



Modeling multivariate landscape affordances and functional ecosystem connectivity in landscape archeology

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Abstract

Quantitative, digital statistics, and spatial analysis have proven to be useful tools in landscape archeological research. Herein, GIS-based data storage, manipulation, and visualization of environmental attributes and archeological records are among the most intensely applied methods to evaluate human-landscape interaction, movement patterns, and spatial behavior of past societies. Recent land use management and land cover change, however, have largely altered and modified present-day landscapes, which decreases the potential replicability of modern surface conditions to past ecosystem functionalities and the individual human landscape affordances. This article presents a comprehensive multivariate environmental analysis from a regional case study in the Upper Rhine Valley and exemplifies the bias of the archeological record based on modern land use, built-up, and surface change. Two major conclusions can be drawn: modern surfaces are the result of long-term past human landscape development, and the archeological data inherent in the landscape is strongly biased by modern human activity ranges, urban, agricultural and infrastructural development, and the configuration and perception of recent surface management.

Keywords Anthropocene · Land use · Land cover change · Spatial analysis · GIS · Remote sensing

Introduction

In recent years, the application of GIS-based spatial analysis and remote sensing techniques in landscape archeology has proven to be a useful tool to further elucidate human-environmental interaction, past land cover transformations, and activity ranges of prehistoric populations (Cao et al. 2019; Dabrowska-Zielinska et al. 2016; Landuyt et al. 2019; Lasaponara and Masini 2011, 2012; Mleczko and Mróz 2018). Particularly open-source medium resolution data like satellite imagery from the Landsat-8 or Sentinel missions allowed for a great variety of low-cost digital and quantitative analyses of ecosystem functionalities and the impact of human and environmental stressors on different spatio-temporal

scales (Abate et al. 2020; Agapiou et al. 2014; Kempf 2019; Malenovský et al. 2012). In addition, current environmental and sociocultural developments have clearly pointed out that there is an increasing need to intensify supra-regional land cover monitoring and to understand the link between natural ecosystem feedbacks and (past) societal transformations (Buras et al. 2020; Erfurt et al. 2019; Rick and Sandweiss 2020). Climatic impacts, land use change, and demographic development have continuously altered the ecological balances and modified the demands, requirements, and movement patterns of groups and individuals in their environmental settings. Consequently, isolating the methodological and physical parameters that enable the development of landscapes and human movement and activity ranges among ecosystem resource patches is one of the most important tasks in landscape archeology (Butzer 1982; Kempf submitted).

To address these challenges, this paper is positioned at the interface of monitoring surface dynamics and land use strategies in a geoarchaeological analysis in the Upper Rhine Valley (Alsace, eastern France). Recent and past surface transformations are considered in detail to set up a comprehensive classification of past and present environmental conditions in the study area (Kempf 2019, 2020). The model further considers the land cover's vulnerability to short-term extreme climatic

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events and the long-term process of landscape development. This consideration is very important because today's intensive land use increases susceptibility to catastrophic flooding and droughts (Himmelsbach et al. 2015; Martin et al. 2010). That, in turn, demonstrates how natural spatial parameters are fundamental preconditions for the classification of locations as potential settlement sites or arable land. The strong connection of land-use vulnerability, modern climate variability, and the perception of the landscape affects our understanding of pre-modern human-landscape interaction. Consequently, the following questions are of central importance: What controls the spatial and temporal resolution of ecosystem functionalities in the study area? How is our modern understanding and perception of an archeological landscape biased by modern land-use concepts and the recent built-up change? And how can GIS-supported environmental data attributes and remote sensing applications foster the concept of a comprehensive or even holistic land cover reconstruction?

In combination with a methodological approach that contextualizes the concepts of landscape affordances and functional ecosystem connectivity (Kempf submitted), this article provides a comprehensive overview of current digital methods in landscape archeology and critically discusses the anthropogenic impact on terrestrial and hydrologic ecosystems over the past decades.

Material and methods

In this research, two approaches towards socioenvironmental modeling have been applied—each dependent on the respective research question, the geographical extent, and the topographical conditions in the study area. Among other formal approaches of statistic applications in (geo)archeology (Carlson 2017; Conolly and Lake 2006; Nakoinz and Knitter 2016; Verhagen et al. 2010), multicriteria decision analysis (MCDA) and multivariate modeling (MM) have proven to be useful tools for the integration of human behavior in geospatial quantitative research (Groenhuijzen 2019; van Lanen et al. 2015a). Besides the premise of multiple criteria, MCDA incorporates decisions made by individuals who have very specific views, demands, and goals on how their interests could be realized (Mendoza and Martins 2006). Technically, both methods are based on the integration of various GIS-attributed datasets that contain environmental data and surface classifications (Groenhuijzen 2019; Howey 2011; Howey and Brouwer Burg 2017; van Dinter 2013). In some cases, MCDA is used to study movement corridors or model least-cost paths (LCP) based on so-called accumulative cost surfaces (van Lanen et al. 2015b; van Lanen et al. 2015a). It is part of the conception of these models to predict communication networks and short-distance travel options. MCDA identifies the locations that best fulfill the preexisting theory of how

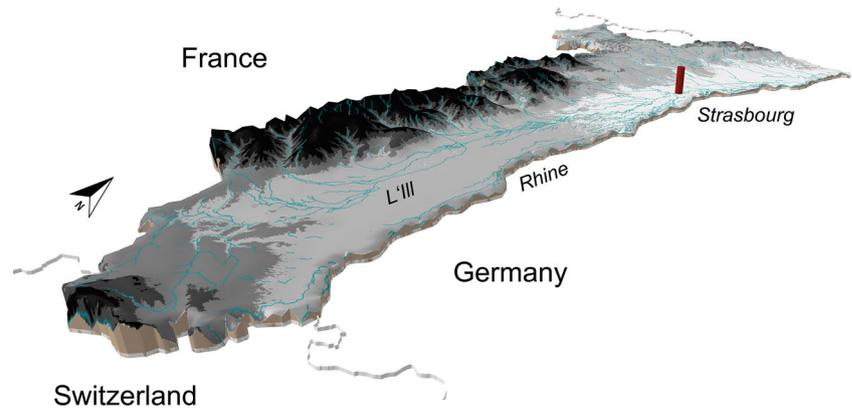
individuals would behave in specific environments. This is a *deductive* approach that strongly depends on a theory of how certain contexts are embedded in their standardized settings (Kamermans 2000). Multivariate modeling (and particularly multivariate site location analysis) rather follows an *inductive* approach that evaluates the specific site conditions in a particular region to detect preferences of human patterns in the landscape (Güimil-Fariña and Parceró-Oubiña 2015; Weaverdyck 2019). Accumulative surfaces deriving from environmental data analyses thus enable the inductive evaluation of physical parameters without excluding human interactions. The division between MCDA and MM is not clear cut, but in principle, the inductive approach tries to build up a model from the evidence, while a deductive approach builds a model from theory (Nakoinz and Knitter 2016; Verhagen 2018) and then tries to see if the evidence fits. In reality, theory always lies behind the inductive process of building a model from evidence, and evidence always lies behind the theory that you try to fit the model to.

Regional settings and landscape history

The Alsace is located in the eastern rain shadow of the Vosges mountain range and stretches towards the Upper Rhine Valley (Fig. 1). The particular location leads to dry conditions and low annual mean precipitation values (Minářová et al. 2017a, 2018). The Alsace is characterized by steep slopes and forested mountainous zones over 1000 m a.s.l., extensive foothills that mostly consist of high-quality vineyards, and the floodplains of the river Rhine and the various tributaries. The lowlands are covered by thick Quaternary alluvial deposits that originate from various anastomosing and meandering sequences of the river Rhine (Carbiener and Schnitzler 1990; Przyrowski and Schäfer 2015; Schmitt et al. 2007). Consequently, soil formation is mostly tied to the grain size and the chemical and physical fractionation of the Late Pleistocene and Holocene fluvial and eolian (loess) deposits (Dambeck and Thiemeyer 2002; Tricca et al. 1999). Locally, the sedimentation of fine-grained clayey material in depressions and cut-of palaeochannels produced soil conditions that are prone to waterlogging, flooding events, and upwelling groundwater. The high groundwater table increases the vulnerability to broad extensive flooding during heavy precipitation events and increased groundwater upwelling through the alpine aquifer (Kempf 2018, 2019; Pfister et al. 2006; Wetter et al. 2011).

Land use activities have been impacting the Upper Rhine Valley since the Neolithic (Faustmann 2007; Mischka 2007). In particular, the lower parts of the floodplain, the intensely used forelands, and the valleys of the mountain ranges have experienced increased surface transformation, soil erosion, and groundwater lowering due to the massive demand for water by monoculture irrigation. But human impact is not

Fig. 1 Digital elevation model of the study area. The Alsace is situated east of the Vosges mountain range and stretches towards the river Rhine



the only cause of surface transformation. Extreme events such as droughts and floods have been documented frequently during the past centuries (Giacona et al. 2018; Glaser et al. 2010; Glaser et al. 2012; Himmelsbach et al. 2015; Pfister et al. 2006). Particularly, the lowlands suffer from rising annual average temperatures and groundwater (Duchne and Schneider 2005; Muthers et al. 2017). The comparison of a historical topographic map from 1866 with images from two satellite missions (Landsat-1, sensing date 9 October 1972; Landsat-OLI8, sensing date 24 September 2018) reveals significant changes in total surface vegetation cover. The forest-covered areas in the Alsace show severe modifications and anthropogenic interventions to gain settlement space and arable land within the last 46 and 150 years (Fig. 2, Fig. 3).

To understand the dynamic character of the Upper Rhine Valley, a combination of historical maps and recent satellite

images (Landsat-1, sensing date 9 October 1972; Landsat-OLI8, 30 m spatial resolution, sensing date 24 September 2018) were digitally analyzed and modeled in a GIS. For this research the stable versions of the open source software QGIS 2.18.6 and QGIS 3.6.0 (Open Source Geospatial Foundation Project, <http://qgis.osgeo.org>) which include GRASS GIS 7.2.0 and GRASS GIS 7.6.0 (Geographic Resources Analysis Support System, <http://grass.osgeo.org>) were used.

