Large-scale mapping of anthropogenic relief features—legacies of past forest use in two historical charcoal production areas in Germany

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Abstract
With the increasing availability of high-resolution digital elevation models (DEMs), large-scale mapping of anthropogenic relief features has become feasible for more areas. However, the landscape-scale distribution patterns of anthropogenic landforms and the quality of DEM-based mapping can be highly heterogeneous. In this study, we mapped relict charcoal hearths (RCHs) in two study regions with differing environmental backgrounds, covering forest areas of more than 15,000 km², analyzed the RCH distributions and evaluated possibilities for predictive modeling of RCH occurrence with respect to natural and cultural landscape structures. More than 45,000 RCHs were recorded in each region, with high site densities even in areas remote from charcoal-consuming industries. Variations in the quality of DEM-based mapping were related to small-scale differences in the DEM quality and larger-scale substrate heterogeneity. A clear association between RCHs and historical industrial sites was found in the Northern European Lowland; while the density of mapped RCHs was predominantly related to geology and morphology in the lower mountain ranges. The results show that variations in mapping quality across scales and the natural and cultural background of a region need to be considered so that the mapping of anthropogenic relief features can contribute to an improved understanding of land-use history.

KEYWORDS
anthropogenic geomorphology, digital elevation models, GIS, land-use legacies, LIDAR, relict charcoal hearths

1 | INTRODUCTION

The increasing availability of high-resolution digital elevation models (DEMs) from LIDAR technology has led to a rapidly growing number of studies on mapping small anthropogenic relief features and analyzing their spatial distribution patterns (Azizi, Najafi, & Sadeghian, 2014; Johnson & Ouimet, 2014; Sofia, Fontana, & Tarolli, 2014; Tarolli, Cao, Sofia, Evans, & Ellis, 2019). Widespread examples for such small-scale anthropogenic relief features are relict charcoal hearths (RCHs), which occur in many forest areas as legacies of historical charcoal production. Before high-resolution DEMs became available for larger areas, RCHs were mainly described for important iron production areas in mountainous areas of Central and Northern Europe, and studies...
have often focused on detailed pedological or anthracological analyses of a few sites. During recent years, large numbers of RCHs have been described for more regions (Hardy & Dufey, 2012; Hazell, Crosby, Oakey, & Marshall, 2017; Johnson & Ouimet, 2014; Mastrolonardo, Franciscos, & Certini, 2018; Rutkiewicz, Malik, Wistuba, & Osika, 2019; Schmidt, Mölder, Schönfelder, Engel, & Fortmann-Valtink, 2016), and the focus of many studies was on mapping sites and analyzing their spatial distribution over larger areas (Carter, 2019; Raab et al., 2019; Rutkiewicz et al., 2019). Automated mapping methods for improved or more time-efficient mapping have been developed and evaluated (Schneider, Takla, Nicolay, Raab, & Raab, 2015; Trier, Zortea, & Tonning, 2015; Witharana, Ouimet, & Johnson, 2018). The growing database of RCH sites allows for the comparison of site densities and morphologies between regions, but a thorough understanding of the possibilities and limitations of DEM-based mapping is a prerequisite for meaningful interpretations of the distribution patterns of mapped features. This prerequisite applies to DEM-based mappings of RCHs but also to other anthropogenic relief features, such as burial mounds, agricultural terraces, and ridge and furrow systems.

Although LIDAR-based mapping often records large numbers of sites, ground-truthing studies indicate that a considerable proportion of sites cannot be captured from DEMs. Because of the effort required for ground-truthing and the limited number of field-based studies, whether DEM-based mapping results in biased databases of RCHs and other small relief features remains unclear (e.g., whether smaller or older sites within charcoal production areas are underrepresented in the mapping results, or whether the mapping quality differs between areas with different environmental background conditions).

Naturally, many mapping studies focus on regions where large numbers of sites can reasonably be expected, for example, in regions where RCHs are already described in archaeological records or where intensive charcoal production is to be assumed because of the presence of historical industry with high charcoal consumption (e.g., Ludemann, 2010; Raab et al., 2015; Rutkiewicz et al., 2019). A mapping of RCHs in such areas can provide valuable information for further studies on charcoal production practices, forest-use history, or industrial history and can contribute to the development of workflows and practices in archaeology and conservation strategies that record and consider RCHs. However, when transferring the results of small-to-intermediate scales to larger areas, the overall number and density of features might be overestimated because of the common focus on "hot spot areas". Furthermore, studies on RCH stratigraphy show clear differences in the practices of using hearth sites between regions, which limits the possibilities of drawing conclusions on the intensity or duration of charcoal production based on the study of site densities. However, the relationships between RCH density and natural or cultural background structures (e.g., geomorphology, soils, industrial history, etc.) are poorly understood.

The central aims of this study were to (a) record the numbers, spatial densities and distribution patterns of RCHs on a large scale, including forest areas close to and remote from historical industries; and (b) contribute to an improved understanding of the possibilities and limitations of DEM-based mapping by comparing RCH mapping results between regions with differing environmental background conditions. The specific objectives of the mapping were to

1. assess the spatial differences in mapping quality across scales,
2. evaluate the spatial heterogeneity in site densities with respect to natural background structures and site locations, and
3. derive a basic understanding of regional differences in charcoal production practices from RCH morphologies and site locations.

Therefore, we mapped RCHs in forest areas within two study regions that include forest areas of 10,000 and 5,000 km² and analyzed the RCH densities and their spatial distributions in relation to the environmental background conditions and basic structures of the industrial history of the regions.

2 | MATERIALS AND METHODS

2.1 | Study areas

The mapping areas of our study cover the state of Brandenburg in northeastern Germany and the historical iron production area of the Upper Palatinate/Northern Bavaria in southeastern Germany (Figure 1). The study regions were delimited based on data availability and the distribution of historical industrial sites. RCHs were mapped in all the forest areas in both study regions.

The study region of Brandenburg is situated in the Northern European Lowland and is characterized by homogeneous geology and topography shaped by Quaternary glaciations. The morphology is predominantly flat, and the substrates are loose and mainly sandy. Forests cover approximately 10,300 km² of the study region (the total area is approximately 29,500 km²) and are dominated by pine in large parts. The potential natural vegetation (pnv) are beech forests in the northern and western parts and basswood-hornbeam, pine-oak and pine forests in the central and eastern parts (Hoffmann & Pommer, 2005). Most of the important charcoal-consuming industries were operating in modern times, with a small number of large iron- and other metalworking centers that were established in the 17th and 18th centuries in different regions. In addition, smaller iron hammer mills operated mainly in the southeastern part of the state. Historical glassworks are concentrated in the northern part of the study region and were operating mainly from the 18th century, with many sites operating for only short time periods.

