Terrain Analysis and Stochastic modelling for Archaeological site prediction and landscape reconstruction in the Lake Manyara area, Northern Tanzania

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SUMMARY

In this study we focus on paleontological sites in the area of Lake Manyara and the Makuyuni River Basin, Northern Tanzania. This region is known for Middle Pleistocene fossil finds and artefacts. To analyze the spatial distribution of potential paleontological find locations we applied two different methodologies based on statistical mechanics and on boosted regression trees. The first one is able to handle presence-only datasets such as the locations proper. The second approach was used to study the variable importance and to derive information on the related geo-processes for classified paleontological sites. The locations and their spatial distribution were retrieved from literature and collected by own field work over the last years. For the modeling we utilized environmental information such as spatially continuous layers of topography (30 m SRTM DEM), derivatives of topography, vegetation information as well as ASTER multispectral data as predictor variables. The results reveal potential areas where further fossil sites may be located. Moreover, we assessed the processes that are related to sites with specific archaeological evidences. Therefore, the sites were grouped in three categories: i) artefacts sites, ii) fossil sites and iii) mixed sites. We applied boosted regression trees to analyse the processes related to the classified sites. The methodology considers not only site specific characteristics but implicitly also the related pedogenetic and morphogenetic processes. We were able to differentiate between artefact and fossil sites. Moreover, our analyses indicate an influence of transportation processes on the artefacts, whereas deposition of fossils does not seem to involve large scale transportation. Finally, we show that also the landscape can be reconstructed such as the former lake margin.

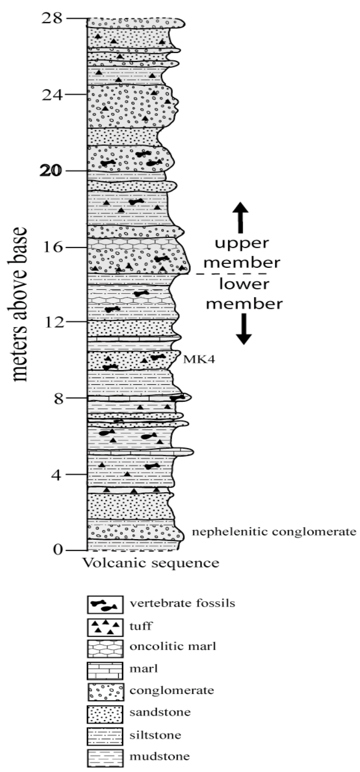
Keywords: *Tanzania, environmental prediction, mechanical statistics, boosted regression trees, paleontological sites, landscape reconstruction*

INTRODUCTION

As stated by Leakey (1979, 1986) Tanzania is well known for prehistoric specimens of early hominids that were found for example in Olduvai Gorge or at Laetoli. Research on human evolution is strongly based on these sites and numerous research teams are still working there. The geographic centre of this study lies close to Olduvai, but within the central arm of the Tanzanian Rift around the eastern margins of Lake Manyara and along the Makuyuni River. Jäger (1913), Reck (1921) and Reck and Kohl-Larsen (1936) were the first to study the deposits in the vicinity of the locality Makuyuni. The Pleistocene sequences in the valley of the Makuyuni River were discovered early on by Louis and Mary Leakey, and were later examined by Kent in 1935 (Kent, 1941, 1942). Keller and colleagues collected Pleistocene faunal material, Acheulean and MSA lithics, and published several stratigraphic sections (Keller et al., 1975). Recent studies investigated the geology, paleontology, and archaeology of the Lake Manyara Beds e.g. Schrenk et al. (1995), Kaiser et al. (1995), Kaiser (2000), Saanane (2004), Ring et al. (2005), Schrenk et al. (2008) and Kaiser et al. (2010).