Environmental datasets

A variety of environmental datasets were accessed to set up the multivariate model. The following part briefly summarizes the data processing and the evaluation of the environmental characterization of each landscape component of the Upper Rhine ecosystem.

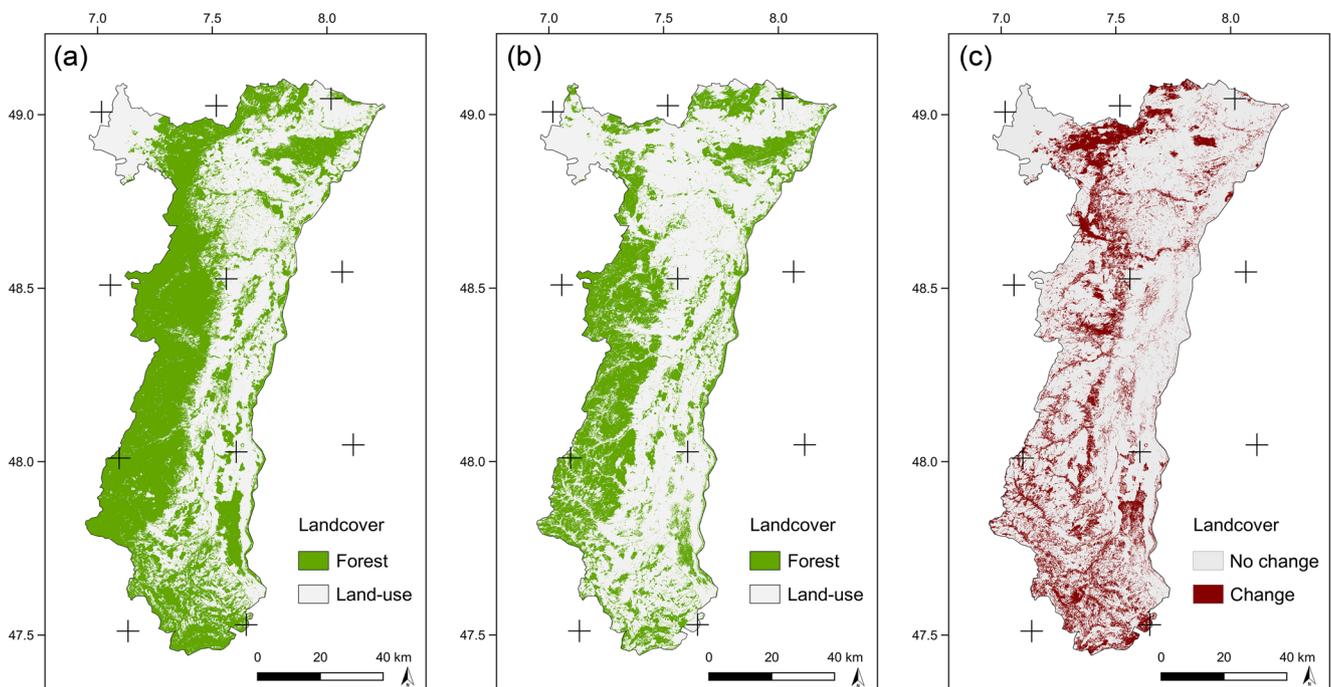


Fig. 2 Forest cover change in the Alsace between 1972 and 2018 based on Landsat-1 and Landsat-OLI8 multispectral satellite imagery analysis. **a** Forest coverage 1972 (Landsat-1). **b** Forest coverage 2018 (Landsat-OLI8). **c** Land cover transformation 1972–2018

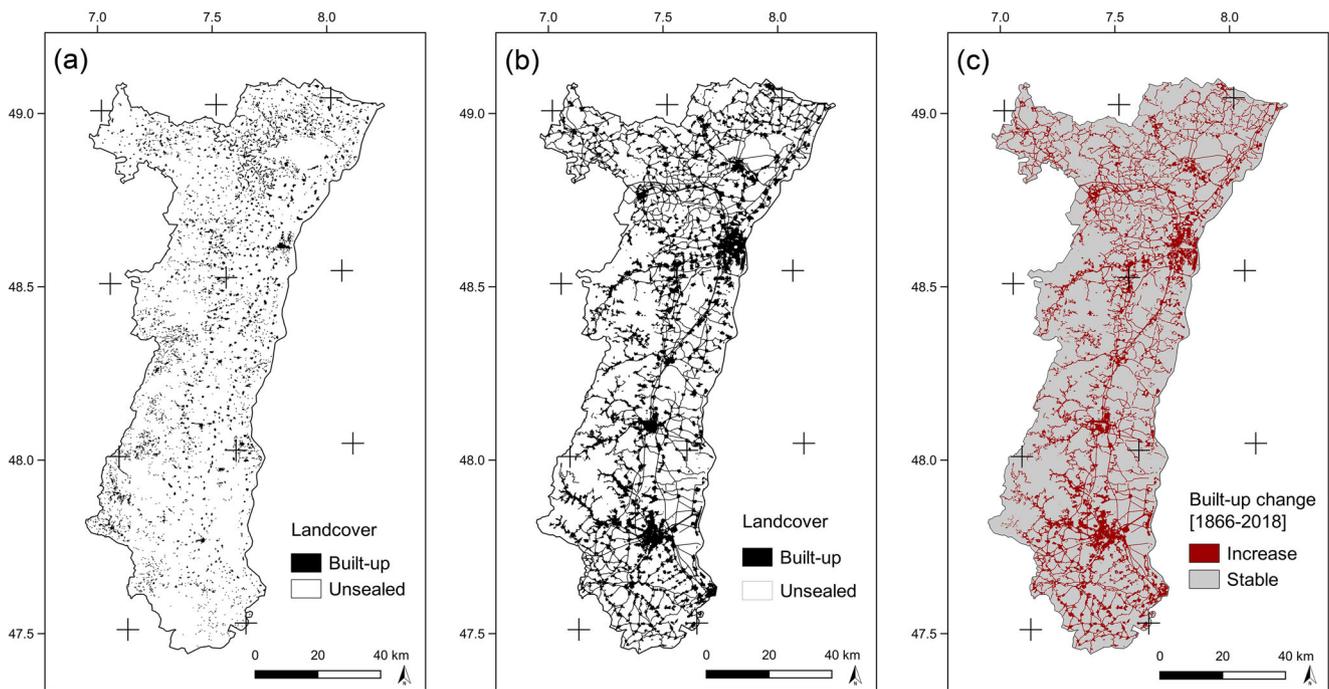


Fig. 3 Built-up change in the Alsace between 1866 and 2018 based on historical maps, GIS attributes and satellite images. **a** Built-up in 1866. **b** Buffered built up in 2018 buffer = 100 m. **c** Built-up change to detect infrastructural agglomerations

Groundwater interpolation

The groundwater level plays a major role in the determination of flooding events in the Alsatian part of the Upper Rhine Valley. Local variations of the groundwater table were calculated using the mean and maximum values of 327 piezometer stations in the Alsace. The data was processed from Aprona 2019 via <https://www.aprona.net/> (last accessed 21 April 2019). The corresponding elevation data of the soil surface served as a reference grid for the interpolation of a local digital elevation model. Finally, the difference of the groundwater maximum values from the absolute height of the soil surface generates a grid that represents the susceptibility to groundwater pressure through the aquifer (Fig. 6b).

Soil data

Soil data from the ARAA (Association pour la Relance Agronomique en Alsace 2019e, <http://www.araa-agronomie.org/>, last accessed 19 January 2019) and the API-AGRO 2019 (Paris, <https://api-agro.eu/>, last accessed 19 April 2019) were evaluated to identify waterlogged soil conditions. Periodic waterlogging and continuous sedimentation of fine-grained material during flooding events result in the development of saturated soils. Since saturated soils are no longer able to drain properly, a far-reaching wetland developed above areas with high aquifer. These soils are considered of low quality and are primarily used as forest or grassland (Fig. 6a).

Climate data

Daily precipitation and wind-speed records from January 2018 in the Alsace were derived from www.historique-meteo.fr, 2019 (last accessed 18 May 2019). The raw data was spatially interpolated in QGIS to visualize precipitation patterns during a severe flooding event on 23 January 2018. In this context, radar imagery analyses were applied to estimate the flooding extent. Wind-speed in this period has been cross-checked to estimate the impact on the data (Kempf, 2019). Due to the polarization of the active radar sensors, high wind-speed can have an effect on the backscattering behavior of water surfaces through increased surface roughening.

Hydrologic system

The modern and historical hydrologic conditions in the research area were assessed through Corine Landcover data (Corine, 2018, <https://land.copernicus.eu/pan-european/corine-land-cover>, last accessed 10 January 2020), Open Street Map (OSM) plugins in QGIS, and georeferenced historical maps that date prior to the massive river channelization processes in the nineteenth century AD (www.mapire.eu, last accessed 10 January 2020).

Vegetation cover and land use

Vegetation coverage can easily be assessed via CLC to distinguish forest stands, agriculturally utilized areas and artificial built-

up infrastructure. However, the spatial resolution does not always meet the scientific requirements—especially for small-scale case studies that demand a high temporal resolution of changing land cover scenes at different stages of the year. For this reason, the vegetation composition was estimated from remotely sensed multispectral satellite data that derived from medium resolution optical sensors of the Sentinel-2 (Copernicus Open Access Hub, 2019, <https://scihub.copernicus.eu>, last accessed 20 April 2020) and the Landsat-OLI8 missions (USGS (2019), <https://earthexplorer.usgs.gov/>, last accessed 13 May 2019).

Infrastructure, built-up, and land cover change

Roads, railways, and residential and industrial buildings form large parts of the artificial land cover of modern surfaces. These structures were considered of twofold significance: modern settlement patterns and infrastructural utilization in favorable parts of the landscape created our perception of the environment. However, these location factors were not necessarily the same in premodern societies.

