SPATIAL DISTRIBUTION OF MEGALITHIC MONUMENTS IN THE SUBALPINE BELT OF THE PYRENEES: INTERPRETATION AND IMPLICATIONS FOR UNDERSTANDING EARLY LANDSCAPE TRANSFORMATION

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Abstract

Using a database of all the catalogued dolmens and stone circles in six Pyrenean valleys, we investigated the distribution of these megalithic monuments on the basis of elevation, gradient, aspect, terrain ruggedness, and terrain position, and identified factors potentially explaining the distribution of the monuments. A map of the areas having the highest probabilities of occurrence of megalithic monuments was developed, and showed that megalithic monuments are located in relatively accessible areas having gentle gradients and low terrain ruggedness close to the fluvial network, with wide U-shaped glacial valleys being the preferred locations. The altitudinal distribution showed one concentration of dolmens and stone circles at relatively low elevation (1250−1400 m a.s.l.) in the mid montane belt, and another at high elevation, at approximately the level of the timberline (1750−1900 m a.s.l.) adjacent to the alpine belt. Today, both areas are pastures that have historically sustained livestock, the traditional economic basis of Pyrenean valleys. The map showing the probability of occurrence of megalithic monuments in the study area suggests that a number of potentially favorable areas were largely inaccessible or too far from the main livestock routes, and remained forested until the Middle Ages. These findings and a variety of archaeological studies contribute to propose that the first shepherds: (i) understood the altitudinal organization of mountain areas; (ii) used the best accessible flat areas in the mid montane belt in late spring and early summer; and (iii) used the upper subalpine/alpine belt in summer.

Keywords

Neolithic, Bronze Age, Prehistoric grazing, megalithic monuments, deforestation, central-western Pyrenees

Introduction

The relationships among climate fluctuations, plant cover changes, and human activities in prehistoric times (from the Neolithic to the Iron Age) have been the subject of major scientific interest in the Iberian Peninsula (Carrión et al., 2007, 2009; López Sáez et al., 2009; Anderson et al., 2011; Jiménez-Moreno and Anderson, 2011; Carracedo et al., 2018), and particularly on both the Spanish (e.g. Bal et al., 2011; Catalán et al., 2013; Pérez-Sanz et al., 2013) and French (e.g. Galop, 1998, 2006, 2016; Rendu et al., 2016) sides of the Pyrenees. The altitudinal organization of climate, geomorphic processes, and vegetation has produced distinct geo-ecological belts, and the integration of these belts in a global strategy of land management explains their evolution and present characteristics (García-Ruiz et al., 2015). The changes that occurred after the Neolithic transformation (particularly those related to variable population pressure, environmental characteristics, cultural adaptations, historical events, and the role of markets at distinct spatial scales) were responsible for the development of the so-called cultural landscape (García-Ruiz and Lasanta, 2018; García-Ruiz et al., 2020a). One of the most important altitudinal features is the subalpine belt, because it is a key factor for livestock management and the development of transhumant and transterminant systems. Both systems are a consequence of the abrupt seasonality and complementarity of grassland productivity between the highlands (where productivity occurs in summer) and the lowlands (where optimum productivity occurs from autumn to spring). Transhumance is a very well-known livestock management system in the Mediterranean region (e.g. Violant i Simorra, 1950; Puigdefábregas and Balcells, 1966; Davidson, 1980; Geddes, 1982; Baker, 1999;

Bartosiewicz and Greenfield, 1999; Greenfield, 1999; Costello and Svensson, 2018; García-Ruiz et al., 2020b), that involves long distance livestock displacements between the lowlands and the subalpine belt. Thus, sheep flocks spend 7–8 months at low elevations in winter, where they feed on herbs and shrubs that grow during the cold and relatively wet season, and then ascend to mid and high mountain areas during the short summer season. This enables stock breeders to optimize the differing environmental conditions of the highlands and lowlands, and to enlarge the flock size despite the need to travel hundreds of kilometers. Transterminance or "valley transhumance" (e.g. Pallaruelo, 1993; Fernández Mier et al, 2013; Antolín et al., 2018) also involves livestock movement, although the travel distance is much shorter (<20 km), usually between the villages located at the bottom or on the slopes of mountain valleys and the subalpine belt, in such a manner that all the livestock management occurs within the same mountain.

Both transhumance and transterminance explain the almost general deforestation of the subalpine belt in most Iberian mountain areas, as grazing of large sheep flocks is only possible in large deforested and highly productive summer grasslands (García-Ruiz et al., 2020b). This poses new scientific questions, mainly related to the periods of occurrence of major deforestation and the onset of livestock movements towards the subalpine belt in summer. These issues are highly relevant to understanding the evolution of the subalpine landscape in the Iberian mountains, the influence of deforestation on a variety of geomorphic processes, and the timing of development of ancient land management systems.

The traditional link between megalithism -especially in mountain areas- and pastoral practices (Barandiarán 1927, 1953; Higgs 1976) has been questioned by various authors: Chapman (1979) believes that transhumance implies the need for a complex economy, incompatible with the moments of implementation of the megalithic phenomenon; Andrés Rupérez (1999, 2000) emphasizes the symbolic and religious value of megalithism. Davidson (1980) questions Chapman's position, retaking the seasonal mobility of prehistoric herds as a response to an ecological problem, although without references to megalithism. In spite of the fact that most of megalithic monuments in the central-western Pyrenees have been partial or totally plundered by clandestine excavations, some of them have been dated since the Neolithic (dolmens) until the Bronze Age and the Iron Age (stone circles) (Calvo, 1991a, 1991b; Montes et al., 2016). For our purposes, they are interesting as a sign of human presence in mountain areas.

Plant cover evolution and the occurrence of human activities with its consequent environmental effects in the Iberian mountains have typically been studied by analyzing pollen and the biogeochemical features of sediment accumulated in postglacial lakes and peatbogs. In the case of the Pyrenees, sediment from Tramacastilla Lake (upper Gállego Valley) has provided information on the occurrence of a wildfire at approximately 3500 yr BP (henceforth, BP = cal BP), although the forest, which was dominated by beech trees, recovered quickly. Another fire having large environmental and management consequences occurred in the same area 1000 years ago (Montserrat, 1992), and coincided with the commencement of a general expansion of stockbreeding during the Lower Middle Age (Utrilla Utrilla et al., 2005; Tomás Faci, 2013; García-Ruiz et al., 2020b). More recent analyses of palynological sequences from the Pyrenees have provided more information on plant cover changes during the Holocene (e.g. Galop, 1998; Ejarque et al., 2010; Bal et al., 2011; Pérez Obiol et al., 2012; Pérez-Sanz et al., 2012, 2013; González-Sampériz et al., 2017), and have revealed the occurrence of consistent changes in forest cover during the Late Neolithic and the Bronze Age. These can not necessarily be attributed to large human-induced deforestations or generalized human activities (González-Sampériz et al., 2019). The presence of charcoal in soils from the subalpine belt has enabled the dating of paleo-fires between the Late Neolithic and the Middle Ages, although some of these could have been the result of natural causes. González-Sampériz et al. (2019) noted the complexity of, and contradictions in, the results of studies of the relationships among climate, vegetation, and human activity in the Pyrenean subalpine belt, and the necessity for further study using distinct proxies (particularly lacustrine sediments and archaeological sites), including the pollen content in ice caves (Leunda et al., 2018).

The studies noted above have been supported by archaeological studies that have confirmed the presence of periodic settlement of the subalpine belt in the Pyrenees, particularly the occurrence of shelters, caves, huts, and a variety of enclosures for livestock (Palet et al., 2014; Rendu et al., 2016). For instance, Laborda et al. (2017) studied Late Neolithic/Chalcolithic shelters in the canyon of the Pardina Ravine (Ordesa and Monte Perdido National Park), and found temporal continuity of seasonal grazing at high elevation, approximately 1850 m a.s.l. (hereafter, m = m a.s.l., unless otherwise noted). Two main archaeological sites have been recently excavated, including Els

Trocs at 1600 m near Turbón Peak (Rojo-Guerra et al., 2013, 2018), and Coro Trasito at 1548 m in Tella-Sin, in the vicinity of the aforementioned National Park (Clemente Conte et al., 2014; Obea Gómez, 2014; Antolín et al., 2018). Anthracological studies at these sites have demonstrated the use of mixed forests since the early Neolithic (Alcolea, 2018). Several reviews of human-related subalpine landscape construction in both the central and eastern Pyrenees have been carried out (Cruz Berrocal et al., 2014; Gassiot et al., 2014; Palet et al., 2014; Alcolea, 2018). In a recent study of the Urbión massif (Iberian Range, northern Spain), dating of charcoal from soils affected by shallow landslides following deforestation has revealed that fires occurred during the late Neolithic, Chalcolithic, Bronze Age, Iron Age, and Middle Ages (García Ruiz et al., 2016), although forest clearing was moderate prior to the Middle Ages.