Previous studies showed that two fossil bearing layers of different age occur in the area, namely the Lower and Upper Manyara Beds. Correlations with the sequence in Olduvai seem to indicate Lower and Middle Pleistocene ages for the Upper Manyara Beds (Ring et al., 2005). *Figure 1.* shows the stratigraphical succession published in Kaiser et al. (2010). Upper terrestrial beds and lower lacustrine beds are separated by a net boundary characterized by a colour change from greyish (lacustrine sediments) to reddish (terrestrial deposits). The whole stratigraphy is interspersed with presumably reworked tuff deposits. Both upper and lower beds are also bearing fossil layers especially around the boundary of upper and lower beds.

Figure 1: **Stratigraphy of the Lake Manyara beds after Kaiser et al. (2010)**



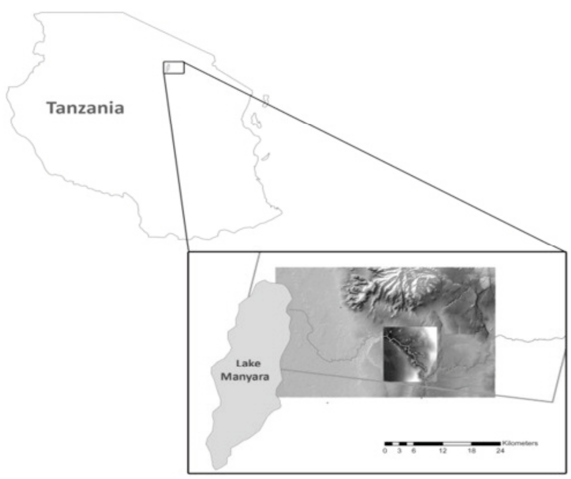
The large number of find locations of specimens of fossil vertebrates and artefacts detected during different field campaigns were the reason for a more in depth analysis of the spatial distribution of these sites in relation to present day environmental characteristics and processes. Therefore, we developed an integrative spatial modeling concept using GIS, remote sensing and sophisticated statistical methodologies. The approach takes into account a variety of environmental data such as topographic data, spectral satellite information, field observations and stratigraphic characteristics.

This paper discusses the methodology and results of the spatial modeling of paleontological and/or archaeological sites. In the following we use the term paleontological sites to describe both, sites with fossils and artefacts. In the second part we analyse the environmental criteria defining specific site locations. Moreover, we assess the processes related to these criteria.

STUDY AREA

The study area is located in the Northern part of Tanzania *(Figure 2)*. The area is situated along the southern end of the Gregory Rift, part of the East African Rift System (EARS). It covers the Eastern parts of Lake Manyara and the lower part of the Makuyuni River Basin. Lake Manyara is extending NNE-SSW, has a surface of about 480 km², and an elevation of 960 m asl. The study area is extensively covered by late Proterozoic metasediments, Neogene volcanic material, and Plio-Pleistocene and Holocene lake beds (Vaidyanadhan et al., 1993). The Lower Manyara beds are made up of grey silty ash clays and marls with horizons of chert nodules and calcareous algal concretions. Interbeded are sandstones, pebbly limestones, conglomerates and occasional tuffs. Those lake beds occur either as low flat-topped hills or as long ridges (Schultz, 1967; Vaidyanadhan et al., 1993).

Figure 2: **Location of Study area, showing Lake Manyara and Makuyuni River as well as the find locations (red)**



Note: the green frame shows the extent of the ASTER spectral data.