Modern change in land cover was modeled from historical maps (1866) and satellite imagery from 1972 and 2018 to detect differences in built-up areas, infrastructure, forest expansion, agricultural utilization, and surface conversion. In comparison with CLC and OSM data for roads, railways, and houses (<https://download.geofabrik.de/index.html>, last accessed 10 January 2020), a very clear picture of the land cover change within the past 150 years has been worked out. In combination with geostatistical methods and GIS-based spatial analyses, the interrelationship between the modern agglomerations and the archeological record is of significant importance to understand human-landscape interaction.

Multispectral satellite data

The archeological research benefitted greatly from remote sensing applications that have largely entered the discipline during the past few years (Doneus, 2013; Lasaponara and Masini, 2011, 2012; Masini and Soldovieri, 2017). Landsat and Sentinel-2 images were processed in this research project (Barsi et al., 2014; Sadeghi et al., 2017; Wulder et al., 2019). The multispectral signals of the surface conditions were evaluated to distinguish agricultural exploitation, sealed urban fabric, and forest covered areas (Montandon and Small, 2008; Pettoelli et al., 2005; Wadge et al., 2011). Multispectral analyses also allow for the monitoring of spatial-temporal variations in the physical growth behavior of plants, underlying soil properties, and superimposed artificial infrastructure (Araya et al., 2016; Carlson et al., 1994; Tapete et al., 2013; Tapete and Donoghue, 2014). Vegetation indices are particularly suitable for this purpose. A useful algorithm to evaluate plant species behavior is the so-called *Normalized Difference Vegetation Index* (NDVI)—a method for measuring vegetation performance and activity in satellite

imagery (Parcak, 2009; Verhulst et al., 2009; Wang et al., 2011). Vegetation indices basically distinguish photosynthetically active vegetation from bare soils or sealed areas using the reflection characteristics of near infrared (NIR) and red light (Barlindhaug et al., 2007; Sarris et al., 2013). The band combination is described as follows (Jakubauskas et al., 2002; Lasaponara and Masini, 2006; Lasaponara and Masini, 2007):

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$$

The higher the values of the ratio, the more active the vegetation coverage at a specific time (Barlindhaug et al., 2007; Parcak, 2009; Zheng et al., 2015).

The algorithm can be combined with the short-wave infrared (SWIR) to distinguish other surface reflection characteristics such as soil moisture (*Normalized Difference Water Index*)

$$\text{NDWI} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}}$$

or permanent water surfaces (Paloscia et al., 2013; Xu, 2006).

$$\text{mNDWI} = \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}}$$

SAR

The Sentinel-1A satellite was launched on 3 April 2014, having on board a Synthetic aperture radar (SAR) C-band sensor with the frequency of 5.405 GHz (Geudtner et al., 2014; Potin et al., 2016; Torres et al., 2012). One of the advantages of SAR imagery lies in the possibility to obtain high-temporal resolution datasets that are not affected by cloud-coverage (Cazals et al., 2016; Chan and Koo, 2008). However, processing SAR imagery demands additional filter methods that reduce noise in the datasets. The Sentinel-1A images that were applied in this research area have been preprocessed using the Lee speckle filter. The data were then reprojected to WGS84 in the SNAP software that is provided by the ESA toolbox (Sentinel Application Platform) (Kumar et al., 2018). A Sentinel-1A SAR composite was processed for January 2018 to provide a flood risk map for the Alsace. The imagery of 11th, 18th, 23rd, 27th, and 30th of January 2018 illustrate the beginning, the maximum spread and the weakening of the flooding event. The observed areas were finally compared with the next available cloud-free multispectral images (14 February 2018) to determine permanent water areas that were masked during the flooding (Fig. 4).

The archeological record

The distribution of archeological sites in the Alsace was used as the basis for the quantitative assessment of land use and the calculation of the bias caused by modern construction

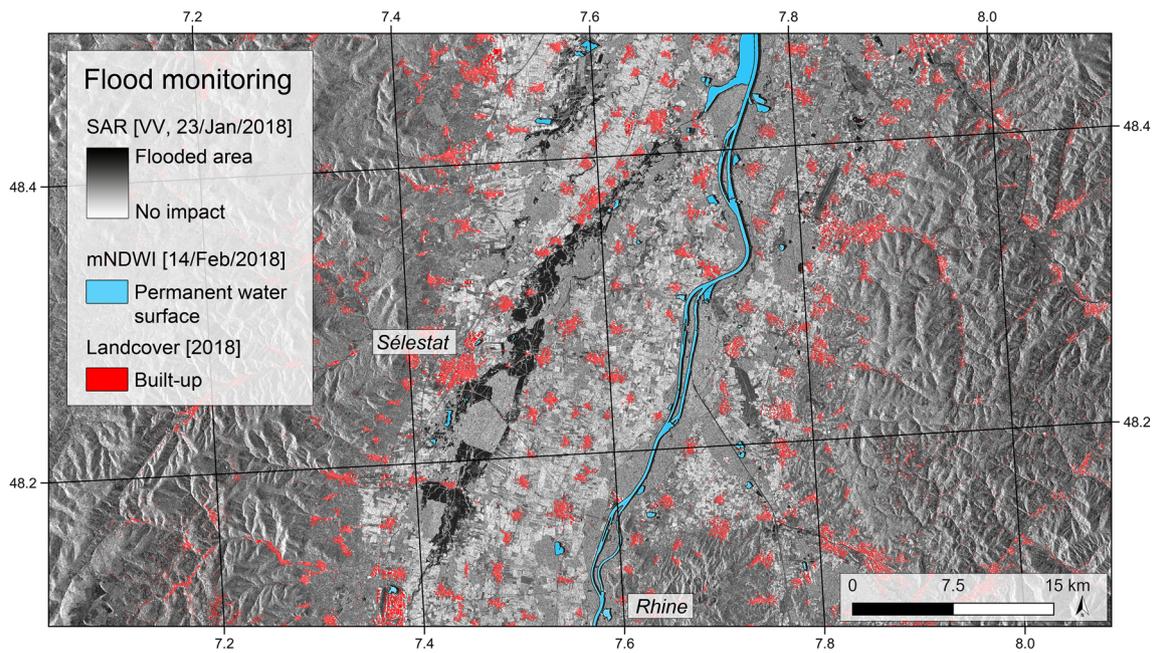


Fig. 4 Methodical overlay of SAR-derived flooding area (Sentinel-1A; VV-polarized; 23 January 2018) and permanent water surfaces from multispectral channel recalculations (Sentinel-2; mNDWI = Green – SWIR /

Green + SWIR; 14 February 2018). The modern built-up illustrates the high amount of sealed area in the Upper Rhine Valley and in the adjacent valleys

activities. Based on the archeological database ArkeoGIS, 2019 (www.arkeogis.org), all archeological records in the Alsace ($n = 10,726$) were mapped and analyzed for their spatial behavior using a kernel density estimation and distance matrix (Conolly and Lake, 2006; Nakoinz and Knitter, 2016).

The database contains a mixture of structured and unstructured data sets that require filtering in an information system (Gattiglia, 2015). The fact that the database consists of both archeological excavation data and archeological survey data (including scattered and stray finds) poses a particular challenge for the interpretation of the spatial context of the data distribution. In particular, survey data are characterized by the specific teleological research foci, the individual interest of the researcher, technical standards, and the site-specific conditions of the selected study area (Cowley, 2016; van Leusen, 1996). However, the major bias is the proximity to modern buildings. This is particularly significant for the intensive built-up activity in the peripheral zones of urban agglomerations and the associated infrastructural development. Figure 5 demonstrates the spatial relationship between archeological sites and large urban agglomerations in the study area. The pull-factor of the larger historical central places (first peak) triggers an increased built-up change in the periphery (secondary peak).

Results

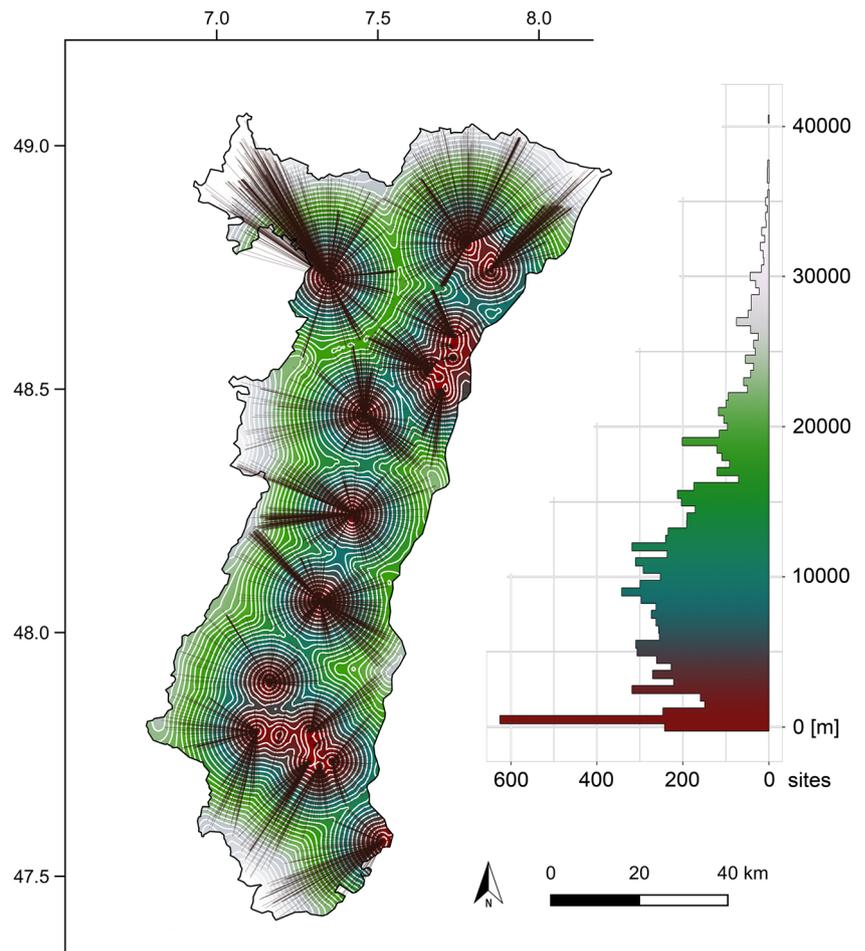
The following chapter describes the results obtained from the short-term flood event monitoring compared to the long-term

environmental conditions in the study area. The link between process-oriented geological, hydrogeological, geomorphological conditions, and the short-term extreme events plays a major role in the decision-making of agricultural strategies, settlement dispersal, and the perception of the landscape. This is particularly visible in the distribution of the archeological record that is plotted on two different land cover models: a modern bias surface and a suitability surface that based on a variety of geospatial attributes and environmental datasets. Both surface models highlight the strong relationship between site location strategies and environmental conditions from prehistory onwards (Figs. 6, 7, 8).