However, paleo-environmental and archaeological studies only reflect the relative intensity of human activities in high mountain areas, including the occurrence of deforestation and fires, indicators of grazing (e.g., the presence of anthropophile plants and spores of coprophilous fungus), and the relationships between arboreal and non-arboreal pollen. As pointed out by González-Sampériz et al. (2019), in some cases the results obtained are difficult to interpret or to compare among different periods. Furthermore, spatial information on the impact of human activities is lacking in general, and it is only possible to partially and indirectly deduce the major features of the subalpine landscape during most of the Neolithic and the Bronze Age. We propose that the spatial distribution of megalithic monuments could contribute to the knowledge of the livestock management patterns, and consequently provide a spatial perspective of the primitive shepherds and the opportunity they had to maximize profits while minimizing exposure to natural hazards.

The subalpine belt of the Pyrenees has many megalithic monuments (mainly dolmens and stone circles), which have been interpreted variously as funerary monuments or territory markers (e.g., Domínguez Arranz and Calvo Ciria, 1990; Andrés Rupérez, 2000; Peñalver, 2005; Rey Lanaspa, 2014). González-Álvarez (2019) reported that “megalithic burial mounds are sometimes related to the best quality summer pastures…usually built at locations with high visibility over the surrounding grazing areas…” (p. 149). Montes et al. (2016) considered that dolmens and cromlech-type stone circles are evidence of the movement of sheep herds, as most of them are located near the main livestock routes between the Central Ebro Depression and the high Pyrenees. A similar interpretation has also been made for the central Iberian

Peninsula (Higgs, 1976; Fairén Jiménez et al., 2006). It is evident that grazing and livestock management was practiced in the subalpine belt of the Pyrenees since Neolithic times, with more or less intensity and continuity.

We hypothesize that an association exists between the location of megalithic monuments in the subalpine belt of the Pyrenees and the use of the land for seasonal grazing. Therefore, we focus on the study of the spatial distribution of dolmens and stone circles in the subalpine belt of the Pyrenees in relation to environmental factors. In the context of previous paleo-environmental and archaeological studies, we then discuss the implications of our findings for interpreting the magnitude of landscape transformation and we propose a conceptual model of prehistory seasonal sheep flock movements.

Study area

The study focused on the upper valleys of the central–western Pyrenees, where the alpine, subalpine, and montane belts are clearly developed, and have resulted in an altitudinal organization of plant cover, land uses and geoecological belts (Troll, 1973). Most of the megalithic monuments are located between the Veral Valley to the west and the Gállego Valley to the east, so the study concentrated in this area, including the Veral, Aragón Subordán, Osia, Estarrún, Aragón, and Gállego valleys. A small area having endorheic drainage (Estanés), to the north of the Aragüés and Estarrún valleys, was also included (Figure 1). The study area includes three of the most important morpho-structural units of the Pyrenees. (i) The Axial (or Variscan) Pyrenees unit constitutes the oldest part of the range and includes part of the Aragón, Gállego, and Aragón Subordán valleys. It is composed of Paleozoic materials (quartzite, limestone, and shale) and granitic batholiths of Carboniferous age, and the highest peaks exceed 3000 m (ii) The Inner Sierras unit corresponds to an abrupt overthrusting anticline dominated by Mesozoic limestone and sandstone that reaches a height of almost 2900 m. (iii) The Flysch Sector unit is composed of thin alternating beds of marl and sandstone, and favors the development of regular slopes and gentle divides. Its homogeneous relief ranges from 700–800 m in the valley bottoms to approximately 2200 m in the highest divides.

The subalpine belt in this part of the Pyrenees occurs from 1600 to 2300 m (Figure 2). It coincides with the altitudinal band where *Pinus uncinata* dominates on both north- and south-facing slopes, frequently accompanied by *Fagus sylvatica* and

Abies alba; *Pinus sylvestris* also occurs at lower elevations. Most of the subalpine belt has been deforested, particularly during the Middle Ages (González-Sampériz et al., 2019), to enable the development of extensive grasslands to feed large transhumant sheep flocks in summer. The lower limit of the subalpine belt roughly coincides with the 0°C winter isotherm (at approximately 1650 m), which approximates the lower limit of the permanent winter snow cover (Del Barrio et al., 1990). Annual precipitation shows high spatial and temporal variability, with approximately 2000 mm occurring at 2000 m and a slight trend of decrease occurring toward the highest divides. Deforestation has been responsible for triggering many geomorphic processes (e.g. solifluction, shallow landsliding, gullying, and rilling), although declining livestock pressure since the 19th century explains more recent forest expansion (García-Ruiz et al., 2015).

The main valleys are U-shaped, reflecting powerful glacial action in the past. Most of the current settlements are in the valley bottoms, from approximately 800 m to almost 1300 m. Below 1600 m most of the sunny slopes have been cultivated mainly in the 14th-15th centuries and during the 18th and the 19th centuries, although only the fields on the alluvial plain and alluvial fans are still cultivated.

Materials and methods

We compiled a dataset of all the megalithic monuments known in the Aragón (central–western) Pyrenees from the Veral Valley to the Noguera Ribagorzana Valley. This was a complex task, as the number of known megalithic monuments is slowly but continuously growing, in most cases because of the efforts of mountaineers and the development of private blogs. In addition, what constitutes megalithic monuments is poorly defined, for example in the case of burial mounds. Furthermore, remnants of isolated huts can be interpreted as stone circles, and many elongated boulders have been uncritically interpreted as menhirs. For these reasons we limited our study to two types of megalith, dolmens and stone circles, corresponding to distinct chronologies.

Dolmens were mainly constructed during the late Neolithic (from 6 ka BP), although their use persisted until the Chalcolithic and beyond (4 ka BP) (Montes et al., 2016). One of the best conserved dolmens, the so-called Cubilar del Barranco I, was dated at 5850 BP (Pérez Arrondo and Martínez Bea, 2004). They comprise three or four slab stones that stand vertically, and these are covered by a large stone creating a table-like shape (Domínguez Arranz and Calvo Ciria, 1990) (Figure 3). Only those megaliths having clear and well-preserved characteristics of dolmens were included in the dataset, along with the burial mounds having a dolmenic chamber.

Stone circles had a funerary function related to cremation rituals, and are dated to the Late Bronze Age and the Iron Ages (3–2.5 ka BP). According to Peñalver (2005), most dated stone circles in the Basque Country and Navarre were constructed during this time period. They are composed of stones up to 60 cm long embedded in the soil to form a circle of variable size (around 6 m diameter on average) (Domínguez Arranz and Calvo Ciria, 1990; Peñalver, 2005) (Figure 4). They have also been referred to as 'cromlechs' or 'Pyrenean cromlechs', although 'stone circle' seems to be a more accurate term.

Our initial dataset was constructed from the Information System of the Aragón Cultural Heritage catalogue (http://patrimonioculturaldearagon.es/bienes-culturales), which has been developed from the list of megaliths of the HILHARRIAK Group, which is accessible at www.euskal-herria.org/ and from the personal blog of one of its members (http://cromlechpirenaico.blogspot.com). This information has been acquired through fieldwork and from the scientific literature, particularly in relation to the western part of the study area, which has the greatest density of megaliths. Important studies include those of Andrés Rupérez (1988, 1992), Andrés Rupérez et al. (1989), Navarro (1989), Utrilla and Orera (1990), Andrés Rupérez and Millán San Emeterio (1993), Pérez Arrondo and Martínez Bea (2004), and Peñalver (2005). We assumed that the surveys have been exhaustive and that no significant megalithic monuments remain to be discovered, and that the survey effort has been similar among valleys, although we return to this assumption in the discussion of the results of our analyses.

In total, the catalogue of the Aragón Pyrenees contained 136 dolmens and 259 stone circles in April 2019. However, in the case of stone circles many occur in groups, and for this reason they were grouped into 76 stations comprising 1–22 circles. This study refers to the western sector of this area from the Veral to the Gállego valleys, where 75% of the megalithic monuments are located, and includes 106 dolmens (77.9% of the total) and 191 stone circles (74.3%) grouped in 63 stations. In the remainder of the Aragón Pyrenees the density of megaliths is much lower, making statistical analysis difficult.

The data consisted of the locations (coordinates) of the megaliths (dolmens and stone circle stations) in the central-western Pyrenees of Spain. Following the inferential approach proposed by Gilman and Thornes (1985) for the study of the patterns of location of archaeological sites, to assess the presence of patterns of megalith occurrence in our study area we performed a statistical analysis based on a set of significant landscape features. Studies with experimental inferential approach based on a set of relevant landscape variables, in which GIS and statistical analysis are combined, have been previously carried out with encouraging results for the analysis of rock art (e.g. Cruz Berrocal, 2005; Fairén, 2006; Cruz Berrocal and Vicent, 2007; Sebastián López, 2011).

Following this methodology, we compared the characteristics of dolmen and stone circle locations against those of a control random sample that we presume summarize the subalpine landscape features of the study area. Despite the likely geographical variability contained in such a wide area, the analysis was performed at a regional scale, considering the entire set of megalithic sites as a consistent phenomenon having identifiable common features.