MATERIALS AND METHODS

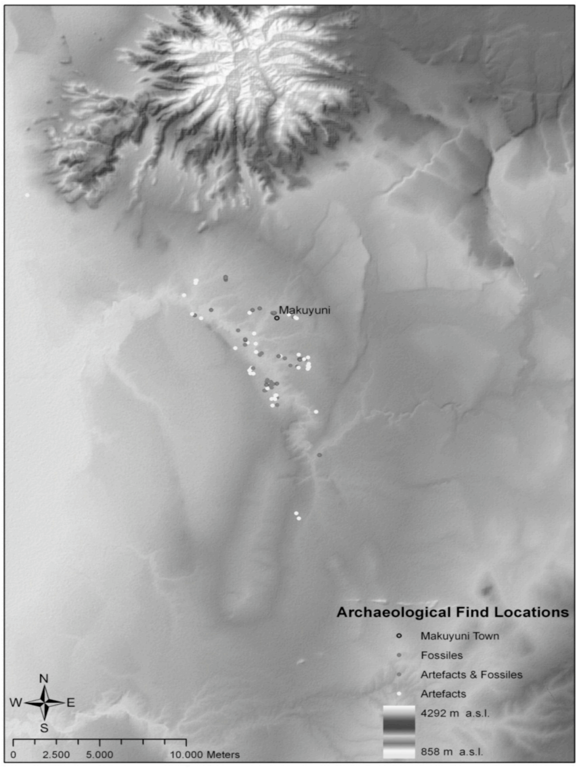
Input Data Preparation

The input data consists of topographic data, spectral satellite information, field observations and stratigraphic characteristics. For the Makuyuni – Lake Manyara area an SRTM DEM with a resolution of 25 m × 25 m was chosen. The SRTM DEM was preprocessed using a simple filter to reduce errors and noise caused by vegetation. Thereafter, the DEM was hydrologically corrected using the algorithm of Planchon and Darboux (2001). Subsequently, the corrected DEM was utilized to derive topographic indices with the SAGA GIS software (Olaya and Conrad, 2008). The dataset applied in the modelling consists of 22 continuously distributed parameters: i) topographic wetness index (Beven and Kirkby, 1979), ii) stream power index (Moore et al., 1991), iii) transport capacity index (Moore et al., 1997), iv) slope after Horn (1981), v) aspect, vi-viii) curvature (plan, profile, combined), ix) relief elevation above thalweg (Olaya and Conrad, 2008), x) upward flow length after Tarboton (1997), (xi) NDVI from ASTER, xii-xxi) single ASTER channels 1–9 and xxii) a principal component analysis of ASTER channels 1–9. The target, response or dependent variable consists in sites with paleontological evidence such as fossils or artefacts. These sites have been measured with DGPS and transformed into point vector type information. Totally, 99 sites were identified that were used in modelling. Subsequently, we distinguished between archaeological (N_2=30, handaxes only), paleontological (N_1=14, fossils only), and mixed locations (N_3=42). *Figure 2.* shows the spatial distribution of individuallocations in the study area. The topographic indices characterize erosion transport and deposition processes as well as climatic and geologic variations in the landscape. They do therefore not only reflect the immediate vicinity of a specific spot, but moreover refer to a wider territorial context. Furthermore, we exploited spectral satellite data from the ASTER platform in the visible channel (3 bands) and near infrared channel (1 band), as well as in the short wave infrared channel (5 bands). We used the single bands and derivatives of them as predictor variable. The Normal Differentiated Vegetation Index (NDVI) and a principal component analysis describe specific environmental characteristics like vegetation density and spatially homogeneous spectral entities such as soil types or stratigraphic units. *Figure 3.* shows a selection of relevant predictor variables characterizing the study area such as DEM, slope, TWI and NDVI. The predictor variables were stacked and resampled to match with the DEM resolution of 25 m. The predictive variables such as the DEM and its derivatives as well as the satellite information were converted into a tabular matrix. The target variable containing the information about the find locations was added to this table. The resulting matrix was then further processed with a sophisticated statistical approach.

Modeling and Prediction

Recently, predictive modeling techniques such as generalized linear models (GLM), generalized additive models (GAM), classification tree analysis (CTA), neural networks (ANN) and multiple adaptive regression splines (MARS) have been applied in various disciplines from geomorphology, and ecology to medicine and social sciences (e.g. Miska and Hjort, 2005). These methods frequently require presence and absence data of the respective target variable or at least a classified variable to be able to generate a model. In our case, we have only find locations whereas areas void of specimens are not mapped. Consequently, we need to develop a suitable method that is able to handle presence-only datasets.

Figure 3: **Location of sites in the Lake Manyara and Makuyuni River area**



Note: in red fossil sites, in blue artefact sites and in yellow sites where both fossils and artefacts are found.