Flood monitoring

Severe flooding caused by persistent heavy precipitation occurred in parts of the Alsace in January 2018 (Fig. 9). Particularly two spatial concentrations are visible in the radar images: the region around Sélestat along the south-north draining river L'Ille and the valley of the river La Zorn northwest of Strasbourg—both important tributaries to the river Rhine. The onset of extensive flooding can be dated prior to the 11th of January when long-term precipitation took place that had a strong influence on the local soil conditions (Fig. 10). Dry conditions in the second week of January were followed by a period of continuous rainfall with the highest daily precipitation record of the whole year on the 22nd to 23rd of January (Sélestat). The precipitation maximum occurred in the region between Sélestat, Obernai, and Strasbourg. Prevailing wet conditions can be detected after

Fig. 5 Archeological site distribution and the bias of modern urban agglomerations. The spatial distribution of the archeological sites in the Alsace is strongly biased by the pull-factor of modern urban agglomerations and an increased built-up change in the periphery of the historical city centers. The chart shows the distance relation between the sites and the larger city centers



the heavy rainfall event in the region. Reaching the maximum storage capacity of the soil, the overstrained system reacted rapidly to a short but intensive water input. The low drainage potential of the soil could not discharge the water surplus (Fig. 6a, b). Furthermore, the very low slope gradient and river flow velocity of the small tributaries caused extensive backwater.

Sediment influx and soil development

The floodplain of the river L'Ille is characterized by the sedimentation of fine-grained clayey material with a high waterlogging susceptibility. Former alluvial fans and terraces are widely covered with loess that can be reactivated and relocated through erosion processes (Froehlicher et al., 2016). The sediment influx and transportation rate of the reactivated loess deposits of the upper slopes depend on extreme weather events, plant species diversity, and broad open soil patches produced by prehistoric land-use activity, forest pasture, and particularly modern monoculture management (Berendse et al., 2015; Burt et al., 2016; Zolitschka et al., 2003). Although the Alsace does not show high slope gradients in the floodplain of the river L'Ille and the river Rhine, a specific sediment transportation regime has been established.

The sediment input can be traced back to the small rivulets draining the Vosges mountain range. They lose large parts of their erosive power and take on an accumulative character after entering the Vosges foreland and finally the Upper Rhine lowlands. In combination with heavy rainfall and significant flooding events, reactivated sediments (mostly from vineyards) reach the course of the larger river Rhine tributaries via small channels (Hagedorn and Boenigk, 2008; Thiemayer et al., 2005).

Vegetation density, soil composition modifications, and the availability of transportable material affect erosion processes, sediment transport, and an increased wash load of fine-grained material in overland flow regimes (Asselman et al., 2003). Prehistoric land use and deforestation processes caused significant surface erosion (Mäckel et al., 2003). However, the local sediment load was mostly trapped in colluvial deposits along the upstream hillslopes. An increase in alluvial and colluvial deposits since the Iron Age has been recognized, and from the Roman period onward, a massive increase in material deposition occurred (Frings et al., 2014; Lang et al., 2003; Mäckel et al., 2003). Colluvial deposits not only point towards the human impact on soil consolidation, vegetation coverage, and deforestation but also towards increased surface water runoff,

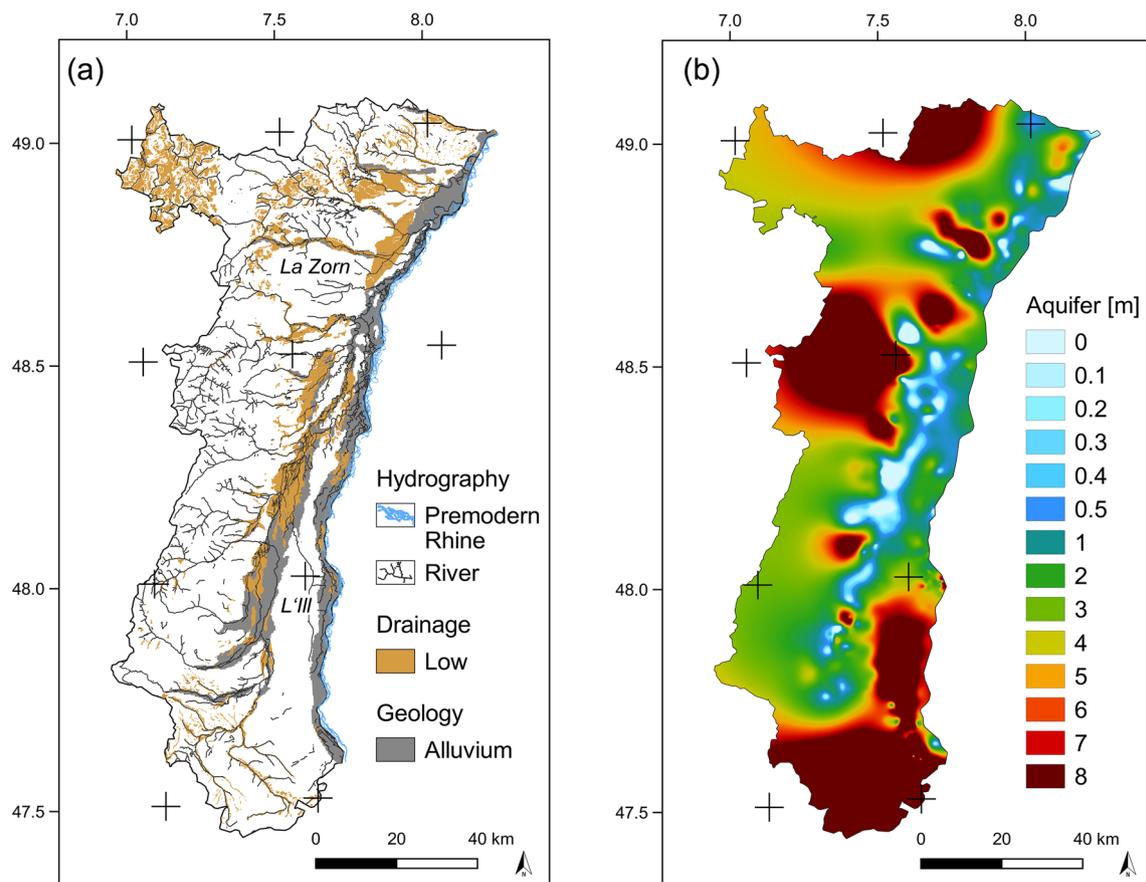


Fig. 6 **a** Sedimentological conditions and drainage potential in the Alsace. The fine-grained alluvial deposits along the river Rhine tributaries produce clayey soils with low water permeability and low drainage potential. **b** Interpolated groundwater grid below the soil surface. The light

blue signature demonstrates the very high water table in the Alsatian floodplain. The local aquifer reaches up to the soil surface, which leads to the development of waterlogged soils

destabilized upper slopes, and consequently intensified material removal (Zolitschka et al., 2003). The increased wash load and slow sedimentation rate strongly affected the soil composition with layered silty and clayey depositions along the river l'III and the several tributaries (Fig. 6a).

Surface transformation

The surface cover model calculated from the satellite imagery analysis reveals a considerable amount of vegetation change between 1972 and 2018. Significant deforestation took place that enabled crop cultivation, construction and infrastructure development. Large-scale surface modification is particularly prevalent in the lower floodplain and the lower parts of the valleys of the Vosges Mountain range. The intense impact on the landscape biases our understanding of past land-use and prehistoric landscape perceptions (van Leusen, 1996; van Leusen et al., 2005). The comparison of the dense archeological record of the Alsace with recent land cover changes illustrates the strong interdependencies between surface remodeling and archeological surveys, stray finds, and excavations. Out of 10,726 archeological records, 4337 were

covered with forest in 1972 (40.44%). In 2018, however, only 2104 archeological sites were covered with forest (19.62%). That means about 80% of the archeological record derives from non-forested areas. Compared to the rather short-term forest transformation between 1972 and 2018 a total of 2438 sites were discovered that are linked to deforestation, agricultural conversion and increased built-up change (22.73%). The fact that a considerable portion of the archeological record known today was covered with forest in 1972 points towards the strong correlation between surface coverage and transformation processes. The distance matrix of the site locations that are not affected by transformation (e.g., deforestation) and the nearest transformed surface reveals a significant spatial interdependency between the two data variables. Of the 8288 records, 3353 (40.46%) lie within a distance of 100 m, 5082 records (61.32%) within 200 m, and 6995 sites (84.4%) are located within 500 m of the areas that experienced significant surface transformation. In combination with the archeological record that is directly affected by deforestation processes, more than half of the total records (53.99%) can be found in deforested areas and within a 100 m buffer range (Fig. 11). The land cover change further transforms the landscape