Thus, at each site the following landscape features were considered:

- elevation in m above sea level (variable *alt*);
- slope gradient in degrees with respect to horizontal (variable *slo*);
- slope aspect in degrees with respect to north (variable *asp*);
- topographic position index (TPI) in m (variable *tpi*);
- terrain ruggedness index (TRI) in m (variable *tri*);
- distance to the closest stream in m (variable *dist*).

The TPI is defined as the difference between the elevation at the central point and the mean elevation of surrounding cells, and is centered around zero. The TRI is defined as the mean absolute difference between the elevation at the point of interest and the mean for that of surrounding cells, and is always a positive number. The elevation was extracted directly from the European Digital Elevation Model (EU-DEM version 1.0) at a spatial resolution of 25 × 25 m (Copernicus, 2011). The remaining variables were derived from this DEM using the Geospatial Data Abstraction Library (GDAL/OGR, https://gdal.org). The TPI data were later smoothed using a focal mean filter of 7 × 7 pixels. The cosine and sine of the slope aspect were also calculated (variables *cos* and *sin*, respectively). The former maximizes the difference between north- and south-facing slopes (with limit values of 1 and −1, respectively), while the latter captures the difference between east and west. The cosine and sine of the slope aspect provide a better option than the aspect angle for use in statistical analyses.

These variables were used to construct eight maps showing the spatial variability of the topographic factors over the study area. The values for the topographic factors at the locations of the megalithic monuments were tabulated, as were values for these factors at 3405 random points in grid cells not containing megalithic monuments, distributed across the study area. The random points layer was created using the 'random points inside polygons' tool of the QGIS 3.6 software (https://www.qgis.org), using a minimum of 500 m distance between points. This dataset represents negative cases (i.e., locations where monuments have not been found), and was used as a contrast in all the statistical analyses.

Descriptive statistics (median and inter-quantile range: IQR) and kernel density plots were used as initial indicators of differences between the topographic factors associated with the occurrence of megalithic monuments and those for the entire study area. A statistical model was constructed to determine the likelihood of occurrence of megalithic monuments based on the topographic features and the valley involved. Among a variety of candidate approaches, for this analysis we used gradient boosting (GBM). GBM is a powerful and flexible machine-learning algorithm for regression and classification, and enables non-linear relationships between variables to be identified. We used the gbm 2.1.4 package (Greenwell et al., 2018) in R 3.4.0 (R Core Team, 2017). As this was a classification problem, to estimate the 'out-of-bag' reliability of the model we used the Bernoulli distribution, and a cross-validation approach having five random split samples. A subsample of N = 500 random points plus all the points where megaliths were observed were used to build the model. Because of the unbalanced nature of the sample set, which had more negative data points (random points) than positive ones (megaliths), a per-class weighting was used to impose a heavier cost on errors in the minority class. The weighting was set to be proportional to the prevalence of megaliths in the sample set (0.25). The performance statistic used was the Bernoulli deviance. We used a grid search approach to fine-tune the model hyperparameters, starting from generally recommended predefined values. This is a time-consuming process, but usually produces better results than simply using predefined parameters. Once the best model was determined we used several approaches to analyze the results.

- Plots of the model loss function (the Bernoulli deviance) as a function of the number of trees added to the ensemble, for both the test sample and the cross-validation samples. As the latter offers an independent estimate of the model's performance in making predictions based on data not used for model fitting, we used this approach to determine the optimum number of model trees that minimized the loss function.

- Feature importance plots, which indicate the relative influence of each topographic feature on the classification of megaliths, integrated over all the other features.
- Partial dependence plots, which indicate the nature of the relationship (for example, positive or negative, or shape) between the likelihood of occurrence of megalithic monuments and each topographic feature.
- Standard goodness-of-fit statistics for classification problems. These included: (i) confusion matrix and derived statistics such as the global accuracy (the fraction of observations that are correctly classified), and the sensitivity and specificity (Agresti, 1990; Altman and Bland, 1994a, 1994b), which are defined by:

$$accuracy = \frac{TP+TN}{P+N},$$

$$sensitivity = \frac{TP}{P},$$

$$specificity = \frac{TN}{N},$$

where *TP* is the number of true positives, *TN* is the number of true negatives, *P* is the number of positive observations, and *N* is the number of negative observations; (ii) the Cohen's kappa (Cohen, 1960), which is defined by:

$$kappa = \frac{p_o + p_e}{1 - p_e},$$

where p_0 is the accuracy and p_e is the probability of chance agreement, computed from the ratio of positive to negative observations in the sample, or from prevalence; and (iii) a p-value from the McNemar's test of marginal homogeneity (McNemar, 1947; Kuhn, 2008).

Once a satisfactory model was found, a likelihood map was developed by applying the model to the maps of the topographic features.

A model was also created to discriminate between dolmens and stone circles, based on their topographic features. The approach described above was also used for this purpose, although the analysis was restricted to valleys were there was a significant number of each type of monument, which included the Aragón, Gállego and Subordán valleys.

Results

Figure 5 shows the spatial distribution of dolmens and stone circles in the study area. These megalithic monuments are particularly abundant in the northernmost sector of each valley, and particularly along the Aragón Subordán River and its tributaries. They are almost absent in the eastern part of the Gállego Valley and in the lowest parts of the Veral, Aragón Subordán, Osia, and Estarrún valleys.

Figure 6 shows maps of the topographic characteristics of the study area. It is noteworthy that elevation increases markedly towards the north, and that the highest elevations occur in the northeastern sector of the Gállego Valley. The slope gradient increases in the Inner Ranges, following a long band from west-north-west to east-south-east, and also in the northeastern part of the Gállego Valley. The *cos* aspect analysis showed the classical north–south contrast because of the effect of the west–east orientation of the main tributaries, whereas the *sin* aspect analysis showed the contrasts between west and east slopes in proximity to the main rivers in each valley, which run from north to south. Table 1 shows that the median elevation for the entire study area is 1680 m, the median gradient is 22.9°, and the median aspect is slightly biased towards southwest aspects (negative cosine and sine). The median TPI is also slightly negative, indicating the prevalence of concave topographies (i.e. lower on average than their surroundings), while the median TRI was 8.12, which is a value characteristic of mountain areas having rough relief. The median distance to the closest stream was 962 m.

Table 1 also shows the number of dolmens and stone circles (and random points) in each of the valleys, and that a particularly high concentration of these megaliths occurs in the Aragón Subordán River valley, followed by the Aragón, Gállego, and Estarrún valleys. No large differences were found between the number of dolmens and stone circles in relation to the median values for the topographic features. Thus, the median elevation was 1740 m for dolmens, and for stone circles was only slightly less (1680 m); this is a very small difference considering the large IQR values for these megaliths (327 and 515 m, respectively). These values are also similar to the median elevation for the entire study area. The gradient was also very similar (12° for dolmens and 13.5° for stone circles), but in this case these values are markedly lower than the median gradient for the entire area (22.9°). A similar situation was found for the TRI, whereby the values for dolmens and stone circles (4.17 m and 4.6 m, respectively) were markedly lower than that for the entire area. The TPI values for dolmens and stone circles (−0.348 and −0.207 m) were also lower than that for the entire area, as were the distances to the closest stream (675 m and 625 m for dolmens and stone circles, respectively).

Figure 7 also shows the distribution of topographic variables for dolmens and stone circles in relation to the entire study area, providing additional information to that in Table 1. While the median elevations (*alt*) were not highly dissimilar between megalithic monuments and the entire area, the kernel density plots show that the variability in the elevation of occurrence of dolmens and stone circles was lower, with most present in two altitudinal belts at approximately 1250−1400 m and 1750−1900 m, with the latter having the highest concentrations. Nevertheless, a slight difference between dolmens and stone circles is evident in Figure 7, with a higher proportion of dolmens tending to occur at higher elevations.

In relation to slope gradient, dolmens and stone circles were found to be concentrated on slopes of approximately 15−18°, with stone circles showing a slightly higher density in higher gradient locations. No differences were found between the megalithic monument types with respect to the distance to the fluvial network, with a greater concentration occurring in areas close to streams, and a greater decrease in number as the distance to the stream increased, compared with the entire area. Dolmens and stone circles showed a similar distribution in relation to the TPI and TRI, although stone circles show a slightly higher density around values of 5 m for the TRI. The density curves, especially for the TRI, differed markedly from that for the entire area. Aspect was the only variable for which there was substantial difference between the two types of monument, as dolmens showed a higher concentration on southwestern slopes, whereas stone circles were found to be distributed in a more homogeneous way, similar to the distribution for the entire study area.