The study region of Northern Bavaria is situated in the lower mountain ranges of southern Germany. The geology, morphology, and soils in the region are heterogeneous, with a dominance of Mesozoic sedimentary rocks in the western part and metamorphic and igneous rocks of the Bohemian Massif in the eastern part of the study region. Approximately 5,000 km² of the 10,700 km² study region is covered by forests, which are mainly dominated by spruce or pine. The pnv for the largest parts of the region is dominated by beech forests, and fir-beech
forests are present in the eastern part (Bayerisches Landesamt für Umwelt, 2012). The study region extends around the mining and iron production area of the Upper Palatinate, which was of supraregional importance in the High Medieval and early modern period. Ironworks are concentrated along several small rivers, especially in the central part of the study region, whereas glassworks were mainly concentrated in the eastern part of the region.

### 2.2 Large-scale RCH mapping

RCHs were mapped from LIDAR-based DEMs provided by the state topographic survey for forest areas in both study regions (Landesarvermessung und Geobasisinformation Brandenburg, LGB; and Bayerische Vermessungsverwaltung, BVV). The denominated original ground point density of the LIDAR datasets was at least 4 points per m² for most areas in both study regions except for the northeastern part of the Bavarian study region, where it was at least 1 point per m² (Figure 1). The mapping areas were confined to forest-covered areas based on state forest maps provided by Landeskompetenzzentrum Forst Eberswalde (LFE) for Brandenburg and CORINE Land Cover data (European Environment Agency, 2016) for Northern Bavaria. The DEMs show considerable surface disturbances by land in some parts of the study regions use (e.g., in mining or military training areas), which we delineated during the mapping based on the DEMs and topographic maps to be able to specifically consider such areas in further GIS analyses. Because of differences in data availability, we followed slightly different RCH mapping procedures in the two study regions.

For the Brandenburg study region, we mapped the location and diameter of specific RCHs in three consecutive steps. First, we examined the occurrences of RCHs in a 1 km² grid for all forest areas based on the shaded relief map (SRM) visualization of the 1 m DEM provided by the LGB via a Web Map Service (WMS). Cells of the 1 km² grid with low and high numbers of RCHs were identified from the WMS SRM with a scale of 1:4,000. In the second step, specific RCHs were mapped for areas with high numbers of prospected sites using a combination of automated mapping by a template matching algorithm (Schneider et al., 2015) and manual postprocessing using a principal component analysis (PCA)-SRM visualization (Devereux, Amable, & Crow, 2008) at a scale of 1:3,000. DEM derivatives based on elevation data aggregated to a 2 m grid were used in both methods. In the third step, we manually mapped specific RCHs based on the 1 m WMS SRM at a scale of 1:3,000 for areas with low numbers of prospected sites. Finally, we revised the mapping for all areas based on the 1 m WMS SRM displayed at scales of 1:2,500 and 1:1,500. RCHs were mapped as circular polygons along the outline of the RCH platform, that is, the area within the surrounding ditch. Sites too small for a clear identification of their extent were assumed to have a diameter of 8 m, which corresponds to the minimum hearth site diameter mentioned in historical forest regulations for Prussia (cf. Raab et al., 2019). For the area of the Tauersche Forst in southeastern Brandenburg (Figure 1), we incorporated the RCH data set described by Raab et al. (2019).

For the Northern Bavaria study region, the mapping was based on the SRM visualization of the 1 m DEM provided by the BVV, which could be visualized in a web viewer but could not directly be integrated into ArcMap. Therefore, instead of mapping the location of specific sites, we recorded the number of RCHs in the cells of a 1 km² grid along with additional information on the RCH morphometry assigned as attributes to the grid cells. To allow for further analyses of the RCH distribution, we, in addition, generated a RCH point data set based on this information. Therefore, points representing approximative RCH locations were randomly generated within the forest areas in the grid cells according to the number of RCHs recorded from the SRM of the area.
2.3 Mapping quality assessment

The small-scale quality variations of RCH mapping from LIDAR data available for the Brandenburg study region could be estimated based on the results of previous studies. Detailed ground-truthing studies (Bonhage et al., 2019; Raab et al., 2019) show a mapping sensitivity of 40–60%, with a better mapping quality for areas with large and regularly distributed RCHs and pine forest cover, compared with areas with small and irregularly distributed sites and deciduous forest cover. We used ground survey data from the 0.4 km² area described by Bonhage et al. (2019) to assess the RCH mapping quality based on the DEM derivatives used for large-scale RCH mapping, that is, the PCA visualization of the aggregated 2 m DEM and the WMS SRM visualization of the 1 m DEM. The area is covered by oak and pine forest and dominated by sandy substrate and even topography.

For Northern Bavaria, the small-scale variations of mapping quality was assessed by comparing the DEM-mapped RCHs to RCHs mapped in a field survey described by Zenger (1972) for a 16 km² area. Field survey RCHs were therefore digitized from the overview map provided by Zenger (1972) after georeferencing the map. The survey area is mainly covered by pine forest with undergrowth of varying density and covers different geologic units (see Table 1). The original anticipated ground point density of the DEM for this area, as reported by the data provider, is at least one point per m². To allow for a detailed, spatially distributed analysis of the results, we mapped the locations of specific RCHs for this area.

To perform a basic assessment of the larger-scale mapping quality, we validated the mapping results against field surveys in several forest areas and mainly focused on verifying or refuting mapped RCHs. No regular survey pattern was used but we recorded additional sites in the vicinity of previously mapped RCHs during the surveys. Furthermore, we compared the mapped RCHs with hearth sites recorded in the databases of the archaeological surveys of Brandenburg (Brandenburgisches Landesamt für Denkmalpflege und Archäologisches Landesmuseum, BLDAM) and Bavaria (Bayerisches Landesamt für Denkmalpflege, BLfD). However, this evaluation can provide only a rough approximation of the mapping sensitivity because RCHs are not systematically integrated into these databases and records are mainly limited to archaeological survey sites. For the entire Northern Bavaria study region, we also analyzed historical maps from the early 19th century (Bayerische Uraufnahme, 1808–1864) for map symbols representing charcoal hearth locations and field or settlement names indicating the existence of charcoal hearths and compared the resulting data set with the mapped RCHs.

### TABLE 1

Mapping quality assessment for the ground-truthing areas in the Tauersche Forst, Brandenburg, and in the forest areas west of Weiherhammer, Northern Bavaria (see Figure 2)

| Brandenburg - field-mapped RCHs: n = 120 (Bonhage et al., 2019) | 2 m DEM, PCA | 1 m DEM, SRM |
|------------------|------------------|------------------|
| mapped RCHs: 60  | TP = 56          | FP = 4           |
| FN = 64          | mapped RCHs: 64  | TP = 59          |
|                  | FN = 61          | FP = 5           |
| sensitivity (TP/TP+FN) | 47%              | 49%              |
| precision (TP/mapped RCHs) | 93%              | 92%              |

| Northern Bavaria - field-mapped RCHs: n = 1,326 (Zenger, 1972) | 1 m DEM, SRM |
|---------------------------------------------------------------|------------------|
| mapped RCHs: 548                                             | mapping sensitivity for geologic units |
| sensitivity (TP/TP+FN) | 41%          | terrace sand and gravel | 51% |
| Buntsandstein (sandstone) | 38%          |
| Oberrottledengendes (sandstone/mudrock) | 43%          |
| Abbreviations: DEM, digital elevation model; PCA, principal component analysis; RCHs, relict charcoal hearths; SRM, shaded relief map. |

2.4 RCH distribution—GIS analyses

The spatial distribution of the RCH density was analyzed in relation to environmental background structures using ArcGIS (ESRI, Redlands, California). To evaluate the mapping results and quality in relation to geology, we analyzed the RCH distribution across petrographic units as mapped in the overview geologic map for Germany at a scale of 1:250,000 (Bundesanstalt für Geowissenschaften und Rohstoffe BGR, 2019b). The overview soil map at a scale of 1:1,000,000 (Bundesanstalt für Geowissenschaften und Rohstoffe BGR, 2019a) was used to analyze occurrences of RCHs on different soil types. The distances of RCHs to waterbodies were determined using waterbody layers of the 1:250,000 digital landscape model (GeoBasis-DE/BKG, 2019).