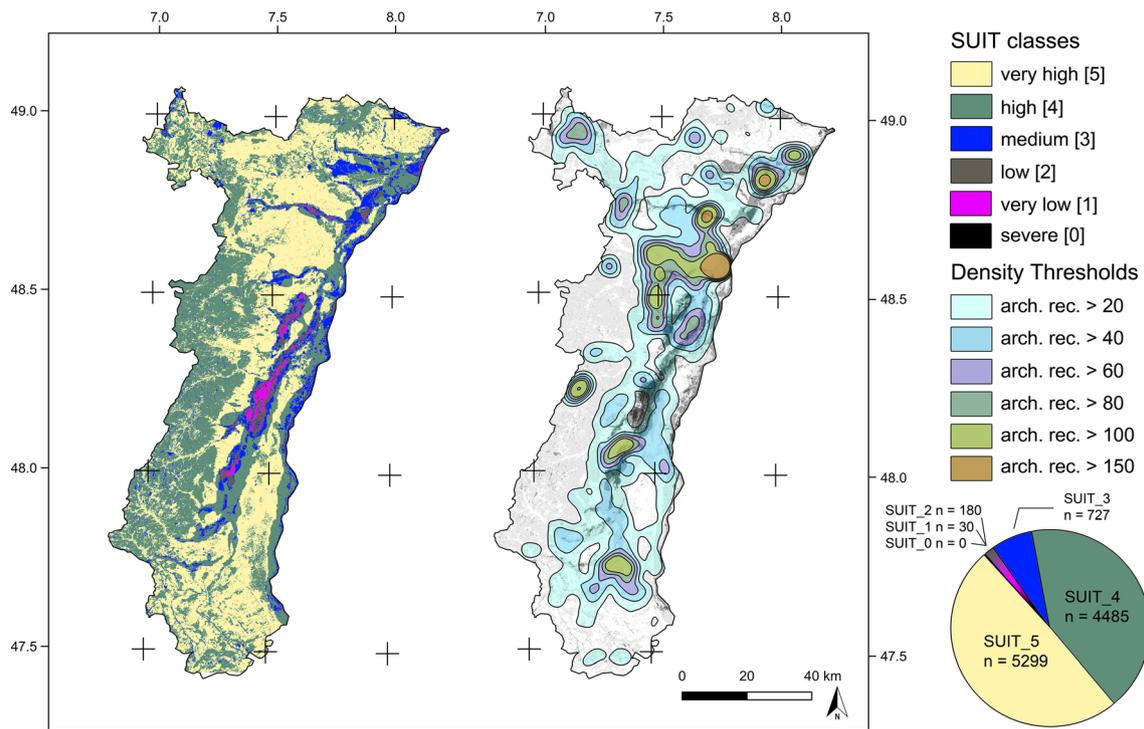


Fig. 7 Accumulative multivariate suitability surface (left) and the archeological distribution plotted on the surface classification (right): the study area is characterized by very favorable surface conditions for areas that are intensively used as settlement locations and for agricultural production. However, there is a clear unsuitable corridor with very poor surface suitability mostly characterized by a high flooding vulnerability,

corresponding sedimentation processes and soil conditions. The archeological distribution correlates well with the suitability model. This demonstrates a strong site-location and land use continuity from prehistory onwards and/or the influence of modern intensive land consumption

through enhanced terrain accessibility and surface permeability caused by smaller coherent forest stands. That allows for expanded landscape penetration and hence greater findability of archeological material.

The impact of increased landscape visibility and accessibility on the archeological distribution was measured in fixed distance buffers. The distance model between the sites covered by forest in 2018 and the closest non-forested area (e.g., cropland, built-up) confirms the relationship between high archeological density and intensely used surfaces. Archeological traces have only been recorded in the forest margins.

Built-up change (1866–2018)

The change in the built-up area has been estimated through historical maps, satellite imagery, and GIS attributes of infrastructure and residential/industrial coverage. Six thousand twenty-nine archeological sites (56.21%) are spatially congruent with modern built-up areas. In order to identify anthropogenic influence linked to infrastructural maintenance, increased land accessibility, and terrain permeability in the immediate vicinity of modern human activity areas, the modern built-up area (including roads, railways, and general infrastructure) was buffered at 100 m, and the distances between this enlarged area and the archeological sites falling outside of

it were calculated. A total of 3041 sites (28.35%) lie within 500 m distance of this area. Including the coextensive records, 9070 sites (84.56%) can be found within or at 500 m from modern built-up area and infrastructure (Fig. 12). Even without the spatial infrastructural maintenance buffer of 100 m, 8670 sites (80.83%) are located in direct relationship to modern artificial land cover.

Agricultural land use

Surprisingly, there is no strong relationship between the distribution of the archeological record and agricultural land use (cropland, vineyards, and orchards). This is most likely because of terrain differences between the western upland and the eastern lowlands where most of the agriculture is situated. The slopes of the northern part of the Vosges foreland are particularly suitable for growing wine. Valleys and elevated areas of the mountains are rather used as pasture or grassland due to their low potential crop yield (Fig. 13).

Hydrologic system

Archeological sites are supposed to be situated close to freshwater. However, the concept of river systems as location factors is not yet fully understood. Van Leusen (2002)

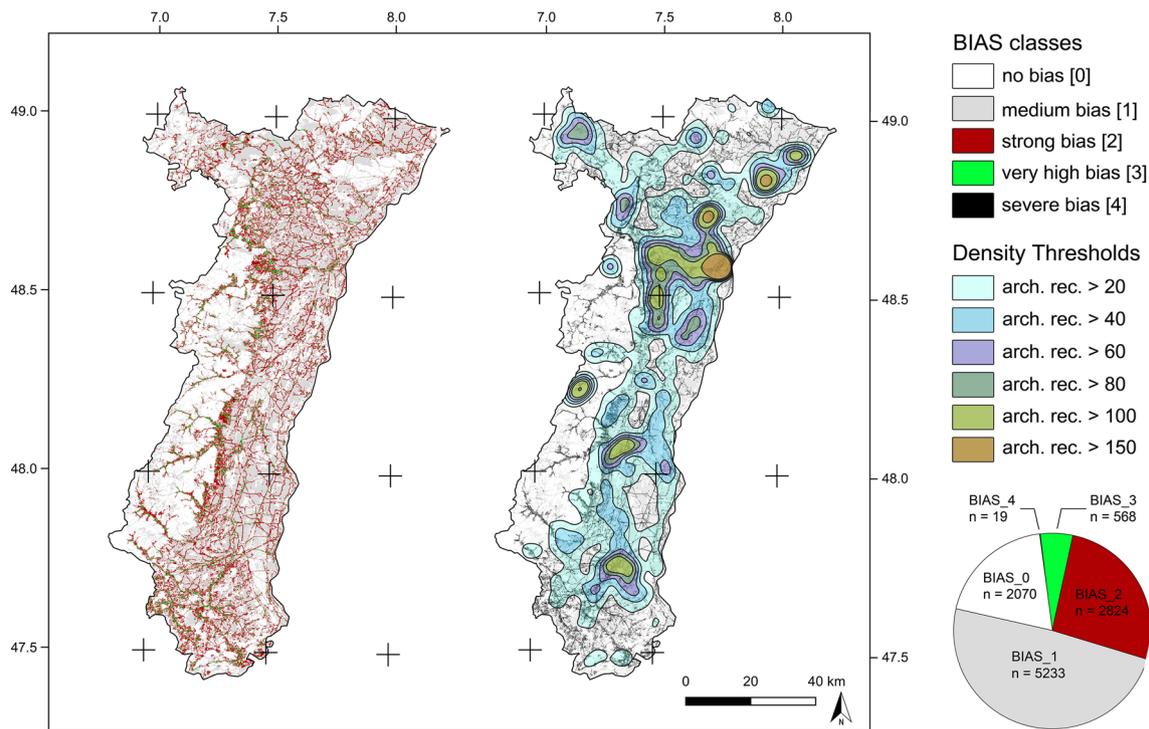


Fig. 8 Accumulative multivariate bias surface (left) and the archeological distribution compared with the surface classification (right). Five bias classes have been defined on the basis of environmental and anthropogenic parameters. The lowlands and especially the intensively utilized

marginal zones between the lowlands and the Vosges Mountain range (vineyards, built-up) show significant modern surface modification. The archeological distribution in the study area is strongly affected by the land cover change that occurred during the last 150 years

pointed out, that modern changes in groundwater circulation and the various landscape affordances of premodern societies make it difficult to assign clearly defined spatial hydrological attributes to archeological sites (van Leusen, 2002). Spatial buffers with $r = 100, 200, \dots, 500$ m have been calculated around the river system to evaluate the relationship between the archeological record and the hydrological system in the Alsace (Canning, 2005; Esquivel et al., 1999; van Leusen, 2002). Almost half of the record (5120 sites, 47.73%) is situated within 400 m of the nearest available modern river system. The impact declines at 500 m distance (5814 sites, 54.2%).

Multivariate landscape model

The environmental parameters presented above not only control the composition of the vegetation cover, potential cropland, settlement areas, and infrastructural networks but also general landscape permeability, accessibility, and availability—parameters that regulate the human-environmental interactions and landscape perceptions in the past and in the present.

Two landscape models have been calculated from the multivariate environmental datasets. The first samples all information that is supposed to be decisive for the choice of potential human utilization: adequate drainage potential, aquifer height below 0.5 m, non-alluvial geology, very low-flooding

vulnerability, and non-forested areas. The multivariate model generates six suitability classes from 5 (= very high surface suitability, all classes represent excellent surface and subsurface conditions) to 0 (= severe surface unsuitability, all classes represent severely unfavorable surface and subsurface conditions). The suitability model visualizes all environmental conditions that distinguish potential settlement and land-use corridors from areas with unsuitable surface and subsurface conditions based on the evaluation of their qualitative location factors (Fig. 12).

The second model represents the modern biased surface conditions in the study area. Dominant parameters are deforestation, modern hydrological system, intense modern built-up change, and extensive agricultural utilization. The variables create a landscape model with five classes from 0 (= no modern bias) to 4 (= very strong bias) (Fig. 13).

Kernel density estimates were plotted on each model to estimate the spatial relations between the archeological distribution and the respective bias and suitability classes. The bias model shows a strong spatial correlation of bias class 1 and bias class 2 with the location of the total archeological record. Five thousand two hundred thirty-three sites are biased by one and another 2824 sites are biased by two variables. Only 2070 sites are not affected by direct surface transformation. In total, over 80% of the archeological record in the Alsace experienced modern surface transformation. That is mostly due to land demand by modern built-up and agricultural processes.