The results of the preliminary analysis clearly indicated differences in the distribution of topographic variables between the megalithic monuments and the remainder of the study area, indicating the potential for development of a discriminating model. This was confirmed by the results of the GBM analysis. Figure 8 shows the relative influence of the various topographic factors on the location of dolmens and stone circles, integrated over all the features once other effects had been considered. Elevation and the TRI were the most important factors, and differences among valleys were also important. Other features in order of decreasing importance were TPI, *cos*, *dist*, *sin*, and *slo*. The feature importance plot indicates the relative strength of each predictor in the model outcome, but not the sign of its influence (positive or negative) or the plot shape (e.g., rectilinear, curvilinear). This information is provided in the partial dependence plots (Figure 9), and illustrates the benefits of using a non-linear approach such as GBM. The plots show the change in the logarithm of the odds ratio (where higher values indicate higher probability of occurrence of megaliths) as a function of the various topographic features. For some variables such as slope, TRI, or distance to streams, there is a monotone, but non-linear dependence. In the case of slope, the likelihood of occurrence of megaliths increased rapidly from 0–10°, then slowed progressively to become nearly stable from 20° or greater. The TRI showed a relationship of linear decrease from 0 m to almost 10 m, and then become stable (flat line). A similar situation occurred with respect to the distance to streams, with a sharp reduction in the likelihood of megalith occurrence from approximately 50 to 250 m, a gradual decrease in likelihood up to 2000 m distant, and no effect at greater distances. For other topographic features the patterns were more complex and is not monotone anymore. This was the case for elevation, with a sharp increase in the likelihood between approximately 1200 and 1500 m, a peak at approximately 2000 m, and then little influence at higher elevations. The TPI and the *cos* and *sin* parameters of aspect also exhibited complex relationships with megalith occurrence.

The cross-validation confusion matrix for the model is shown in Table 2. The overall accuracy (i.e., the proportion of cases correctly predicted) was 87.9%, but this figure is misleading because of the large imbalance between the positive and negative values in the sample. The model had a high specificity (0.972), implying a very high success rate in predicting negative cases (i.e. locations where megaliths were not found), and a more moderate sensitivity of 0.601 (the probability of correctly detecting the location of a megalith). The Kappa statistic was 0.640, which implies a substantial agreement between prediction and observation (Landis and Koch, 1977). These are normal values for binary variables where there is a low prevalence of positive cases and a potentially large number of negative cases having a high possibility of being positive. Overall the model was significant, with a p-value < 0.0001 in the McNemar's test.

The relative influence of particular factors changed when dolmens and stone circles were considered individually. For dolmens, the most influential factor was elevation, followed by terrain ruggedness, distance to the fluvial network, and topographic position. For stone circles the most important factor was terrain ruggedness, with elevation, topographic position, and gradient being substantially less influential.

The predictive map for the location of megalithic monuments in the study area is shown in Figure 10. It is noteworthy that both dolmens and stone circles are located in the areas highly predicted by the model. The western part of the Gállego Valley showed the highest probabilities, coinciding with generally non-rugged relief, wide valleys, and large shale outcrops. The headwater of the Aragón Subordán Valley contained the most likely areas for megalithic monuments to be located. Scattered favorable areas were also evident in the Aragón Valley, and in the Veral Valley. High probability areas were also located in the highest parts of the Flysch Sector of the Aragón Subordán, Osia, and Estarrún valleys. Likely locations for dolmens and stone circles clearly decreased with decreasing elevation toward the lower parts of the valleys, and in the eastern part of the Gállego Valley at higher elevations and in areas having very rugged relief.

Discriminating likely sites for the occurrence of each type of megalith (dolmens vs. stone circles) was much more difficult. The cross-validation confusion matrix is shown in Table 3. The model produced a low accuracy value (0.594), and the Kappa statistic (0.166) was indicative of a model showing poor agreement between predictions and observations. The McNemar's test p-value (0.123) was also non-significant. Because of the potential for misinterpretation, no other results are shown for this model, and a prediction map was not produced.

Discussion and conclusions

The spatial distribution of megalithic monuments in seven valleys in the central-western Spanish Pyrenees was investigated for patterns that could provide hints on the strategies used in prehistoric livestock management and deforestation. We are conscious of the difficulties to interpret the landscape evolution and livestock management from the location of megalithic monuments. Dolmens and stone circles represent not only a symbolic and funerary function (Andrés Rupérez, 1999, 2000), but also indirect strategies of land appropriation (González-Álvarez, 2019). For this reason, we can deduce that their presence in the subalpine belt of the Pyrenees is a signal of a relatively high frequency of humans in summer, i.e. the only period during which the use of natural resources and particularly grazing has sense.

The presence of shepherds in the montane and subalpine belt of the Pyrenees since at least Neolithic times has been assessed in both the northern (e.g. Marsan and Utrilla, 1996; Dumontier et al., 2016; Galop, 1998, 2016) and southern versants (e.g. Ejarque et al., 2010; Miras et al., 2010; Rojo Guerra et al., 2013; Cruz Berrocal et al., 2014; Gassiot et al., 2014; Orengo et al., 2014; Palet et al., 2014; Montes et al., 2016). Several proxies have been used to indicate human presence and grazing, particularly archaeological evidence like megalithic monuments and structures including shepherd huts and livestock enclosures (e.g., Palet et al., 2014: for the Madriu, Perafita and Claror Valleys in Andorra; Rendu et al., 2016: for the Ossau Valley), anthracological remnants, and sediments from lakes and peat bogs, which can indicate the occurrence of fires, grazing and other indirect information (e.g., changes in plant cover and erosion). The oldest evidence of human presence in the subalpine belt of the Pyrenees is from the Mesolithic (in the Aigües Tortes and Estany de Sant Maurici National Park, central-eastern Pyrenees; Gassiot et al., 2014), although most of the megalithic monuments correspond to the late Neolithic and the Chalcolithic, particularly in the case of dolmens (Calvo, 1991a, 1991b; Andrés Rupérez, 1992; Pérez Arrondo and Martínez Bea, 2004; Montes et al., 2016), whereas stone circles have mainly been dated to the Late Bronze Age (Montes et al., 2016).

No large differences were found in the patterns of spatial location of dolmens and stone circles, even though they were constructed in different periods over a long-time interval. Our results show that both types of megalithic monument were located preferentially in areas having relatively gentle slopes and low levels of terrain ruggedness, indicating deliberate selection among the various topographic conditions in the entire study area. The distinct topographic signature of the megalithic sites with respect to the general characteristics of the area enabled a predictive model of megalith occurrence to be developed. We can hypothesize if the location of megalithic monuments, together with the location of other archaeological evidence, is a sign of spatial occupation, representing, at least partially, the intensity of spatial occupation by those populations that built the monuments. However, based on the model we identified some areas (e.g., the right side of the Gállego valley) that, despite exhibiting a high likelihood of megaliths, only have a few occurrences on the catalogue. Whether this implies that not all the existing monuments have been detected and catalogued, or that these areas were not as intensely occupied as others remains unclear, but suggests that further investigation of these areas may be warranted.

One of the most interesting result was the finding of a bi-modal altitudinal distribution of the megaliths within the general relief of the area, with more than expected numbers of megaliths in the 1250–1400 m and 1750–1900 m bands. Considering the topographic characteristics that are dominant at these two altitudinal belts, this suggests that the first shepherds in the central-western Pyrenees preferred: (i) flat areas at relatively low elevations (i.e. in the mid montane belt), close to the main rivers and in accessible positions; and (ii) areas located close to the limit between the subalpine and the alpine belts (i.e., in the upper forest level), near main mountain passes or in flat, wide areas in the U-shaped headwaters of perched tributary valleys. Conversely, most of the originally forested subalpine belt, which lies in between, has no megalithic monuments. According to the results obtained in relation to the spatial distributions of megalithic monuments, our interpretation is that shepherds in the Neolithic to the Iron Age period had a perspective on the altitudinal organization of mountain areas, and that this enabled them to establish patterns of livestock management including the following:

(i) The gentle, accessible slopes of the mid montane belt (1250–1300 m) were a preferred area for grazing during the second half of spring and the beginning of summer, because of their accessibility and the ease of control of small sheep and goat flocks. This practice and routine have functioned for centuries and continued to the present, although for socioeconomic reasons most of the sheep and goat flocks have been replaced by large numbers of cows (García-Ruiz et al., 2015). This first pressures on the landscape would have resulted in initial opening of the forest to provide limited clearings. Archaeological sites in the central Pyrenees have also demonstrated the occurrence of transitional grazing areas, including the Coro Trasito shelter (Obea Gómez, 2014) and the Els Trocs cave (Rojo Guerra et al., 2013, 2014, 2018), and seasonal occupation. As deduced from these archaeological sites, at the beginning of October the flocks would descend again to the transitory grasslands of the mid montane belt, and finally move to the hamlets in the valley bottom (800-900 m), where the villages would be located (Clemente Conte et al., 2014; Rojo Guerra et al., 2013, 2014, 2018; Antolín et al., 2018).
(ii) The highest slopes of the subalpine belt joining the alpine belt would be grazed during most of the summer until the end of September, when the lower transition grasslands were depleted and the heat forced the shepherds to move the flocks up to the cooler environment of the transition pastures until mid-October. Shelters having