The landscape morphometry around RCHs was characterized based on the 25 m Digital Elevation Model over Europe (EU-DEM) (Copernicus Land Monitoring Service, 2017), which we aggregated to a 200 m DEM that captures medium-scale morphological variations. We determined the altitude, slope and aspect values for this aggregated DEM. Subsequently, the terrain roughness was characterized by determining the standard variation of slope values within a 5 × 5 cell moving window following Frankel and Dolan (2007). With this method, terrain roughness was described independently from the overall slope (Berti, Corsini, & Daehne, 2013) within an area of 1 km² to reflect the effort of transporting charcoal from the hearth site related to relief variations. The morphometric parameters were then transferred from raster datasets to the mapped RCH datasets, and the distribution of mapped RCHs with respect to the morphometry was analyzed.

The locations of historical industries that represented potentially significant consumers of charcoal or competing consumers of firewood were integrated into the GIS database. For Brandenburg, we assembled information on metal works, glassworks, lime kilns and tar kilns based on the historical literature and gazetteers (e.g., Bratring, 1804; Cramer, 1872-1809; Büsching, 1775; Enders, 2013). Additional historical
glassworks were located based on the catalog from Friese and Friese (2006). Historical maps (Schmettausches Kartenwerk, 1776–1787; Preußische Uraufnahme 1830–1865) and catalogs of the Brandenburg State Office for Monument Protection (BLDAM) were used as additional information to localize historical industrial sites and integrate the locations of tar kilns. For Bavaria, we localized iron hammer mills based on information assembled by Götschmann (1986) and Hirschmann (1997). The databases and catalogs of the Bavarian State Offices for Monument Protection (BLfD) were used to localize additional iron, metal and glassworks and lime and tar kilns. The distances between the RCHs and industrial sites were determined using the resulting datasets for both study regions.

2.5 | RCH distribution - statistical analyses

To test for systematic distribution patterns of RCHs, we compared the mapped RCH datasets with randomly distributed point datasets. Randomly distributed points were generated within a minimum distance of 25 m of each other within the forest areas. We compared the distances of RCHs and random points to industrial sites and waterbodies with Mann–Whitney U tests and the frequencies of mapped RCHs and random points for examined landscape units with chi-squared tests in R 3.5.1 (R Core Team, 2018).

Based on the results of exploratory data analyses and distribution pattern tests, we combined the environmental background variables in binomial logistic regression models, using the occurrence of RCHs in a cell as the dichotomous dependent variable of the models. The probability of RCH mapping for a 1 km² area was modeled as follows:

$$P(y = 1) = \frac{\exp(x^T \beta)}{1 + \exp(x^T \beta)}$$

where $$\beta = (\beta_1, \ldots, \beta_n)^T$$ is the vector of regression coefficients and $$x_i (i = 1, \ldots, n)$$ are the environmental background continuous or dummy-coded categorical variables for each cell. In all the 1 km² cells of the study regions, we assigned the forest area, mean slope, roughness, altitude, and distance to metal works and large cities, glassworks, tar kilns and waterbodies as continuous variables; and surface disturbance, low DEM quality, geology, and soil units as

TABLE 2 Distribution of the mapped RCHs with respect to geology and soils, compared with randomly distributed points in forest areas (expected RCHs)

| Petrographic units                        | Mapped RCHs (%) | Expected RCHs (%) |
|-------------------------------------------|-----------------|-------------------|
| **Brandenburg**                           |                 |                   |
| Coarse sediments (2 units, 28 RCHs)A      | 0.1             | 0.3               |
| Sand (12 units, 42,496 RCHs)B             | 93.0            | 77.2              |
| Silt (12 units, 2,432 RCHs)A              | 5.3             | 13.9              |
| Clay (8 units, 102 RCHs)A                 | 0.2             | 1.3               |
| Peat (1 unit, 585 RCHs)A                  | 1.3             | 4.5               |
| **Northern Bavaria**                      |                 |                   |
| Magmatic and igneous rocks (48 units, 4,620 RCHs)B | 10.0           | 34.1              |
| Sandstones and conglomerates (9 units, 19,152 d RCHs)C | 41.6           | 11.3              |
| Mudrock (14 units, 2,719 RCHs)B           | 5.9             | 9.3               |
| Limestones (7 units, 1,176 RCHs)A         | 2.6             | 19.8              |
| Coarse sediment (6 units, 1,194 RCHs)B    | 2.6             | 1.5               |
| Sand (6 units, 9,070 RCHs)C               | 19.7            | 7.2               |
| Silt (6 units, 574 RCHs)B                 | 1.2             | 4.1               |
| Clay (9 units, 5,762 RCHs)B               | 12.5            | 9.2               |
| Peat (1 unit, 47 RCHs)B                   | 0.1             | 0.1               |
| **Soil units**                            |                 |                   |
| Gleysols, Fluvisols, Histosols (4 units, 2,004 RCHs)A | 4.4             | 15.9              |
| Podzols (2 units, 26,319 RCHs)C           | 57.6            | 36.3              |
| (Brunic) Arenosols (2 units, 8,957 RCHs)B | 19.6            | 8.0               |
| Stagnic Cambisols, Retisols, Luvis Planosols (3 units, 256 RCHs) | 0.6             | 6.3               |
| Luvisols, Retisols (3 units, 3,849 RCHs)A | 8.4             | 17.5              |
| Regosols on loamy sand (1 unit, 4,076 RCHs)B | 8.9             | 12.0              |
| **Northern Bavaria**                      |                 |                   |
| Gleysols, Fluvisols, Histosols (3 units, 468 RCHs)A | 1.0             | 1.1               |
| Podzols (3 units, 26,908 RCHs)C           | 58.5            | 28.7              |
| Cambisols, Brunic Arenosols (8 units, 16,689 RCHs)B | 36.3           | 51.0              |
| Luvisols, Retisols (1 unit, 1,460 RCHs)A  | 3.2             | 2.3               |
| Regosols on limestone (1 unit, 422 RCHs)A | 0.9             | 16.7              |

Note: The RCH distribution among units significantly (p-value <.005) differs from a random distribution in both study regions. The superscripted symbols for the units show the petrography and soil class assignments for the logistic regression analysis and model (see Table 5).