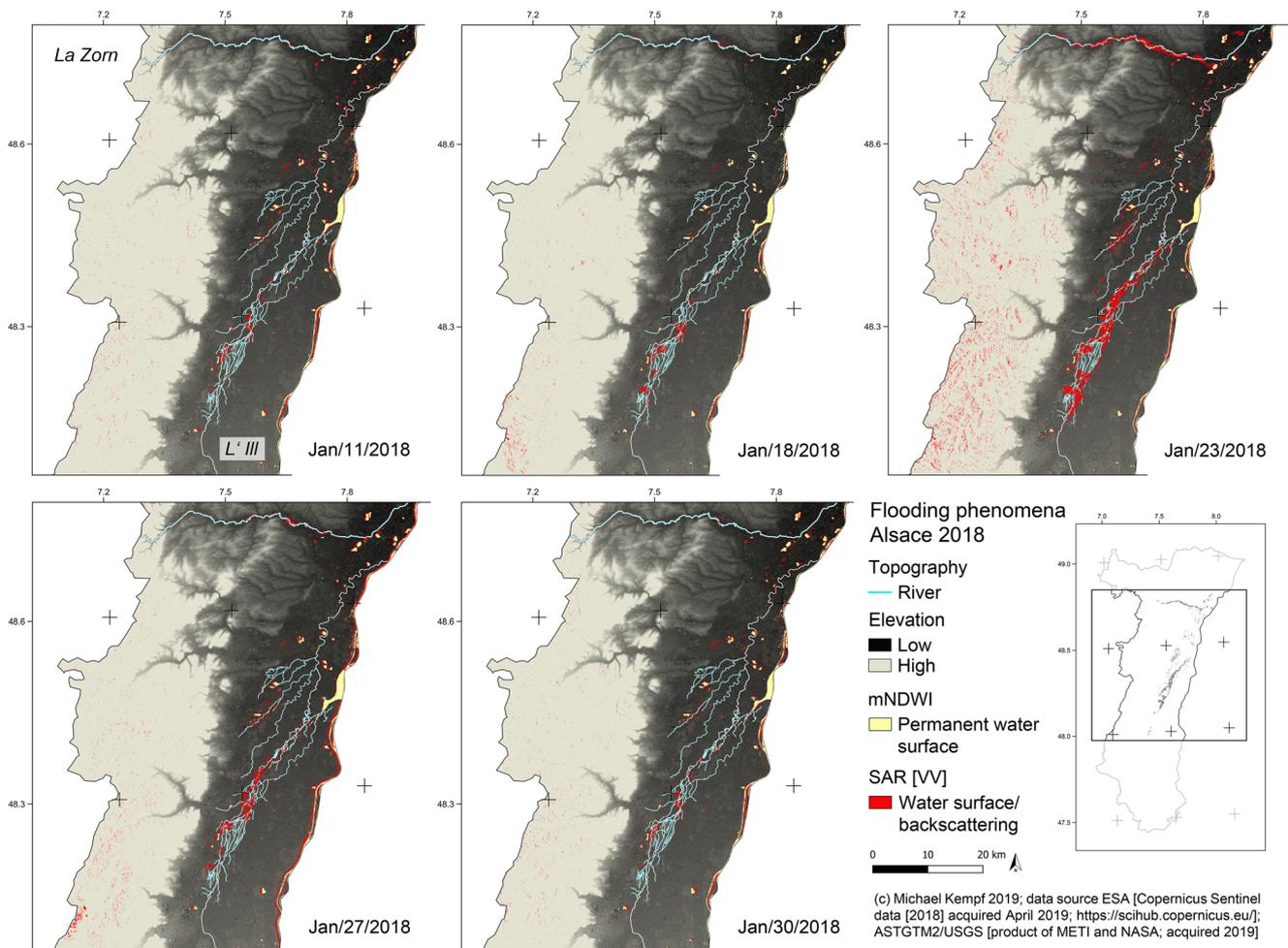


Fig. 9 Flood monitoring in the Alsace in January 2018. The onset of flooding after continuous rainfall is visible in the VV-polarized SAR-Sentinel1A imagery starting from the 11th of January onwards. It increases slightly until the 23rd when heavy precipitation rates triggered a

rapid expansion of the flooded surfaces particularly along the rivers L'III and La Zorn. The flooding event continued for more than 1 week due to the saturated topsoil and the high groundwater table

The suitability landscape model provides very significant results. The archeological record plotted on the suitability model clearly shows the spatial correlation between the site location and the potential land cover classification. Five thousand two hundred ninety-nine sites are located directly on surfaces that are classified as very high potential locations (suitability class 5). Another 4485 sites are located on surfaces with a high potential land-use quality (suitability class 4). Only a few sites lie outside these two quality classes.

Discussion

Multivariate modeling of surface transformations in sensitive and vulnerable areas through remote sensing and GIS-based applications is a well-known concept in environmental research (Carrara, 1983; Hargrove and Hoffman, 2004; Tehrani et al., 2013). In the past years, these concepts were widely integrated

into landscape and geoarchaeology, which has proven the transferability of geoscientific methods to archeological questions (and vice versa) (David and Thomas, 2010; Doneus, 2013; Fleming, 2006). Spatial modeling in archeology, however, is still strongly connected to cultural heritage management, protection, and conservation (Kamerlans and Wansleben, 1999; Verhagen, 2018). The models demand the categorization of the landscape and the various environmental datasets into potential suitability classes, which allows for the categorization of archeological vulnerability in so-called potential maps (Brandt et al., 1992; Fry et al., 2004; Hesse, 2010). However, these methods are not completely unbiased. As pointed out by the author in the current issue of AASC, the mere transferability of modern datasets and landscape perception to supposed premodern cultural activity ranges is not possible without the integration of the landscape affordances of the respective cultural groups (Kempf, submitted). The individuals' affordances and the environmental parameters in the landscape are both highly

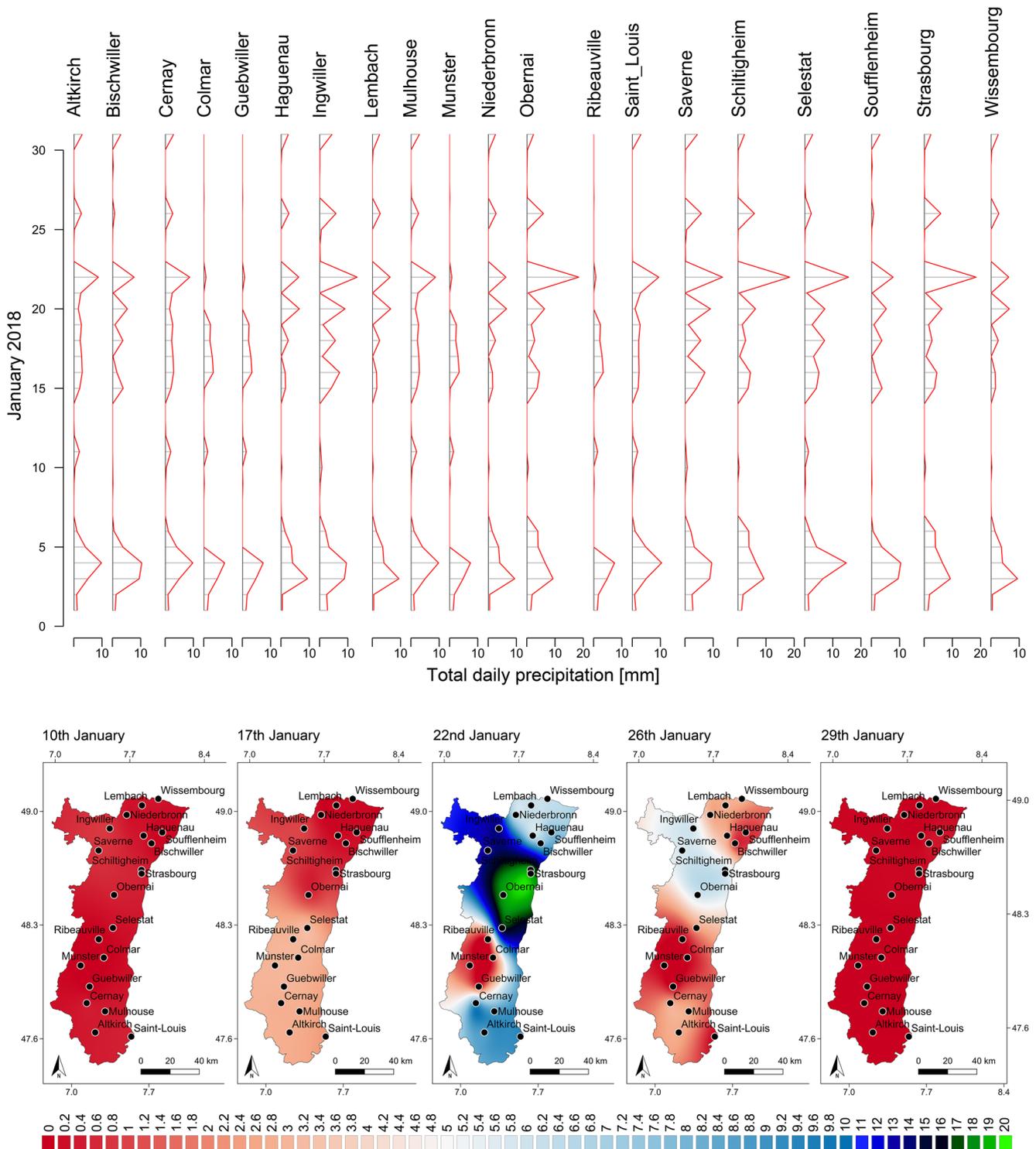


Fig. 10 Precipitation record in the Alsace, January 2018. A peak at the beginning of the month is followed by rather dry conditions until the 15th of January. Continuous rainfall occurred after the 15th with a significant maximum on the 22nd of January. After the 22nd, low precipitation rates were recorded. The interpolated spatial indices show increasing precipitation penetrating the Alsace from the south-west after the 17th

of January. The core of the heavy rainfall event on the 22nd of January is located between Sélestat and Strasbourg. The interpolations were calculated 1 day earlier than the sensing date of the SAR image to estimate the buffering and reaction time of the soil, geology, and the aquifer during the flooding event (Disse and Engel, 2001)