Neolithic, Chalcolithic, and early Bronze Age hearths and pottery remnants found in the La Pardina ravine (Ordesa and Monte Perdido National Park) at about 1850 m (Laborda et al., 2017) corroborate the frequentation of livestock at high altitude during the warmest months. Shepherd huts and livestock structures at high altitude, even exceeding 2200 m, have been found in several valleys, particularly the central-eastern Pyrenees. For instance, a pastoral hut at 2530 m was dated to circa 6500 yr BP, revealing early Neolithic husbandry in the Madriu Valley, southeastern Andorra (Ejarque et al., 2010; Palet et al., 2010, 2014; Orengo et al., 2014). Similarly, Miras et al. (2007), Pèlachs et al. (2007), Cunill et al. (2012), Gassiot et al. (2014), and Antolín et al. (2018) reported human presence in high mountain areas, based on evidence of deforestation in favor of grasslands, fire occurrence and the presence of domestic taxa, and the presence of archaeological sites in the upper subalpine and alpine belts in the western Catalan Pyrenees dating to the early Neolithic. In fact, Miras et al. (2010) dated the earliest Neolithic human impact in the subalpine belt to 7300–6900 yr BP, although no lasting and consistent changes in plant cover have been reported, as has occurred in the Cantabrian Mountains, northern Spain (González-Álvarez, 2019). Based on archaeological remnants (Dumontier et al., 2016; Galop, 2016), the subalpine belt in the Ossau Valley (French Pyrenees) was also grazed by small sheep and goat flocks from 6000 to 5000 yr BP, with intensification from 3500 to 3000 yr BP (Late Bronze Age).

(iii) In the remainder of the subalpine belt dense forests dominated the landscape in steep slopes between approximately 1500 and 1800 m. It is probable that a number of clearings in the forest would have occurred naturally, given the activities of herbivores in the evolution of plant cover within the forest (Vera, 2000; Montserrat-Martí and Gómez-García, 2019). However, the low number of megalithic monuments between 1400 and 1800 m and their remarkable presence above 1800 m suggests that the forest was, in general, avoided as a grazing area. This was probably because of: (a) the large area occupied by grasslands in the upper subalpine and alpine belts, which would have been sufficient to feed the small sheep and goat flocks during most of the summer; (b) the technical difficulties of cutting down old trees and opening glades in the forest using only Neolithic stone axes (Mathieu and Meyer, 1997), and the likelihood that most fires during the Neolithic were probably a result of natural causes rather than human-induced (González-Sampériz et al., 2019); and (c) the need to avoid the forest because of the dangers (bears, wolves) associated with grazing in the forest, and instead focusing on grazing the flocks in the most accessible mid montane and upper subalpine areas, at approximately the elevation of the timberline. We find no other reasons to maintain forested the intermediate slopes, particularly because the presumably low livestock pressure did not require the enlargement of the summer grassland areas. Not surprisingly, based on studies of pit bogs in the Cantabrian Mountains, northern Spain, Carracedo et al. (2017) reported that the maximum fire frequency occurred in the lower parts of the mountains between 5800 and 3500 yr BP, and in the higher parts between 3600 and 1700 yr BP, whereas the zone in between was deforested as late as the last millennium. This is quite similar to what we interpret that occurred in the central-western Pyrenees. Recent studies on the deforestation process in the subalpine belt of the Pyrenees reveal that the period of most intense deforestation occurred during the Late Middle Ages, coinciding with the huge increase in the number of transhumant sheep and goat herds, and not before (García-Ruiz et al., 2020b).

It is noteworthy that the actual and subactual landscape organization tends to partially overlap the prehistoric landscape, such that grasslands dominate the valley bottoms of U-shaped valleys at 1300-1500 m (e.g. in the Aragón Subordán and Estarrún valleys) and above 1700 m, configuring a landscape that enables livestock grazing from May to October.

Although no direct information exists on the distance traveled by the flocks in their seasonal movements, our interpretation is that only transterminance occurred prior to the Roman Period, as suggested by Leveau (2016) for the Gaul and Italian Peninsula. Transhumance is a complex livestock management system that would have required substantial organization among territories (Chapman, 1979; Davidson, 1980; Galán Domingo and Ruiz Gálvez, 2001; Fairén Jiménez et al., 2006; Antolín et al., 2018; Martín Rodríguez and Mozota, 2018), and relatively large herds related to well-developed markets to compensate for the large labour investment and risks of all kinds inherent in long displacements (García-Ruiz et al., 2020b).

A slight increase in human pressure during the Bronze Age has been deduced in the Pyrenees by Galop (1998, 2016), Rius et al. (2009), Ejarque et al. (2010), Orengo et al. (2014), González-Sampériz et al. (2017) and Leunda et al. (2020). In fact, the evolution of fire activity during the Holocene shows a strong influence of climate during the early- to mid-Holocene, whereas human-induced fires at the beginning of the

Bronze Age (ca. 3700 BP) are clearly related with the opening of the landscape (Leunda et al., 2020). An increasing human presence in the subalpine belt could also be tentatively deduced from the spatial distribution of dolmens and stone circles, since dolmens occur at higher elevations than stone circles. This would indicate a progressive downwards advance of the deforestation front during the Bronze Age, as suggested by Galop (1998) for the Ossau Valley, French Pyrenees.

The map showing the probability of occurrence of megalithic monuments in the study area is an indicator of places where archaeologists should concentrate their efforts to look for new dolmens and stone circles. However, it could also be hypothesized that several potentially favorable areas were inaccessible or too far from the main livestock routes and therefore had very little or no use. If these areas are now deforested would probably be because of human pressure that occurred much later, when generalized deforestation of the subalpine belt in the Pyrenees accompanied the Middle Ages expansion of the transhumance systems (García-Ruiz and Lasanta, 2018; González-Sampériz et al., 2019; García-Ruiz et al., 2020b).

This paper suggests an intimate relationship between the early human occupation of the subalpine belt and livestock management in a mountain area, the capacity of Neolithic and Bronze Age humans to progressively change the landscape, and the mental construction of a perspective on the spatial organization of mountain areas in different geoecological belts, i.e. the basis for the development of a cultural landscape. Most likely, this is a general feature of other mountains in the Iberian Peninsula and most European mountains.

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FIGURE CAPTIONS:

Figure 1. The study area, including the valleys, their limits, and the main rivers. Reference system: ETRS89 / Lambert azimuthal equal-area Europe (EPSG:3035).

Figure 2. A view of the subalpine belt in the Acherito Valley, a tributary of the Aragón Subordán Valley, with trees re-colonizing the summer grasslands slopes.

Figure 3. Dolmen in the Aragón Subordán valley bottom. Note the accumulation of stones and the presence of large slab stones on the top.

Figure 4. Stone circle in the divide of the Sierra de Sis, eastward of the study area.

Figure 5. Location of dolmens and stone circles.

Figure 6. Topographic attributes of the study area including elevation, gradient, distance of each point of the valley to the streams, aspect (aspect: general, cosine, sine), position of each point in relation to the topography of surrounding sites, and ruggedness of the relief.