Abbreviation: RCHs, relict charcoal hearths.
categorical variables (see Table 2). For the Northern Bavaria study region, we included all the variables into the model, whereas for Brandenburg, we did not consider the altitude and distance to waterbodies relevant variables. Logistic regression was carried out and evaluated in R 3.5.1 using the glm (generalized linear model) function and the ROCR package (Sing, Sander, Beerenwinkel, & Lengauer, 2005). Probability surface rasters for RCH mapping were constructed in ArcGIS from the predicted values of the fitted models.

3 | RESULTS

3.1 | Mapping quality assessment

The comparison of the RCH mapping results with the field-surveyed RCH data set of Bonhage et al. (2019) (Table 1) shows that 56 of the 120 sites were correctly mapped using the PCA visualization of the aggregated 2 m DEM. Using the WMS SRM visualization of the 1 m DEM, 59 sites were captured, and only a few sites were falsely mapped using both methods. This finding corresponds to a mapping quality that is only slightly lower than that found by Bonhage et al. (2019), who used several visualizations of the 1 m DEM. The validation of DEM-mapped RCHs against the field-surveyed data set from Zenger (1972) in the 16 km² Northern Bavaria ground-truthing area (Table 1) shows that 548 of the 1,326 sites within recent forest areas could be captured by the DEM. Because the location of field-surveyed RCHs could not be determined exactly from the generalized map from Zenger (1972), the characteristics of sites missed in the DEM-based mapping could not be assessed in further detail. A separate evaluation within specific units of the geologic overview map suggests slight differences in the mapping sensitivity for different geologies (Table 1). However, detailed visual analysis of the DEM and field surveys showed that the lower mapping quality in parts of the ground survey area is mainly related to the lower resolution of the DEM in areas with considerably dense vegetation cover (Figure 2).

Field surveys in Brandenburg confirmed 338 RCHs distributed over 55 survey areas. During the surveys, 64 additional RCHs that were not previously mapped were detected among the surveyed areas. Records from archaeological surveys (BLfD) provide evidence for RCHs in 16 additional forest areas. RCHs were captured by the DEM-based mapping for 11 of these areas; however, in the other five areas, no traces of RCHs were observable in the DEM. In Northern Bavaria, field surveys in 19 forest areas confirmed several RCHs in each area. Only five additional RCHs not previously observed in the DEM were found in the surveys; however, RCHs were hardly visible because of dense undergrowth in most areas. Information on RCHs from archaeological surveys (BLfD) provides evidence for 20 additional RCHs or RCH groups in forest areas. For 70% of these sites, we did not detect RCHs in the DEM. Evidence of RCHs from archaeological surveys was more frequent for nonforested areas. Although these RCHs could not be directly observed from the DEMs, other sites could be detected in nearby forest areas in more than 85% of the records. Historical maps of the Northern Bavaria study region show charcoal hearth symbols in 371 of the studied 1 km² cells distributed throughout the study area. Hearth symbols are recorded in forest areas, as well as close to settlements, directly adjacent to iron hammer mills or along roads leading towards settlements. In 55 of these cells with mapped hearths, the RCHs had been mapped from the DEM, and for only 23 additional cells, indistinct RCH morphologies were observable in the SRM at the location of the symbol. This finding corresponds to only 15% of RCHs that were actually captured or 21% of RCHs that can
potentially be captured from DEMs. For the majority (i.e., 60%) of the grid cells with hearths recorded in the historical maps, the ground surface around the hearth locations was overbuilt or significantly disturbed by subsequent land use. For approximately 20% of the hearth symbol areas, no indications of RCHs were observable in the DEM, although the areas were located within recent forest areas with no obvious surface disturbance. The proportion of such “nonvisible” RCHs was higher in the areas with a low DEM ground point density in the eastern part of the study region (29% vs. 16% in other parts of the study region). No relation to geology can be found in the distribution of these nonvisible RCHs. For 180 of the 1 km² cells, field or settlement names in historical maps hinted at the existence of charcoal hearths, and RCHs were mapped in 50 of these cells. Areas where historical maps hinted at RCH occurrence but where no RCHs were mapped are largely (30%) located in limestone areas.

3.2 Large-scale RCH distribution

In the Brandenburg study region, we mapped more than 41,000 RCHs in addition to the almost 6,000 RCHs in the data set from Raab et al. (2019). RCHs were found in almost all of the larger forest areas but their spatial density varied across a wide range (from only a few sites within several km² of the forest to several hundreds of sites per km², Figure 3). Considerably high RCH densities occur in the vicinity of the Peitz ironwork, the historical metal industrial sites in Eberswalde and the glassworks in the northern parts of Brandenburg. However, very high densities also occur in areas remote from larger historical industrial sites, for example, in forest areas north of Berlin and along the Berlin ice-marginal valley between Berlin and Frankfurt (Oder). The vast majority of mapped RCHs show the characteristic morphometry of sites on flat landscapes, for example, a slightly elevated platform and a surrounding ditch, as described in detail by Raab et al. (2015). For small sites, surrounding ditches were often not observable in the DEMs and field surveys. Some larger sites have several pits located concentrically around the platform instead of a continuous ditch, which is a common morphology for sites in southern Poland (Rutkiewicz et al., 2019). RCHs shaped as leveled platforms on slopes were mapped in only a few individual cases.

The diameter of mapped RCHs varies from a few meters to approximately 30 m, but small RCHs are clearly more frequent, as seen by the mean diameter of 10.7 m for all mapped RCHs. Considerably large RCHs are highly concentrated in large charcoal production fields, for example, in the forests south of Eberswalde and north of Peitz. Within the charcoal production fields, RCHs occur in a large variety of distribution patterns, from a nearly uniform distribution over large areas to frequent “microclusters” (see Raab et al., 2019) and larger isolated clusters of several RCHs. However, the mapping results do not reveal clear relationships between these spatial distribution patterns and the environmental background structures or RCH diameters.

In the Northern Bavaria study region, we recorded more than 47,000 RCHs, that is, a similar number of sites to that mapped for Brandenburg despite the considerably smaller extent of the study region and forest areas. The RCH densities are clearly highest in the westernmost part of the study region, south of Nuremberg, where we found more than 20,000 sites over an area of only 400 km². RCH densities of more than 50 sites per km² also occur in other charcoal production fields, mainly in the vicinity of modern-age ironworks (e.g., Auerbach, Weiherhammer, Bodenwöhr, Figure 3). Lower RCH densities up to 25 sites per km² were mapped in other forest areas in the vicinity of historical industrial sites, that is, around the accumulation of medieval to early modern iron hammer mills in the southern part of the Vils River valley (Figure 3) and in the eastern part of the study region (see Figure 1). Very few RCHs were recorded on the heavily disturbed military training areas in the western part of the study region.