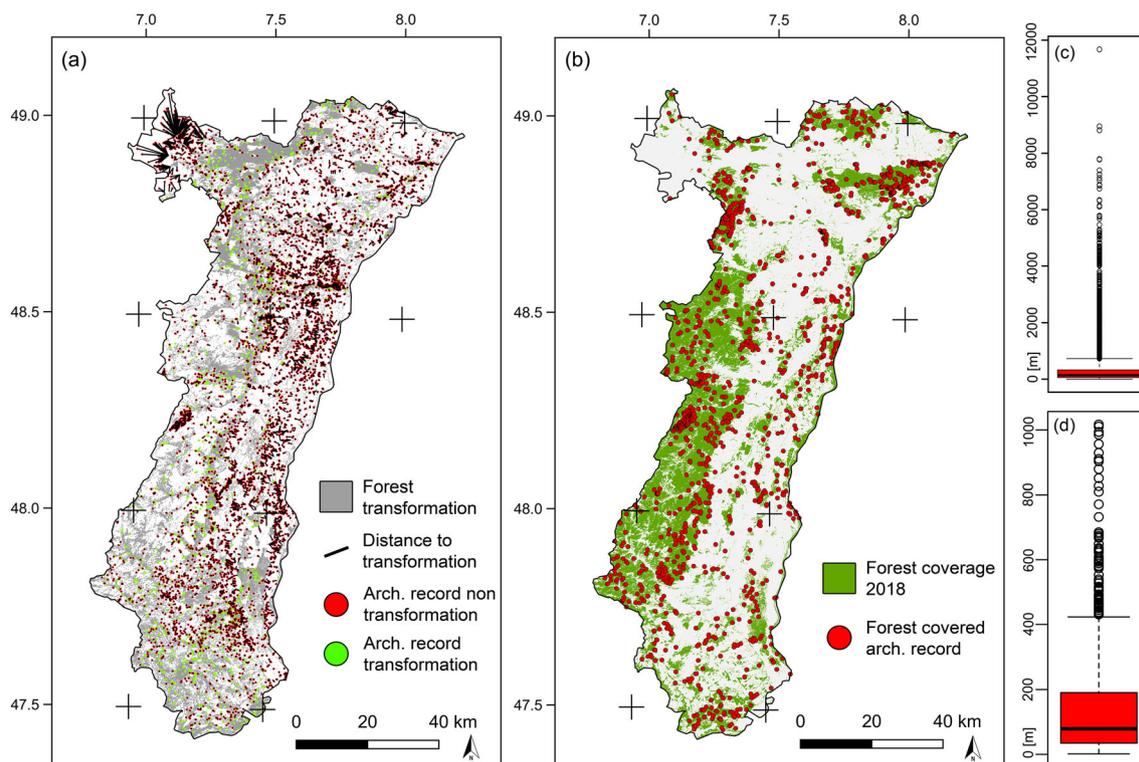


Fig. 11 Forest coverage transformation and the biasing of the archeological record by deforestation activity in the Alsace. **a** Archeological site distribution in the Alsace as a function of deforestation between 1972 and 2018. The distances between the archeological sites that lie outside of the surface modifications (red) and the nearest modified area (gray) are plotted in **c**. Most of the sites are located in close proximity to areas that experienced strong surface

transformations. **b** Forest covered areas in 2018 (green) that were calculated from vegetation indices (NDVI). The archeological record that is covered by forest (red) was mapped to calculate the distance matrix between the site location and the closest non-forested areas (**d**). The plot shows the strong relationship between site location and the vicinity to non-forested areas (cropland, built-up)

dynamic sociocultural properties that constantly develop over time. The difficulty lies in the multi-layered landscape assemblages of various cultural periods that contribute to the perception of the modern surface. Simple superimposition of all archeological records does not produce an accurate predictive model of archeological activity ranges but rather visualizes the maximum extent of current archeological research. The interpretation of these maps needs to reconsider the incompleteness of the archeological record. Just like the interpretation of only a selection of material objects, the local selection of specific archeological sites simulates coherent patterns. In reality, they just mirror the current knowledge, choice of the chronological period, or the interest of the respective research framework.

However, there are different modeling techniques to combine multivariate environmental data and archeological datasets. Fuzzy categories, for example, create data ranges that dissolve breaks and thresholds in landscape and archeological classifications (Knitter et al., 2019; Popa and Knitter, 2016). The method offers tendencies (e.g. good-bad, unsuitable-suitable) instead of distinct breaks. That aligns with the semantics of how favorable certain landscape patches have been at specific periods. On the other hand, a binary model creates

intentional classes depending on the data range (e.g., 0,1,2..X) and hence the idea and the conception of absolute data at specific locations (Adriaenssens et al., 2004; Alexakis and Sarris, 2010; Nakoinz and Knitter, 2016). But both methods can create uncertainties in predicting archeology (Verhagen, 2007) – and predicting archeology does not automatically mean protecting cultural heritage (Reeder-Myers, 2015). Finally, postdictive modeling creates a theory of how things could have been organized at certain moments in particular environments (Nakoinz and Knitter, 2016; Verhagen, 2018), thus giving an idea of how patterned social and cultural behavior in specific periods could have been (Cowley, 2016; Güimil-Fariña and Parcero-Oubiña, 2015).

These observations also apply for the study area of this paper. The analyses of recent meteorological observations in the Alsace demonstrate the occurrences of heavy rainfall events at small temporal scales (Heitz et al., 2009). Although an increase in heavy precipitation events and in hazardous flash-floods is often related to modern anthropogenic climate change and a significant increase in heat and moisture transfer in areas with a specific flash-flood vulnerability (e.g., high slope gradients, channel-like topography)

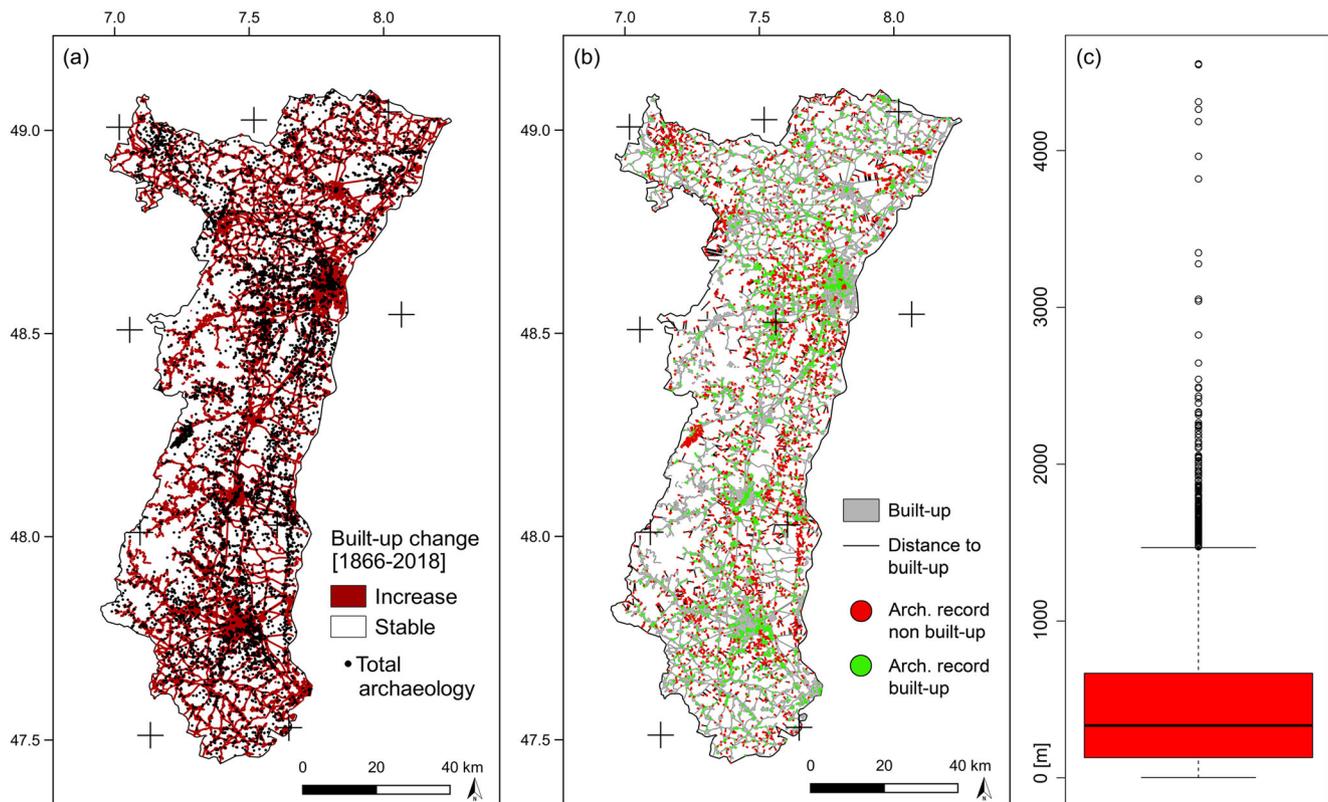


Fig. 12 Archaeological record in the Alsace and the modern bias. **a** Distribution of the total archeological record ($n = 10.726$ sites) compared to the expansion of the built-up area between 1866 and 2018 based on historical maps, modern satellite imagery and GIS-attributes. This expansion includes increased land consumption by residential areas

and infrastructure development. **b** Graphical split of the archeological record coextensive with the modern built-up area (green, $n = 6029$) and outside of it (red, $n = 4697$). **c** distance plot of the archeological record that is not coextensive with the modern built-up area. Most of the site locations are situated within a small distance of the nearest built-up area

(Borga et al., 2014; Simonneau et al., 2013), these phenomena can also be assumed for premodern periods (Ely, 1997; Starkel, 2011). The reconstructed climate oscillation from tree-ring data sampled by Ulf Büntgen et al. (2011) illustrates climate variability in Europe within the past 2500 years. Especially precipitation ratios fluctuated at different frequencies with a significant decline in modern April–June precipitation totals (Büntgen et al., 2011).