In this study we utilized the Maxent approach developed by Phillips et al. (2006). Maxent is a general-purpose method for making predictions or inferences from incomplete information. Its origins lie in statistical mechanics (Jaynes, 1957). The fundamental idea behind Maxent is to estimate a target probability distribution by identifying the probability distribution of maximum entropy (i.e., that is most spread out, or closest to uniform), subject to a set of constraints that represent our incomplete information about the target distribution. The information available about the target distribution often presents itself as a set of real-valued variables, called "features", and the constraints are that the expected value of each feature should match its empirical average (Phillips el al., 2006).

When Maxent is applied to presence-only species distribution modeling, the pixels of the study area make up the space on which the Maxent probability distribution is defined, pixels with known species occurrence records constitute the sample points, and the features are terrain variables derived from the SRTM DEM and spectral ASTER information and functions thereof. The advantages of Maxent can be summarized as follows: (1) It requires only presence data, together with environmental information for the whole study area. (2) It may utilize both continuous and categorical data, and may incorporate interactions between different variables. (3) Efficient deterministic algorithms have been developed that robustly and reliably converge to the optimal (maximum entropy) probability distribution. (4) The Maxent probability distribution has a concise mathematical definition, and is therefore amenable to analysis. For further model information we refer to Phillips et al. (2006).

For the sites classified according to the occurrence of artefacts and fossils we applied another method based on classification regression trees, namely the Tree Net approach (Friedman, 1999), it employs a learning algorithm to identify a model that best fits the relationship between the attribute set (predictor variables) and the class label of the input data (response variables). The TN is a stochastic gradient boosting model also known as boosted regression tree (Elith et al., 2008). Gradient boosting constructs additive regression models by sequentially base fitting a simple parameterized function to current "pseudo"-residuals by least-squares at each interaction (Friedman, 1999). In particular, the TN model computes several hundreds to thousands of small classification trees, each one contributing to construct a portion of the model and refine on its predecessors.

The advantages of using TN model are related to different strengths: being insensitive to data errors in the input variables; automatic variable subset selection; to handle data without pre-processing; resistance to outliers; automatic handling of missing values; robustness to dirty, partially inaccurate data; high speed and resistance to over-training (Friedman, 1999). Moreover, a recent comparison of methods shows that Random Forest and Boosted Regression Trees out-compete simple regression trees (De'Aht, 2007; Maerker et al., 2011). We ran the TN model with the response variable classified in three classes. However, the number of cases in the fossil class (N=14) is statistically too small for an in-depth validation. Therefore we applied a V-fold cross validation. Nevertheless, the amount of cases especially of the fossil class should be increased in future by further field surveys.

The applied models predict the potential spatial distribution of find sites over the entire area of 120 km^2 in a spatially explicit way (Maxent all sites /TN classified sites). Therefore, the model was applied to the complete data set given all explanatory variables for the entire area. In the last step, the resulting tabulated data, i.e. the predicted probabilities for the sites – or, more precisely, the predicted probabilities of each pixel to be an site – were post-processed to produce probability maps with GIS. In order to evaluate the model's predictive performance beyond classification matrices, we calculated the Receiver Operating Characteristics (ROC) curves. In a ROC curve the true positive rate (sensitivity) is plotted over the false positive rate (1-specificity) for all possible cut-off points (Swets, 1988). Each point on the ROC plot represents a sensitivity/specificity pair corresponding to a particular decision threshold. A perfect discrimination between positives and negatives has a ROC plot that passes through the upper left corner (100% sensitivity, 100% specificity), so that the area under the ROC curve, AUC, is 1 (cf. Reineking and

Schröder, 2006). According to Hosmer and Lemeshow (2000), AUC-values exceeding 0.7, 0.8, and/or 0.9 indicate acceptable, excellent, outstanding predictions, respectively. In order to improve model interpretation, we calculated predictor variable importance ranking all predictors due to their contribution to the final model. The same procedure and validation were also executed for the TN model.