We observed a large variety of RCH morphologies and sizes over the study region. In the areas with considerably high RCH densities, the predominant RCHs are elevated platforms on flat terrain with ditch remains, that is, RCHs with the same morphology as observed in the Brandenburg study region. RCHs shaped as leveled platforms...
on slopes were found in high density in the area west of Auerbach and southwest of Weiherhammer (Figure 3) and dominated in most other parts of the study region with lower RCH densities. Especially in the northern parts of the study region, we also observed RCHs shaped as platforms within a surrounding elevated ridge as described by Hardy and Dufey (2015) and Swieder (2018), and they were often located on flat hilltop positions or on level areas within sloped terrain. There is a high level of variability in the diameters of RCHs on flat terrain, and they range between a few meters and up to approximately 25 m. The slope platform RCHs show less variability in their diameters than the flat-terrain RCHs.

3.3 | RCH distribution with respect to the environmental background structures

The distributions of mapped RCHs with respect to soils and geology significantly differ from random distribution patterns for both study regions (p-values <.001, Table 2, Figure 4). In the forest areas in Brandenburg, the geology is clearly dominated by sand, and 77% of the randomly distributed points in the forest areas (“expected RCHs”) are located on predominantly sandy substrate. However, 93% of the mapped RCH sites are located on sandy substrate while mapped RCHs are clearly underrepresented compared with the expected RCHs on the silty and clayey substrate and in peat areas. Although the soil quality is poor in most of the forest areas, a concentration of RCHs in areas with poorer soil quality is observable (Table 2, Figure 4a). There are clearly more mapped than expected RCHs in Podzol and Arenosol areas, and there are considerably fewer mapped than expected RCHs in Retisol and Luvisol areas.

The RCH distribution over petrographic units (Table 2, Figure 4c) is more complex in the Northern Bavaria study region than in the Brandenburg study area. Similar to the Brandenburg study area, RCHs are overrepresented on loose sandy sediments and even more so in sandstone areas. On the other hand, there are fewer mapped RCHs than expected on magmatic and igneous rocks, which dominate
a large fraction of the study region's forests. An even more significant discrepancy between the numbers of mapped and expected sites was found in limestone areas, in which less than 3% of the mapped RCHs are located. The distribution over soil units for this study region mainly reflects the relationship with the geology, with an overrepresentation of RCHs on Podzols (mainly developed in sand and sandstone areas) and an underrepresentation of RCHs on Cambisols and Brunic Arenosols (dominating in large parts of the magmatic and igneous rock areas). Only very few RCHs were mapped on the Leptosols and Cambisols on limestone in the western part of the study region.

The RCHs in both study regions are predominantly located in flat and even landscapes (Table 3, Figure 4b,d). Furthermore, the fractions of RCHs in the terrain roughness classes (Table 3) show a clear preference of level areas. Although no clear dominance of specific slope aspects is observable for forest areas in general, the RCHs on slopes (≥2°) mapped in Northern Bavaria seem to be slightly overrepresented on north- and south-facing slopes. Furthermore, RCHs are predominantly located in low terrain positions. Nevertheless, more than 2,000 mapped RCHs are still located at altitudes >600 m, mainly in the high northernmost part of the study region.

The distances of RCHs to historical industrial sites, tar kilns, and water bodies significantly differ from a random distribution for both study regions (Table 4). Large distances of RCHs to historical industrial sites are observed in Brandenburg, with a mean distance of almost 15 km to the closest metal works and a mean distance of more than 7 km to an industrial site if metal works, glassworks, and lime kilns are considered charcoal consumers. Nevertheless, the distances to industrial sites are significantly smaller than those for randomly distributed points. The Northern Bavaria RCHs are, on average,
located closer to historical industrial sites than the Brandenburg RCHs; however, no clear association of RCHs to industrial sites is observable for the mapped RCHs (i.e., the distances to industrial sites of the mapped RCHs are larger than those of the randomly distributed points). Both metal works and glassworks are frequently the closest potential charcoal-consuming industrial sites to the Brandenburg RCHs (for 41% and 38% of the RCHs, respectively), whereas a clear dominance of metal works as the closest potential consumer is observable in Northern Bavaria (94% of the RCHs). The mean distances of the RCHs to tar kilns are shorter than for the randomly distributed points in both study regions, although no clear association between RCHs and tar kilns is observable in the overall datasets of both regions. The mean distances of RCHs to waterbodies were relatively large for both study regions; however, the observed RCHs in Northern Bavaria are closer to water bodies than expected and the frequency distribution of RCH distances suggests that colliers preferred sites to be located less than 200 m away from water bodies. No similar trend is observed in Brandenburg, where very high RCH densities occur at distances of several km to waterbodies.

### 3.4 Prediction models for the RCH mapping probability

The coefficients and quality measures of the logistic regression models for the RCH mapping probability are listed in Table 5. McFadden’s pseudo $R^2$ values (McFadden, 1977) indicate a good model fit for both regions, and the area under the receiver operating characteristics curve (AUC) indicates excellent discrimination between classes for both regions (Mandrekar, 2010). The probability surfaces derived from the predicted values (Figure 5) show that high modeled probabilities for RCH mapping correlate well with RCHs that have been mapped on the ground for most areas in the study regions. For the Brandenburg RCH distribution model, all the variables except for slope and roughness show a significant contribution to the probability of RCH occurrence. The probability (log odds) for RCH mapping increases most prominently with increasing forest area in a 1 km² cell and decreases with increasing distance from consumers, with similar effects for metal and glassworks. Furthermore, the probability of RCH mapping increases for areas with a higher DEM quality, for sand areas compared with other petrographic units, and for Podzol areas compared with other soil units. However, the model does not reflect the negative effect of surface disturbance. The model for the Northern Bavaria study region describes similar effects of environmental structures; however, compared with the model for the Brandenburg study region, it only reflects slight effects of the distances from glassworks and tar kilns (presumably because of the heterogeneous distribution of such sites within the study region, Figure 3). The model coefficients further show a low RCH mapping probability for limestone areas but a high probability for sand and sandstone areas, and the highest RCH occurrence probability is indicated for Podzol areas. Compared with the Brandenburg model, the modeled effects of geology are clearly stronger (as shown by the model coefficients) than those of the soil units.

### 4 DISCUSSION

#### 4.1 RCH mapping quality across scales

For both study regions, the validation of mapped RCHs against field surveys and the comparison with archaeological records and archival information confirm that both small- and large-scale spatial variations in the mapping quality need to be considered when interpreting the results of the DEM-based RCH mapping.