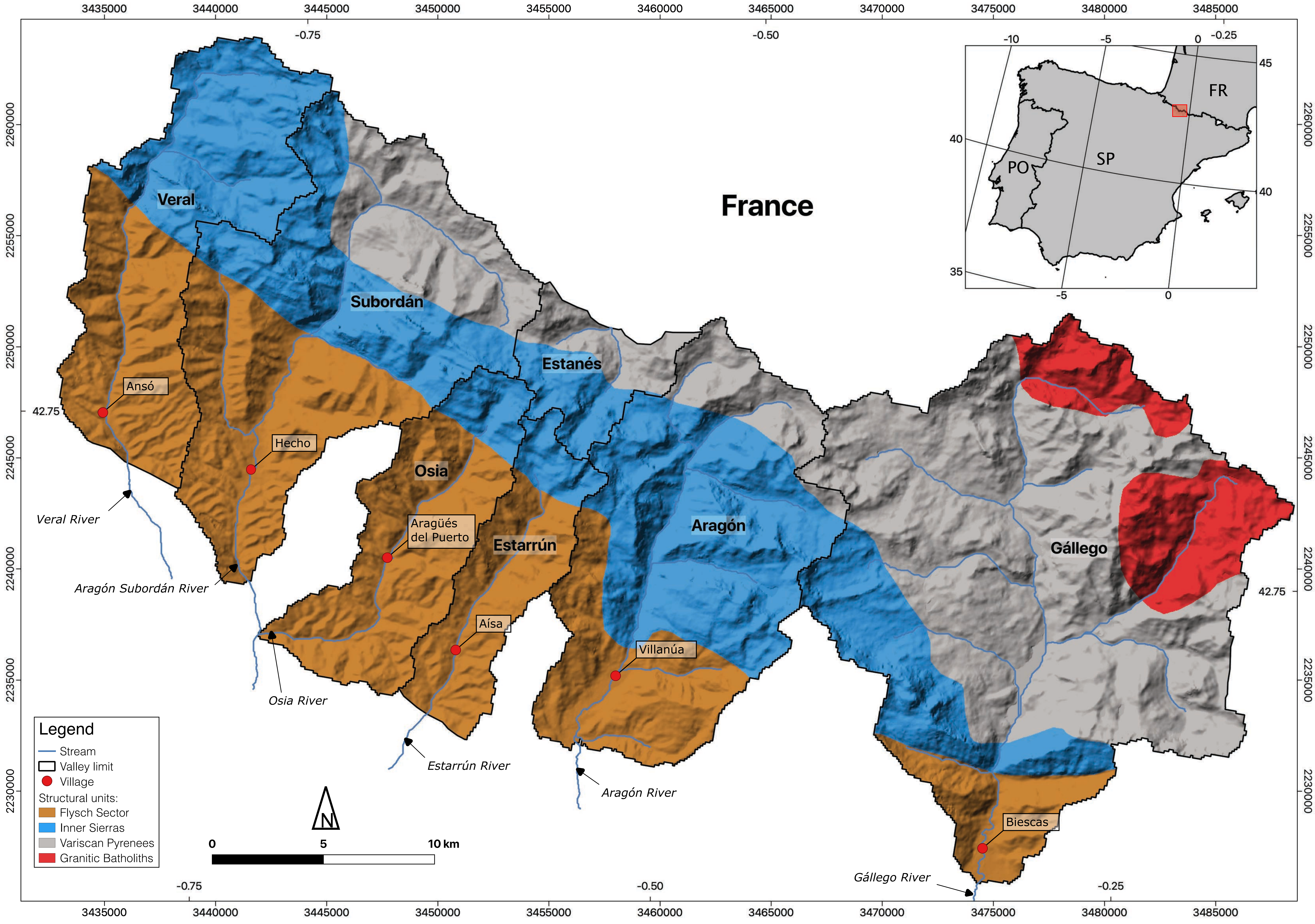
Figure 7. Kernel densities of topographic features at megalithic sites and for the entire study area.

Figure 8. Relative influence of topographic features and valleys on the location of megalithic monuments.

Figure 9. Marginal effects plots of the influence of topographic features and valleys on the location of megalithic monuments.

Figure 10. Probability of occurrence of megalithic monuments.

Figure 1



France
Veral
Subordán
Estanés
Osia
Estarrún
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Gállego
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Hecho
Aragüés del Puerto
Aísa
Villanúa
Biescas
Veral River
Aragón Subordán River
Osia River
Estarrún River
Aragón River
Gállego River
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Stream
Valley limit
Village
Structural units:
Flysch Sector
Inner Sierras
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Figure 2

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Figure 3

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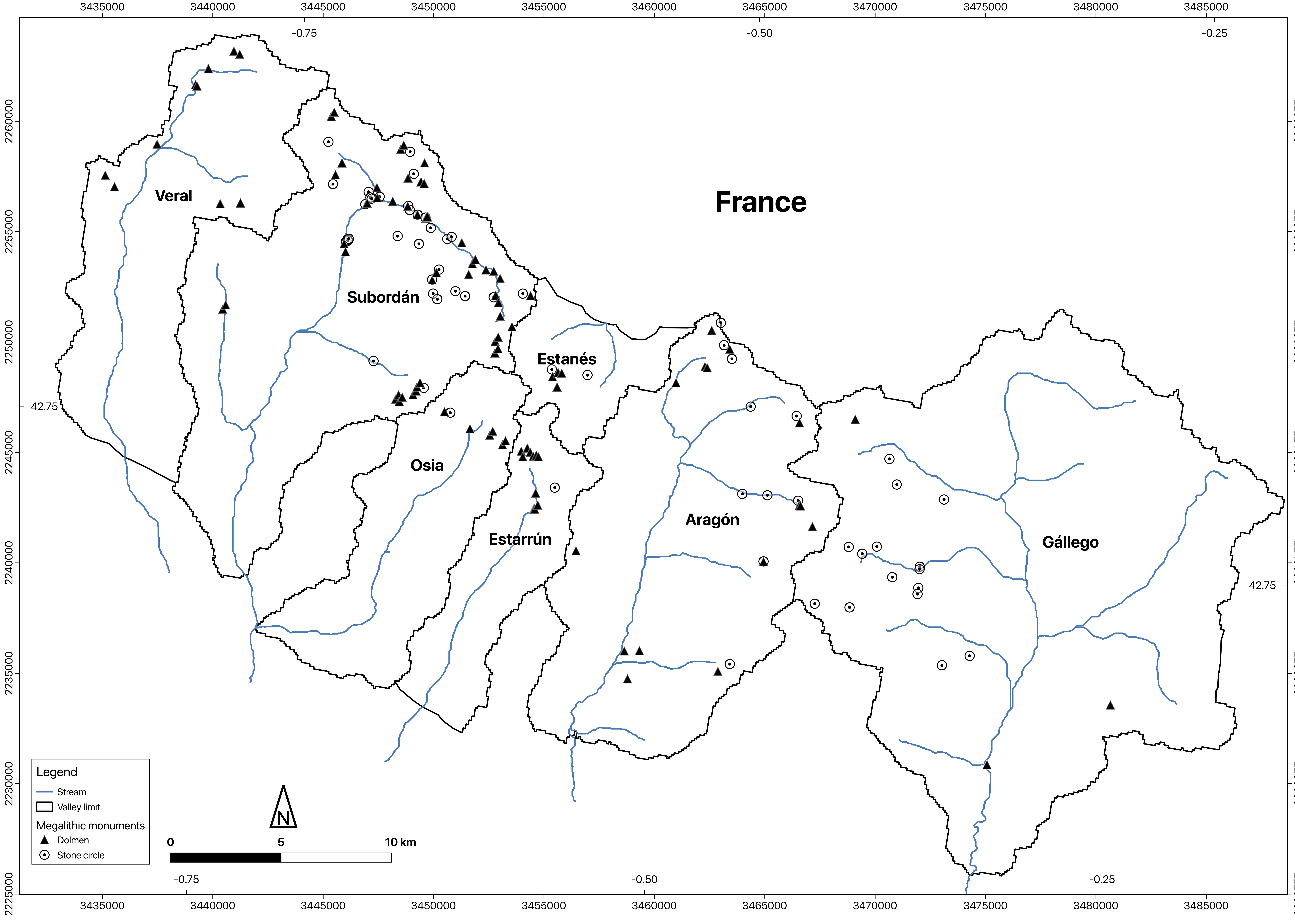
Figure 5



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Estanés
Osia
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Valley limit
Megalithic monuments
Dolmen
Stone circle
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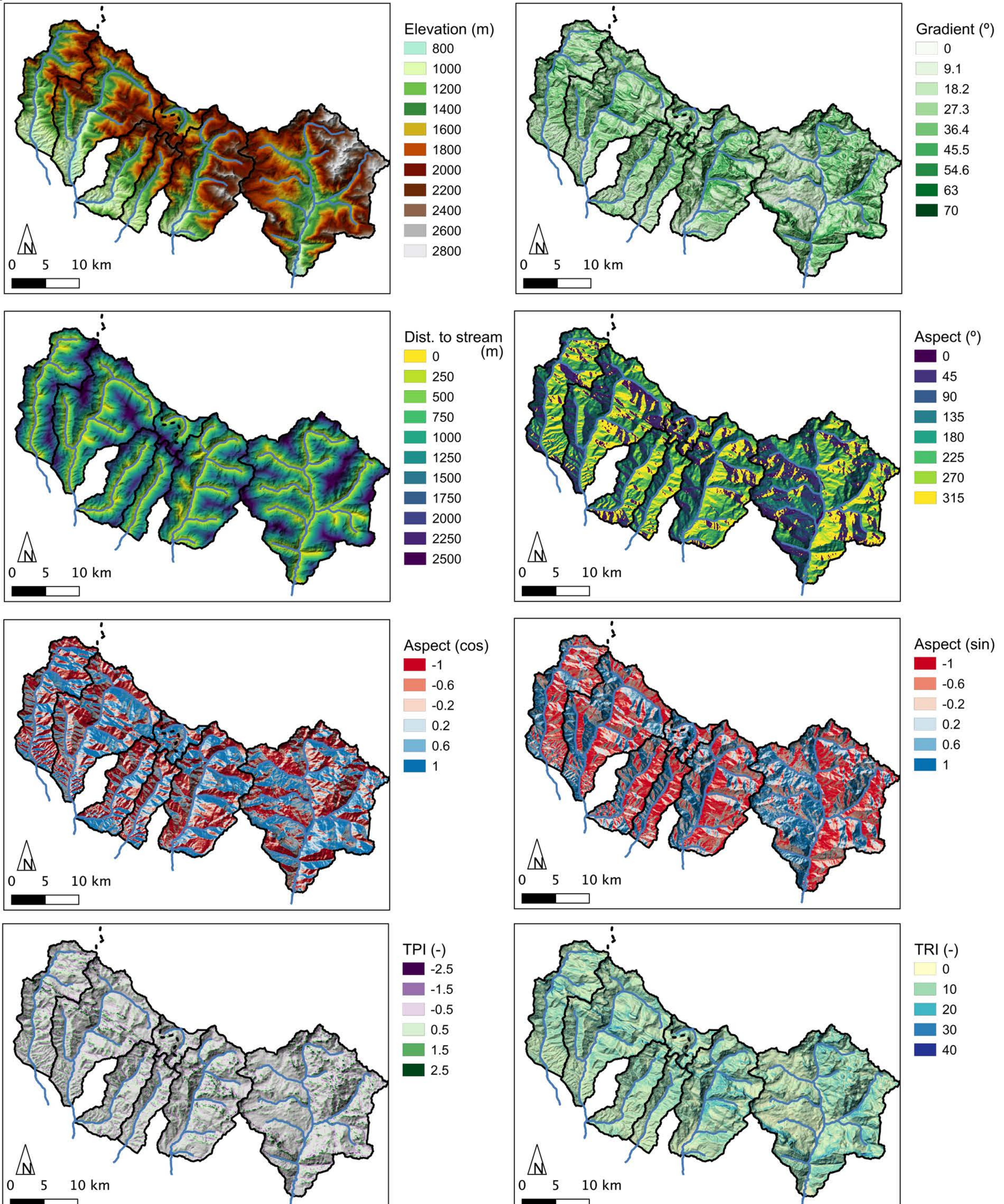
Figure 6



