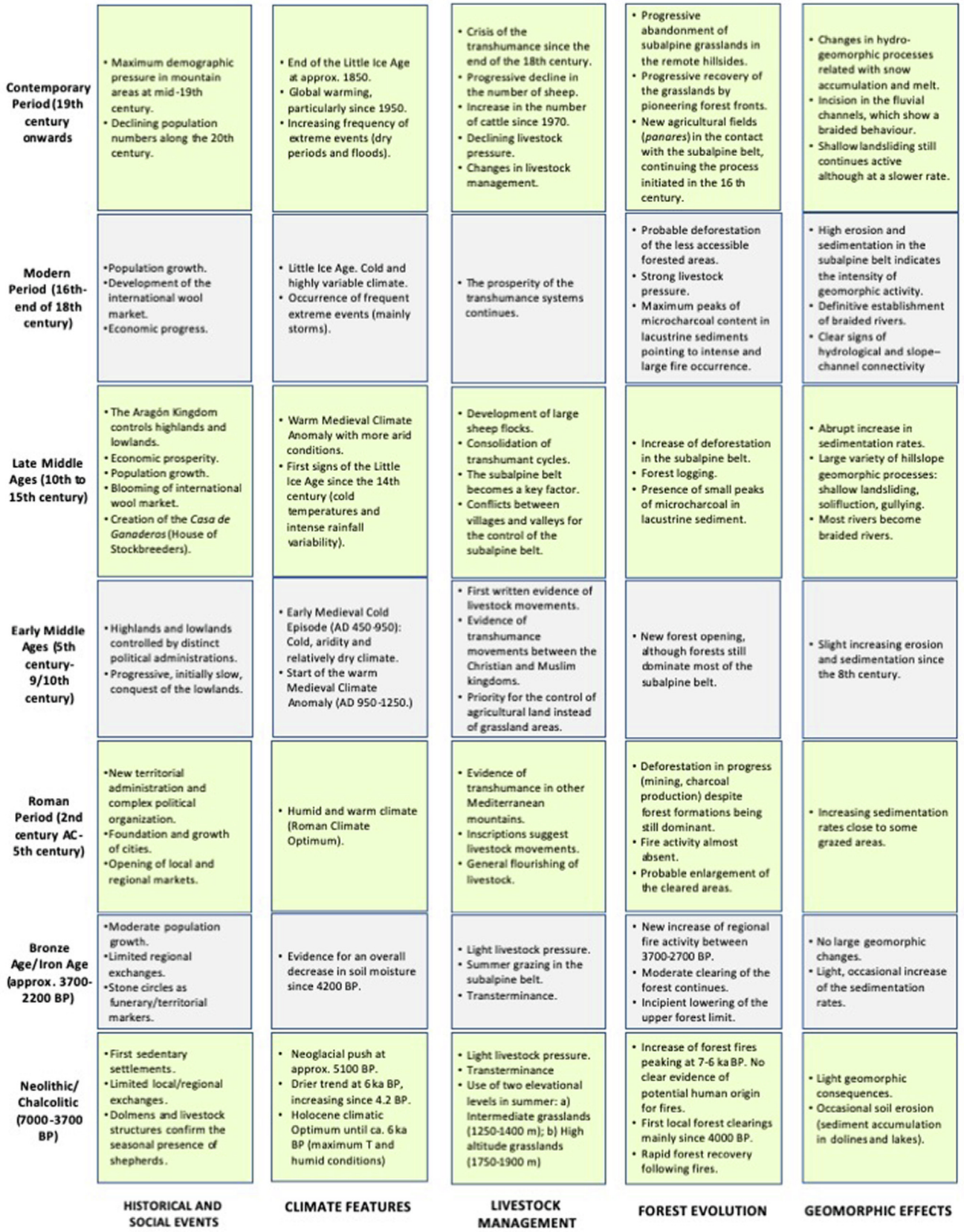

Fig. 4. Summary of changes in forest and livestock management from the Neolithic to the present, with indication of climate features and geomorphic consequences.

forest openings and slight increases in erosion and sedimentation rates.

(vii) The Late Middle Ages (10th–15th centuries) represented abrupt political, demographic and economic changes leading to a general establishment of transhumance and the generalization of deforestation in the subalpine belt of the Pyrenees. Presence of

microcharcoal is abundant in lacustrine sediments. There is evidence of an abrupt increase in erosion and sedimentation rates, with a large variety of geomorphic processes. Large sheep herds are developed in both the Pyrenees and the Central Ebro Depression.

(viii) Changes in plant cover and the hydrogeomorphological consequences during the Late Middle Ages were so intense that they initiated the Anthropocene era in the Pyrenees during the 12th and 13th centuries, when general changes occurred in landscape configuration, rainfall partitioning, soil erosion, landsliding, overland flow, fluvial dynamics, and the spatial distribution of fauna and flora. In high mountain areas, this was a major geoecological change, much more intense than any since the Neolithic and the Bronze Ages.

(ix) During the Modern Period (16th to the end of 18th centuries) a remarkable population growth occurred, together with the consolidation of the international wool markets. Deforestation of the subalpine belt concluded, including the less accessible areas. The recurrent use of fire resulted in the maximum presence of microcharcoal in lacustrine sediments. High erosion and sedimentation rates in the subalpine belt and the establishment of braided rivers indicate clear signs of intense geomorphic activity.

(x) The Contemporary Period (since the beginning of the 19th century) saw the highest demographic pressure in the Pyrenees at mid-19th century and a strong and rapid decline in population afterwards. Transhumant systems experienced a strong crisis, with a rapid decline in the number of sheep. A progressive increase in the number of cattle occurred since 1970. Partial abandonment of livestock grazing occurred in the subalpine belt, which promoted forest expansion on former pasture lands. Declining erosion and sediment yield resulted in incision of the fluvial channels.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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