The validation of the mapped RCHs by field surveys shows a considerable underestimation of the RCH numbers. The mapping sensitivity in the ground-truthing areas of this study ranged between 40% and 50%, which is within the range of values reported in other

### TABLE 5 Coefficients and quality measures from the logistic regression models

|                      | Northern Bavaria | Brandenburg |
|----------------------|------------------|-------------|
|                      | $\beta$          | Significance | $\beta$          | Significance |
| Intercept            | −6.59 ***        |             | −2.46 ***        |             |
| Forest area          | 3.49 ***         |             | 3.57 ***         |             |
| Slope                | −0.08 **         |             | −0.07            |             |
| Roughness            | −0.10            | ***         | −0.11            | ***         |
| Altitude             | 0.00             | ***         | –               |             |
| Distance to metal    | −0.07 ***        |             | −0.03 ***        |             |
| works and cities     |                  |             |                  |             |
| Distance to glass    | −0.01            | *           | −0.03 ***        |             |
| works                |                  |             |                  |             |
| Distance to tar      | −0.01            | *           | −0.24 ***        |             |
| kilns                |                  |             |                  |             |
| Distance to water    | −0.29 ***        |             | –               |             |
| bodies               |                  |             |                  |             |
| Undisturbed          | 1.74 ***         |             | −0.78 ***        |             |
| surfaces             |                  |             |                  |             |
| High DEM quality     | 1.00 ***         |             | 0.19 **          |             |
| Petrography class    | 1.17 ***         |             | 0.38 ***         |             |
| B                    |                  |             |                  |             |
| Petrography class    | 1.59 ***         |             | –               |             |
| C                    |                  |             |                  |             |
| Soil class A         | 0.36 ***         |             | 0.60 ***         |             |
| Soil class B         | 0.71 ***         |             | 0.72 ***         |             |
| AUC                  | 0.834            |             | 0.903            |             |
| McFadden’s $R^2$     | 0.259            |             | 0.353            |             |

Note: significance levels: ***, 0.001; **, 0.01; *, 0.05. For the petrography and soil classes, see Table 2. Abbreviation: AUC, area under the receiver operating characteristics curve.
studies that conducted a systematic ground-truthing of DEM-based RCH mappings (Hardy, 2017; Ludemann, 2012; Raab et al., 2019) and similar anthropogenic relief features (Trier et al., 2015). The relatively low mapping sensitivity found for the Northern Bavaria ground-truthing area is most likely related to the lower original ground point density in the DEM for this region (Figure 1). Small-scale spatial variations in the mapping quality were observed within both ground-truthing areas of our study, and a detailed visual analysis of the DEMs together with field surveys suggests that these variations are mainly related to differences in the vegetation cover characteristics, which presumably affect the LIDAR ground point density and, therefore, the DEM quality (Reutebuch, McGaughey, Andersen, & Carson, 2003; Spaete et al., 2011). Considering such effects, we observed only a slightly decreased mapping sensitivity in the RCH mapping from a 2 m aggregated DEM compared with the mapping from the original 1 m DEM. A bias in the mapping sensitivity related to feature size, that is, higher rates of missed features for smaller RCH diameters, was found in detailed analyses by Raab et al. (2019) and is also reflected in the validation against the ground survey data for our mapped RCHs. On the landscape scale, this phenomenon might also result in spatially varying mapping sensitivity, with lower proportions of RCHs captured in areas with characteristically smaller sites.

Field surveys for ground-truthing are mostly limited to small areas and mainly carried out for study areas with heterogeneous conditions and good feature preservation. Therefore, the mapping sensitivities found in such approaches cannot be directly transferred to DEM-based mapping at the landscape scale. Validation of DEM-based mapping against field surveys and archaeological records does not reflect a large-scale spatial heterogeneity of mapping quality, but validation against historical maps indicates that the proportions of RCHs that can be mapped from DEMs differ within our study region. Generally, several additional and often interrelated effects on the mapping quality need to be considered in the interpretation of large-scale mapping results:

- LIDAR-based DEMs for large areas are often composed of multiple datasets recorded in several individual flight campaigns over several years (Baltsavias, 1999), which can result in heterogeneous elevation datasets, even if the final processed DEM is provided at a continuous spatial resolution. We observed spatial differences in RCH visibility in DEMs related to documented differences in the ground point density in the Northern Bavaria study region. We also noted differences in the representation of small surface structures within the Brandenburg study region; however, we were not able to directly relate these differences to information on data acquisition or processing given by the WMS DEM provider (LGB, 2019).

- The preservation of features can considerably differ depending on the subsequent land use. The effects of different forestry practices are observable within the ground survey area in the Taurersche Forst (see the SRM details in Figure 2). Furthermore, our results reflect considerable effects of military activities, which result in areas with almost no detectable RCHs (e.g., in large military training areas such as Grafenwöhr west of Weiherhammer in the Northern Bavaria study region) or only a few mapped sites (e.g., around the Gottow ironworks in Brandenburg, Figure 3). The potential for the quantification of the effects of such surface disturbances is limited as shown by the inconclusive representation of the surface disturbance effects in the logistic regression model for the Brandenburg study area. This limitation is most likely due to the fragmented distribution of disturbed surfaces (Figure 1) and the former frequent use of forests for charcoal production. However, single RCHs are still observable in the DEM despite the high surface disturbances.

**FIGURE 5** Probability surfaces for the RCH mapping as predicted by the logistic regression models and mapped RCHs for both study regions. RCHs, relict charcoal hearths [Color figure can be viewed at wileyonlinelibrary.com]
Furthermore, the underestimation of the number of RCHs in large-scale mapping is even higher than suggested by small-scale ground-truthing studies because many sites are completely destroyed by land use related to urban growth and by the extension of agricultural land in some areas. As noted by Rutkiewicz et al. (2019), this effect is often greatly enhanced for charcoal production areas in the vicinity of major historical industrial sites and can result in high spatial variations in the mapped RCH density. High rates of RCH disturbance are suggested by the high proportions of charcoal hearth symbols on historical maps for Northern Bavaria, which do not correspond to detected RCHs in the DEM.

Larger-scale effects of substrate characteristics on feature preservation and the mapping quality can be assumed but are not clearly observable in our results. Our mapping in the Northern Bavaria study region suggests a low mapping quality in areas dominated by limestone. However, other studies from limestone areas describe successful DEM-based RCH mapping (Dupin et al., 2017), and field surveys within the Northern Bavarian limestone areas do not reveal RCHs that had not been detected by DEM-based mapping. Therefore, significant differences in the mapping results for differing morphologic and geologic landscape units might also be related to differences in the feature morphology or location, for example, a dominance of small charcoal hearths, the repeated use of the same sites, or a preference for hearth sites that are considerably prone to disturbances by subsequent land use. In fact, historical maps frequently show charcoal hearth symbols along forest roads, in valley bottoms, or immediately next to ironworks in the high-relief limestone and magmatic/igneous rock areas.

4.2 RCH distribution in relation to the environmental background structures

4.2.1 Numbers and spatial densities of the mapped RCHs

For both mapping regions in this study, RCHs are detected in many forest areas. The spatial density of sites clearly differs across relief and RCH morphologies, with maximum site densities of approximately 100 RCHs per km² for charcoal production platforms in sloped terrain but considerably higher site densities (up to several hundred sites per km²) on flat terrain. Similarly high or slightly higher RCH densities on sloped terrain have been reported for several regions, for example, in the Black Forest (Ludemann, 2010), Tuscany (Carrari, Ampoorter, Verheyen, Coppi, & Selvi, 2016; Mastrolonardo et al., 2018), or French Pyrenees (Bonhôte, Davas, Dubois, Isard, & Métailié, 2002), whereas very high densities are often observed in charcoal production areas characterized by low relief (Hardy, 2017; Raab et al., 2015; Rutkiewicz et al., 2019). These differences in RCH densities between flat and sloped terrain are most likely a result of differences in hearth site usage. The morphology and stratigraphy of most RCH platforms on slopes indicate multiple uses of the sites (Hirsch et al., 2017; Raab et al., 2017; Stolz, Sebastian, & Grunert, 2012), whereas single-use hearth sites are characteristic of RCHs in sandy flatland areas in Brandenburg (Hirsch, Schneider, Bauriegel, Raab, & Raab, 2018; Raab et al., 2019).