Elevation (m)
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1600
1800
2000
2200
2400
2600
2800
Gradient (º)
0
9.1
18.2
27.3
36.4
45.5
54.6
63
70
Dist. to stream (m)
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
Aspect (º)
0
45
90
135
180
225
270
315
Aspect (cos)
-1
-0.6
-0.2
0.2
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1
Aspect (sin)
-1
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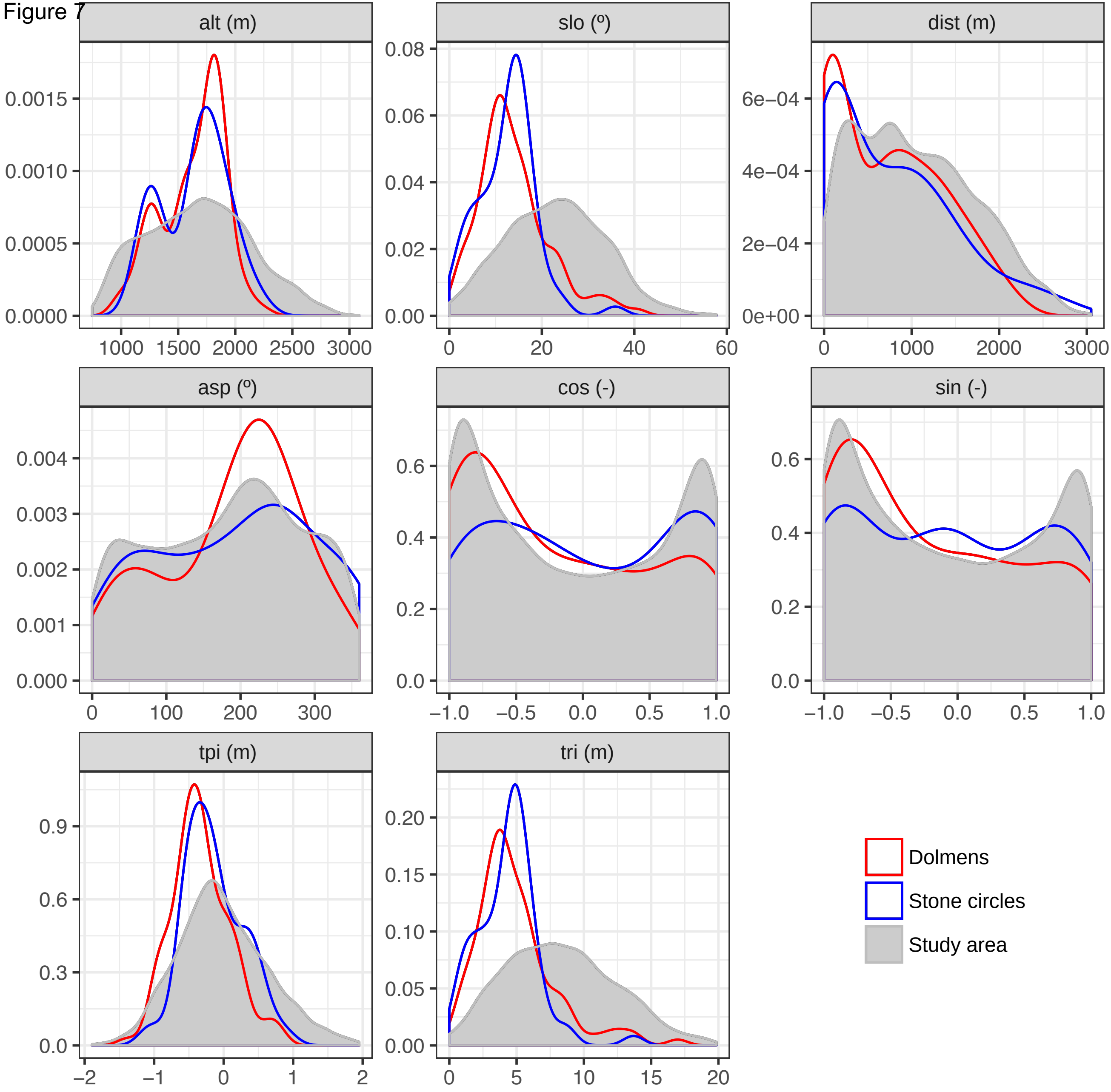
Figure 7


alt (m)
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Stone circles
Study area