That matches the modern anthropological influence on the global climate balance that is visible in the increasing positive temperature anomalies within the last decades of the twentieth century and the beginning of the twenty-first century (Johns et al., 2003; Kornhuber et al., 2019; Overpeck et al., 1990; Rosenzweig et al., 2008; van Oldenborgh et al., 2018). However, a mere interpolation of modern climate anomalies to prehistoric climate conditions is not possible without discussing the amount of extreme weather events that contribute to the total precipitation values of the reconstructed data ranges (Li et al., 2018; Omurova et al., 2018). Modern global climate change and heat transport phenomena cause a significant shift in local moisture balances and the formation of strong thunderstorms with high precipitation ratios in short time (Minářová et al., 2017a; Minářová et al., 2017b). That

leads to extensive flooding phenomena and strong erosion processes due to locally overstrained storage capacities of the soils, broad bare areas without vegetation coverage in spring, and a fine-grained soil texture with a weak structural stability associated with silty material (Heitz et al., 2009; Heitz et al., 2013; Martin et al., 2010; te Linde et al., 2011). In this scenario, a site-specific susceptibility to hazardous precipitation events has been generated that is basically grounded in large-scale monoculture crop cultivation and extensive summer irrigation, broad fallow during the spring precipitation period, and soil compaction due to heavy machine application (Altieri and Nicholls, 2017; Berendse et al., 2015).

Local temperature anomalies as experienced globally in 2018 and 2019 can lead to extreme heat stress in summer and severe thunderstorm activity with high short-term precipitation totals (Kornhuber et al., 2019). The perception of these events and the economic and physical vulnerability of the society are affected by an increasing spread of human interaction in areas that formerly have not experienced an anthropogenic utilization. The data by Büntgen et al. (2011) shows that climate oscillations occurred in historical and pre-historical periods (Borzenkova et al., 2015; Büntgen et al., 2006; Büntgen et al., 2011; Büntgen et al., 2016; von Storch

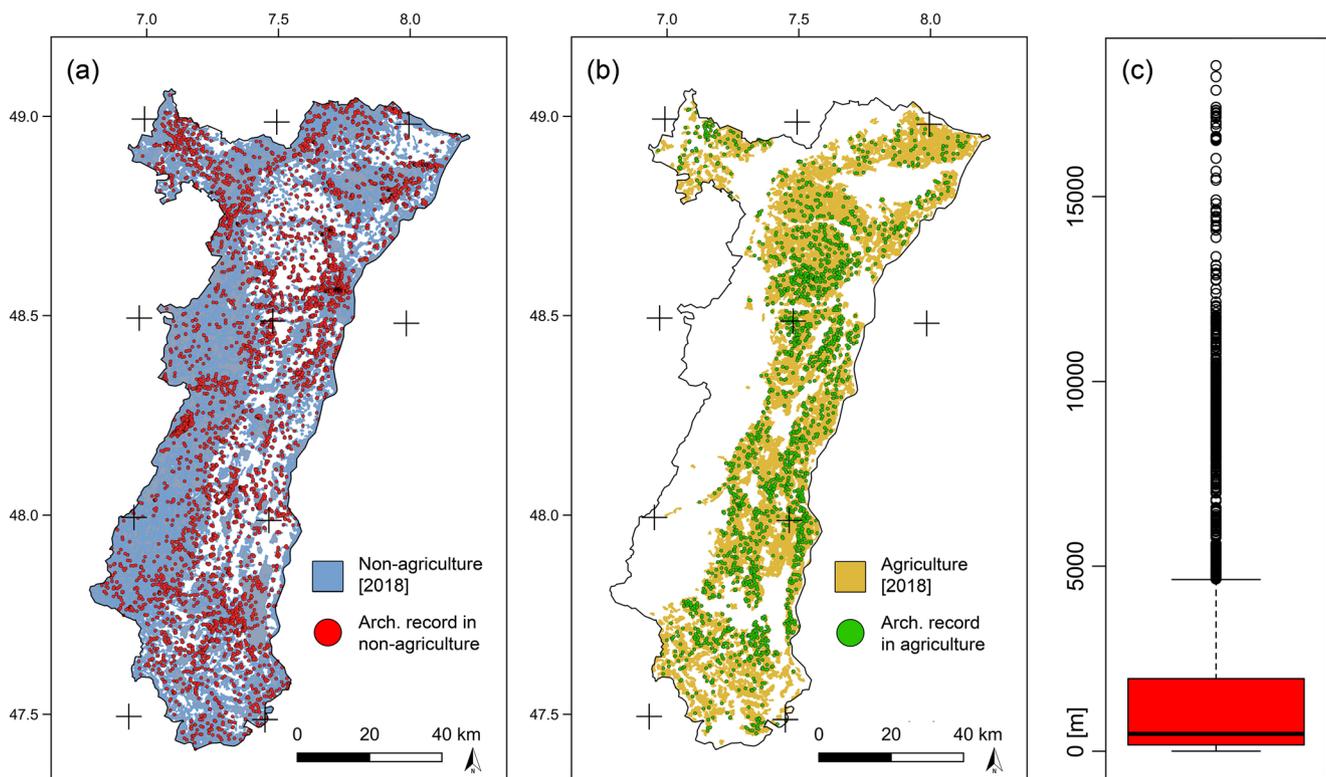


Fig. 13 The distribution of the archaeological record in the Alsace as a function of agricultural and non-agricultural land-use. **a** The area covered with non-agricultural land use (built-up, forest, pasture) contains 8036 archaeological sites what is almost 75% of the entire record. Only about 25%, which corresponds to 2690 sites, fall in agricultural land (vineyards,

non-irrigated cropland and orchards) **(b)**. The distance plot **(c)** of the archaeological record from non-agricultural land-use to the nearest cropland shows that a certain relationship between archaeological sites and modern agriculture might be observable but is most likely to be an artifact of the study site scale and the topography of the Vosges Mountains

et al., 2015; Tegel et al., 2010) and that global trends prevail in most of the palaeoenvironmental datasets (Ljungqvist, 2009).

However, there are micro-climate signals that control local feedbacks. The setup of the environmental conditions in the study area is controlled by geological and climatic dynamics that happen on the *long-durée*. The multivariate modeling, however, led to the identification of a secondary near-surface control factor that triggers small-scale surface modifications and short-term extreme flooding events.

The paper presented here exemplifies a variety of methods to track surface cover development on different temporal scales. Spaceborne satellite missions and remote sensing applications such as LiDAR or SAR provide an extensive selection of tools for digital environmental studies, forecasting, and mapping (Chen et al., 2017; Lasaponara and Masini, 2013; Masini et al., 2018). Multispectral imagery analyses enable rapid access to surface mapping through recalculations of the spectral bands. Especially, the recent Landsat and Sentinel missions offer open source medium/high spatio-temporal image resolution. The spectral band resolution of 10 m is sufficient to create large-scale land cover models. Near-infrared and shortwave infrared channels at 20 m resolution further enable the detection of plant species behavior or water surface and wildfire monitoring (Kaplan and Avdan,

2017). The resolution of the channels can further be enhanced up to 10 m through pansharpener techniques, which increases the utility of the data significantly (Kaplan, 2018; Vaiopoulos and Karantzas, 2016). Radar imagery becomes valuable where optical multispectral satellite imagery reaches its limitations. The active sensor records independently of daylight and penetrates clouds, which makes it particularly suitable for the detection of flooding events accompanied by cloud cover. The image analyses demand some preprocessing techniques that are supported by specialized software applications. However, the European Space Agency (ESA) provides functional open source software (SNAP) to manipulate Sentinel-2 and Sentinel-1 images. In combination with an open source GIS (QGIS, GRASS GIS) and a basic multispectral visualization software (Multispec), advanced image analyses can be conducted.

In digital archeology, most datasets do not provide immediate access to past environmental conditions. In this context, interdisciplinary knowledge plays a decisive role in the interpretation and the choice of the methodological research framework. Archeological narratives and environmental determinism provide manifold pitfalls and do not always facilitate cross-disciplinary cooperation. However, palaeoenvironmental data such as stable isotope ratios, radiocarbon dating, ice-core

samples, lake sediments, pollen, tree ring width, and malacofaunal remains provide a high-resolution chronological stratigraphy of past environmental conditions (Brewer et al., 2017; Dansgaard et al., 1982; Krolopp and Sümegei, 1995; Longin, 1971; Stuiver and Grootes, 2000; Tegel et al., 2010). These proxies are extended by written sources, historical maps and the typology of the respective archeological period (Schuppert and Dix, 2009). On the other hand, the distribution of archeological findings in the landscape can help identify specific environmental structures such as prehistoric river channels. These combinations allow for innovative approaches in both scientific fields—archeology and environmental studies.

Conclusion

David Cowley (2016) is critically asking whether our archeological data collection is a representative reflection of past activity or the product of modern land use (Cowley, 2016). One can also ask for the spatial congruence of arable land, resource availability, and landscape accessibility with the highest archeological density. That means areas where specific landscape configurations accumulate. But are these areas continuously cultivated and utilized since the first human impact? This paper shows that our archeological findings are strongly biased by modern land-use concepts and the location factors behind them. However, chronological classifications must be taken into consideration: detailed chronological intervals, such as the Roman and Early Medieval Period, are not comparable to early and mid-Holocene large-scale Mesolithic or Neolithic periods, in which postglacial geomorphological processes took place that need to be classified on much larger temporal scales. Here, major climatic changes, permanent shifting of river courses, and the remodeling of topographical conditions can be characterized. Although massive geomorphological transformations take place on all chronological scales, linking the processes directly to the respective periods depends exclusively on the chronological classification of the archeological findings. If they originate from non-stratified surveys or are stray finds, no conclusions can be drawn about their origin and their deposition circumstances. Understanding the origin and formation of a site, the frequency and duration of the site-occupation, and the recent overprint by historical and modern land-use activities is one major requirement to interpret the extent of past human activity ranges. However, without the deep knowledge of the geomorphological, topographical, geological, and hydrological fluctuations of a study area, this interpretation is hardly achievable.

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