4.2.2 RCH distribution with respect to charcoal consumers

High densities of RCHs in the vicinity of major, especially modern, ironworks are noticeable for both regions (Figure 3). In the Brandenburg study region, this phenomenon is also reflected in the relatively small mean distances between RCHs and metal works; whereas a statistically significant association between RCH locations and historical industrial sites is not observable for Northern Bavaria. The less clear associations for the Northern Bavaria study region presumably relate to the high spatial density of historical industrial sites and the more heterogeneous geology and geomorphology. The relationships between RCHs and industrial production centers might not be adequately captured in our analyses due to variations in charcoal consumption between different ironworks. The historical literature for the Brandenburg study region states that the metal works in Peitz, Zehdenick, Gottow and Eberswalde clearly dominate over other metal works in the region regarding their production and charcoal consumption (Bratring, 1804–1809). The production times and charcoal consumption of the older ironworks in Northern Bavaria can hardly be quantified despite the detailed analyses of the historical archives by Götschmann (1986).

In addition to the charcoal production fields related to iron- and glassworks, our results clearly show that high densities of RCHs occur in several areas without an apparent connection to historical industries in both study regions, most obviously in the forest areas north and east of Berlin and southeast of Nuremberg. This finding reflects that in addition to major industrial sites, clusters of small industries and households need to be considered important charcoal consumers and that long trade routes, presumably along waterways, occurred. Large RCH fields have mainly been related to major iron production areas in most previous studies (e.g. Groenewoudt, 2005; Raab et al., 2015; Rutkiewicz et al., 2019), whereas intensive charcoal production for smaller consumers has only been assumed for some areas, such as the Black Forest (Ludemann, Brandt, Kaiser, & Schick, 2017) or the Besançon area (Dupin et al., 2017). Furthermore, we recorded relatively low RCH densities in some forest areas for which intensive charcoal production is assumed, most obviously along the Vils River valley (Figure 3), but also around historical iron- and glassworks in the easternmost part of the Northern Bavaria study region.

With a mean distance of 15 km to industrial sites of more than 7 km, the RCH distribution in the Brandenburg study region clearly suggests charcoal transport over large distances, although previous analyses for several charcoal and iron production areas indicate that
charcoal-consuming industries were preferably located in the immediate vicinity of charcoal production areas in forests (as summarized, e.g., by Schmidt et al., 2016). Information on specific charcoal production areas associated with industrial sites is available from the historical literature for some of the ironworks in Brandenburg and confirmed transport distances of more than 10 km (e.g., Bratring, 1804–1804, detailed discussion in Müller, 2017). In the Northern Bavaria study region, analyses of wood consumption for some individual ironworks also suggest charcoal transport over distances of up to 15 km during periods of wood scarcity (Hirschmann, 1997). The assumption that the industries’ charcoal delivery areas were expanded, especially in periods of high charcoal demand and scarce supply, which was also made by Rutkiewicz et al. (2019) and Pasmore (1965), is confirmed by the widespread RCH fields mapped around several major and long-existing ironworks in our study regions.

4.2.3 | RCH distribution with respect to geology, soil, and morphology

The relationships between the RCH distribution and the substrate characteristics differed between the study regions. A correlation between high RCH densities and sandy parent material within the forests in Brandenburg is observable (Table 2), although the effect of geology as modeled by the logistic regression is small. For the Northern Bavaria study region, geological variations have a strong relationship with the RCH distribution. A comprehensive interpretation of the environmental background and RCH datasets suggests that this is mainly a consequence of regional differences in charcoal production practices, which were adapted to the environmental conditions. Higher RCH densities on the sand and sandstone weathering products are almost certainly related to the low effort of hearth construction and, therefore, a dominance of single-use charcoal burning sites. Lower densities in other areas reflect the repeated use of hearth platforms. A spatial concentration of RCHs in valley bottoms, settlement areas and traffic routes, which leads to higher proportions of disturbed sites, might further affect the lower mapped RCH densities in limestone and crystalline rock areas. Historical instructions for charcoal production support several aspects of this interpretation. Several such documents note that charcoal hearth locations should be chosen carefully with a view to minimizing the work involved in site preparation (Berg, 1860; Klein, 1830; Krünitz, 1773–1858). Furthermore, they note that homogeneously structured substrates are preferable for hearth operations while coarse and fractured substrates should be avoided; in addition, clays or clayey loams have considerably bad substrate conditions for charcoal burning (Berg, 1860; Krünitz, 1773–1858). It was also noted that pure sand provides unfavorable conditions that can be overcome by an admixture of topsoil material (Berg, 1860). Similarly, the observed underrepresentation of RCHs on Gleysols, Fluvisols and Histosols, and stagnic soils probably results from hearth location preferences because instructions for charcoal production consistently note that wet sites have unfavorable conditions for hearth operations (Berg, 1860; Klein, 1830), especially because of the higher groundwater tables during the last centuries (Kaiser et al., 2015). Among other forest areas, those with poorer soil quality (Podzols and Arenosols) clearly show higher RCH densities. Higher RCH densities in poorer soils were similarly observed by Rutkiewicz et al. (2019); however, the soil distribution over the total landscape was interpreted in this study and the pattern might largely reflect general site preferences for forest use. The relation between RCH concentration and poorer soils in Brandenburg might be related to the specific location and spatiotemporal contingency of forest areas in relation to soil properties. In fact, most of the large, historically old (i.e., continuously forested) state forest areas in the region are located in areas with poorer soils (Wulf, 2004). Forests with decent soil quality, for example, Retisols and Luvisols, are often fragmented and distributed over areas dominated by agricultural land use. High RCH densities in these areas might further be related to wood type distribution under the assumption that hardwood was preferably used for purposes other than charcoal production. This assumption is supported by the observation of a clear dominance of pine wood in RCHs on the poor soils of the Tauersche Forst (Raab et al., 2019). Therefore, our results do not reflect higher densities of RCHs in areas with better wood growth. This finding is in contrast to the analyses by Schmidt et al. (2016) and the frequent observation of a preferred use of hardwood in hearths, which allowed for the production of higher-quality charcoal.