Figure 8

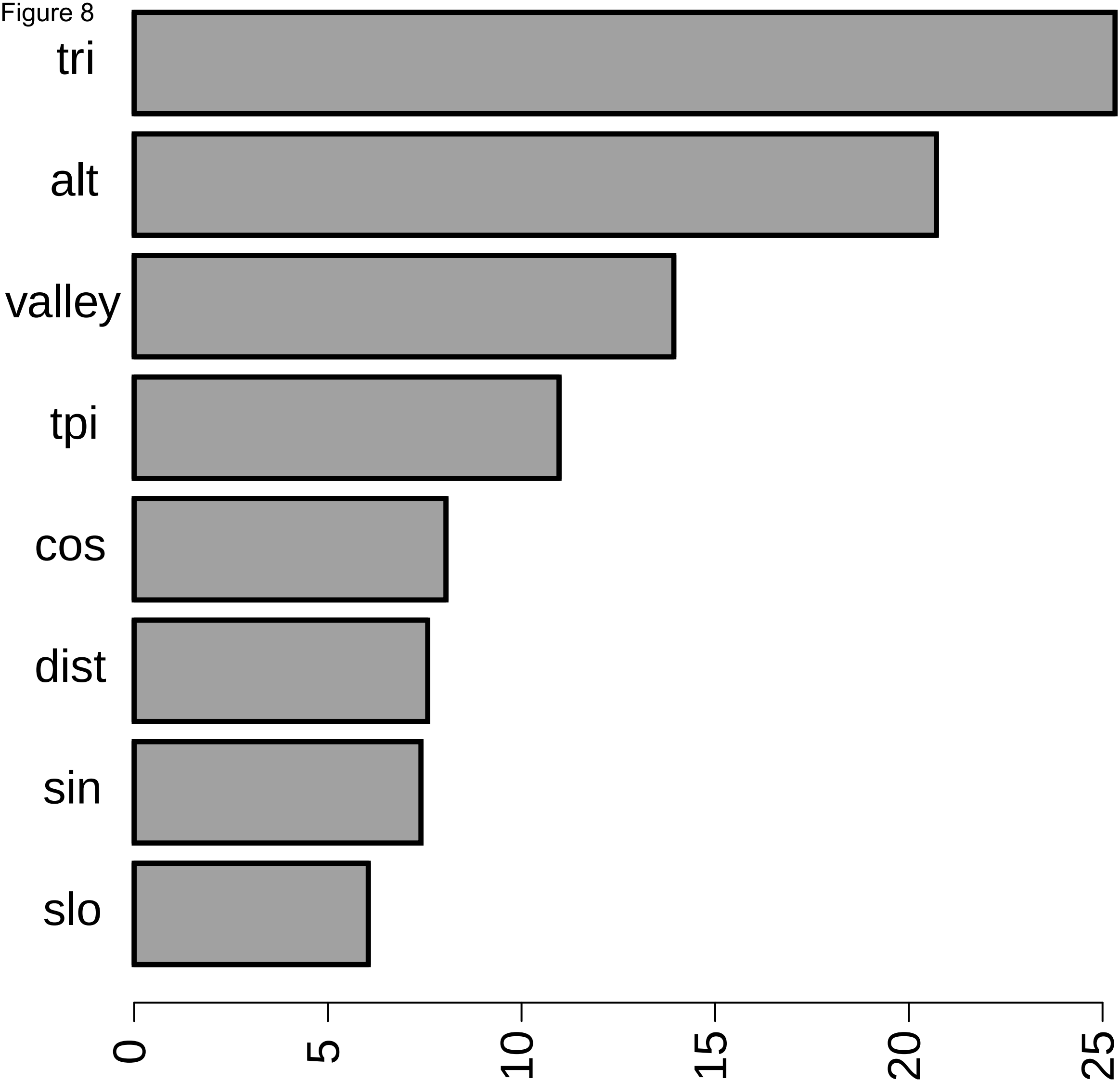

Figure 9

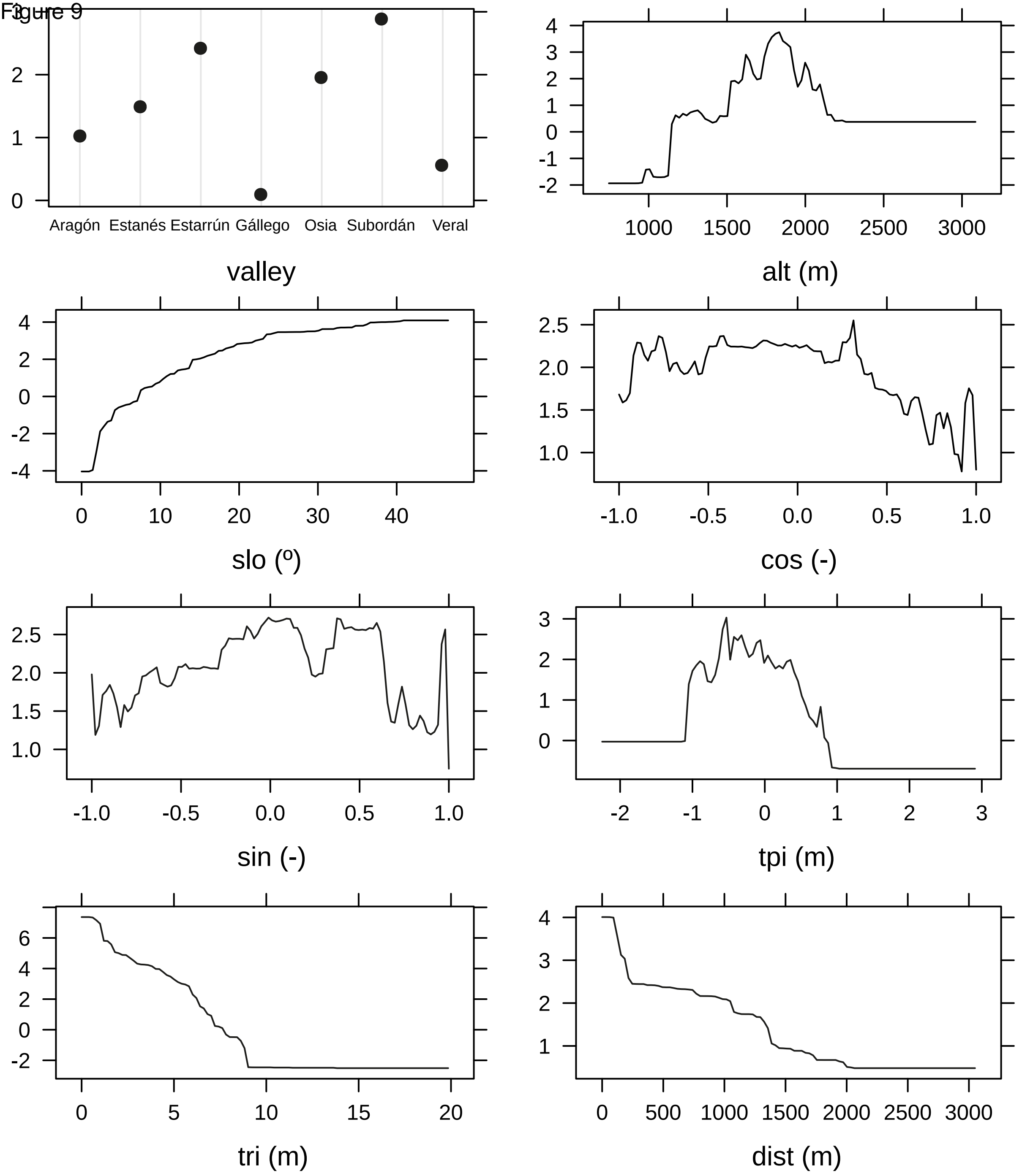
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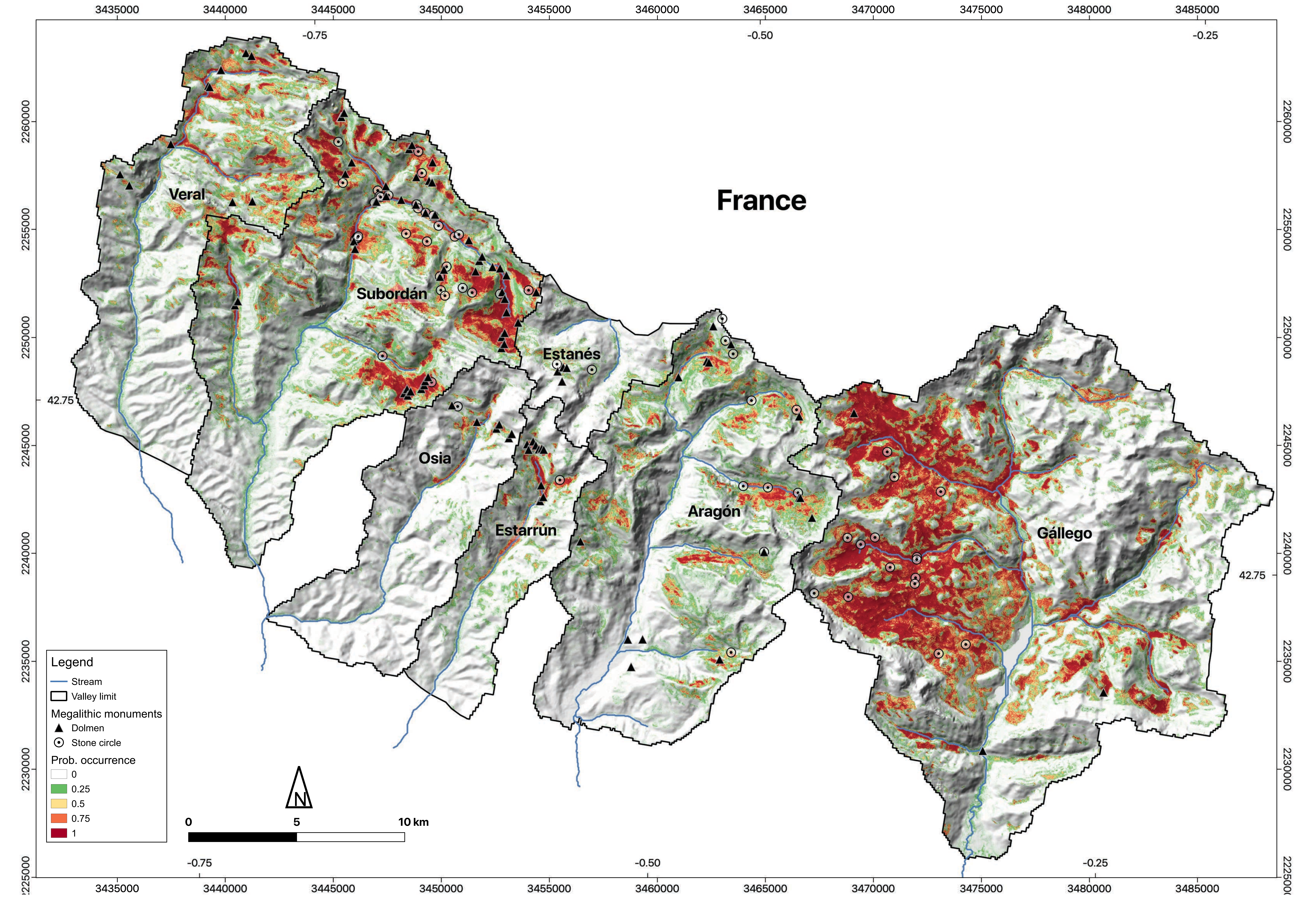
Figure 10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France
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Subordán
Estanés
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Estarrún
Aragón
Gállego
Legend
Stream
Valley limit
Megalithic monuments
Dolmen
Stone circle
Prob. occurrence
0
0.25
0.5
0.75
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10 km

Table 1

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Table
Table 1.docx

Table 2

Table 3