The mapped RCHs in both study regions are clearly concentrated on flat and even landscape positions, but the distribution patterns related to relief vary slightly between the regions, presumably indicating differences in hearth site location and operation. In Brandenburg, the RCHs are concentrated in areas with slopes <0.5° but they are only slightly overrepresented at slopes between 0.5 and 1°. This finding suggests that colliers preferred flat positions over positions on very slightly inclined surfaces, which might be related to the observation that wood for the hearths was commonly stacked directly on top of the undisturbed soil surface, as shown by stratigraphic analyses of RCH soils in the Tauersche Forst (Hirsch et al., 2018, Schneider, Hirsch, Raab, & Raab, 2018). In the Northern Bavaria study area, the RCHs are similarly concentrated in flat areas and very slightly inclined surfaces but the distribution of mapped RCHs over slope classes suggests a lower differentiation in site preferences related to slope in the higher-relief landscape than in the Brandenburg study area. In addition to the colliers’ site preferences, the higher numbers of RCHs in flat areas in Northern Bavaria presumably also reflects differences in site usage, with repeated hearth operation on leveled platforms on slopes. A clear preference for areas with low surface roughness is observable for both regions (Figure 4, Table 3), which might reflect a hearth site selection aiming at a low effort for wood and charcoal transport to and from the site. However, more RCHs are located on moderately rough terrain in Northern Bavaria than in Brandenburg, which is most probably related to the limited availability of level areas in the region. The analysis of RCH distribution among slope and surface roughness
classes based on the aggregated 200 m DEM cells and a 5 × 5 cell moving window reflects site preferences related to medium-scale variations in morphology. In addition, site location might also be affected by smaller-scale variations in slope and roughness, which could be captured using smaller pixel and window sizes or parameters specifically adapted to each region’s characteristic morphology as suggested by Berti et al. (2013) and Tarolli, Sofia, and Dalla Fontana (2012).

### 4.3 | Possibilities for and limitations of the predictive modeling of the RCH distribution and charcoal production

The differences between the RCH distribution in the study regions are reflected in the logistic regression modeling results. The probability surfaces derived from the predicted values (Figure 5) show specific areas where the modeled probability of RCH mapping is very high but no or only very few RCHs were mapped, that is, areas where the environmental variables as represented in the models cannot sufficiently explain the RCH mapping results. For some of these areas, these deviations can be explained through a more detailed analysis of the local surface morphology or land-use history. For example, in several areas in Brandenburg, the intensity of the surface disturbances by military activities is very heterogeneous, which cannot be accurately represented in the model. In parts of both study regions, the DEMs show traces of historical agricultural land use, which might have been dominant over charcoal production in these areas or might have disturbed the traces of older charcoal production. Former agricultural use in modern forest areas is indicated by the characteristic morphology of ridge and furrow systems in Brandenburg and by terraced slope structures in some areas in the southeast of the Northern Bavaria study region. In some areas in the northernmost and southernmost parts of the Northern Bavaria study region, the DEMs and historical maps also show that remnants of historical ponds or mining activities cover large parts of the area. Other areas of deviations between the predicted and mapping results correlate with areas where the validation against field surveys and archival information suggests a low mapping quality. Here, the lower number of mapped RCHs could be related to characteristic locations or morphologies of RCHs, for example, a concentration of features along valley bottoms or considerably small and irregularly shaped RCHs. In the Northern Bavaria study region, the deviation between the considerably high probability for RCH mapping predicted by the model and the results of DEM-based mapping is particularly striking for forest areas east and north of Nuremberg. For these large state forests, records of the forest history have provided evidence that charcoal production has been prohibited since the 14th century (Walz, 1986). In addition to the low numbers of RCHs mapped in these forest areas, this ban on charcoal production might also contribute to the exceptional high numbers of RCHs recorded in the forested areas south of Nuremberg.

The differences in the model coefficients between the regions show that one logistic regression model cannot fully capture the effects on the RCH mapping probability in both areas. However, because the study regions cover large areas and a wide range of environmental background conditions characteristic of each region, we suggest that the regression models include the most relevant parameters and effects to determine the probabilities for RCH mapping in the Northeastern European Lowland and the Central European lower mountain ranges. The observations of Rutkiewicz et al. (2019) on the RCH distribution in southeastern Poland are consistent with the results of our analyses for Brandenburg, suggesting that RCH distribution patterns are similar over wider areas of the Northern European Lowland. Higher spatial variations in the variables affecting the RCH distribution might exist within the more heterogeneous mountainous charcoal production areas of Central Europe, where the variety of RCH morphometrics and characteristic site locations suggest a high regional variety of charcoal production practices and traditions.

### 4.4 | Implications for interpreting RCH distribution patterns

The results of our study confirm that comparisons of the number of mapped features and their densities between regions with differing environmental backgrounds are limited. Furthermore, the results show that the number of mapped RCHs is not well correlated to the amount of charcoal produced or the duration of charcoal production when comparing different charcoal production areas. Estimations of wood consumption or iron production based on the number of mapped RCHs can be valid in limited areas with uniform relief and geology, where the processes of hearth construction and hearth site usage are well understood (such as the areas studied by Raab et al., 2019 and Rutkiewicz et al., 2019). However, these estimations are difficult in areas with a heterogeneous morphology or geology, where the numbers of mapped RCH sites correspond to an unknown number of actual charcoal hearths in these sites. Furthermore, the remains of only upright charcoal hearths can usually be captured by DEMs, and charcoal production in pits rarely leaves structures that can be captured by elevation data or even field surveys. These phenomena need to be considered when interpreting the number of RCHs. Although the general transition from charcoal burning pits to upright hearths can be assumed to have occurred around the 10th to 11th century (Groenewoudt, 2005), the continued use of pit hearths at least until the High Medieval Period is described for several regions (Deforce, Vanmontfort, & Vandekerckhove, 2018; Groenewoudt, 2005; Risbøl et al., 2013). For Northern Bavaria, records of charcoal acquisition of several iron hammer mills report that up to one-third of the total consumed charcoal was pit charcoal, which indicates that pit and upright hearths were operated in parallel, even in later centuries (Göttschmann, 1986).

Generally, the distribution of mapped RCHs is dependent not only on the actual original distribution patterns of hearth sites but also on the spatial patterns of feature preservation and visibility. Both factors are difficult to separate; however, detailed information and a thorough understanding of the industrial and technical history and specific charcoal production practices of a region can provide a
more detailed understanding of regionally characteristic preferences for hearth site locations and usage.

5 | CONCLUSIONS

The results of DEM-based mapping in our study confirm that RCHs are widespread legacies of past land use. Capturing small anthropogenic relief features, such as RCHs, from LiDAR-based DEMs is feasible, even for large areas with different environmental characteristics; however, the results of DEM-based mapping are clearly affected by small- and large-scale variations in mapping quality. We suggest that this spatial heterogeneity in mapping quality along with general measures for mapping sensitivity and accuracy should be considered when comparing the results of DEM-based mapping between regions. Our mapping results confirm that the spatial density of RCHs is high in many forest areas, and they also show that high RCH densities are not necessarily associated with major historical iron production sites. GIS-based analyses of RCH distribution patterns in our study regions show a close relationship between charcoal production and historical industrial sites for regions with homogeneous environmental backgrounds but a stronger dependence of the RCH distribution on the relief and geology in more heterogeneous landscapes. These differences between study regions show that comprehensive analyses of database quality and the environmental and cultural background parameters of a region are prerequisites for meaningful interpretations of the spatial distribution patterns of anthropogenic relief features.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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