RESULTS AND DISCUSSION

As shown in *Figure 3.* the spatial distribution of the sites is related to specific characteristics of the predictor variables such as the elevation (DEM), slope, TWI or NDVI. A certain distance to the river network, a particular elevation range and eroded areas without vegetation (NDVI) seem to be intuitively detectable criteria for the site distribution. However, a proper analysis of the entire set of predictor variables is only feasible with more sophisticated approaches such as Maxent or TN.

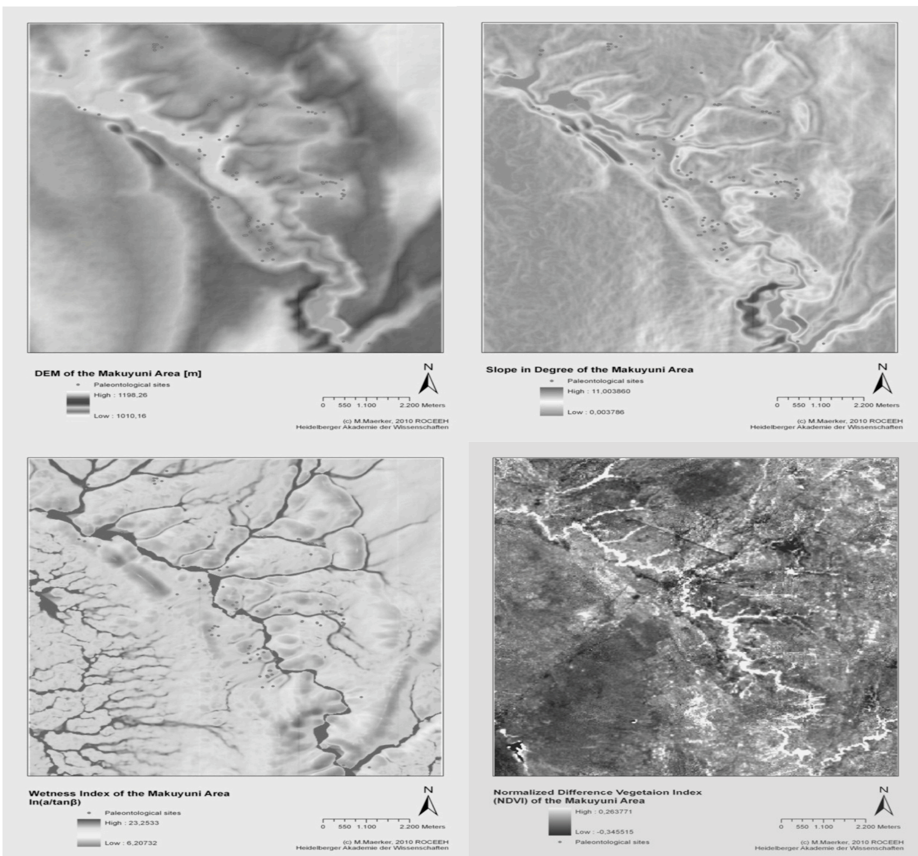
Maxent modelling

In the first Maxent simulations in total 99 points (sites) are used to determine the Maxent distribution. The model results obtained with the Maxent approach show an area under curve value (AUC) for the train dataset of 0.642. The value of 0.642 indicates a weak to acceptable performance of the Maxent model. This poor performance could be related to the fact that all sites are taken into consideration and no distinction is made between the sites. The variable importance can be summarized as follows: i) catchment area (47.5%), ii) curvature (28.3%), iii) profile curvature (16.1%), iv) NDVI (4.7%), v) TWI (1.2%), vi) slope (1%), and vii) ASTER 3rd band (0.2%).

The variable importance that results from the model run illustrates that the variables describing the hydrological characteristics of the test area are most important. Especially, the catchment area yields information on the potential amount of surface runoff and thus on transport capacities. The curvature is an index that describes the accumulation or distribution of water on one hand as well as the acceleration or deceleration of surface runoff (profile curvature). The importance of the hydrologically relevant indices triggering surface runoff might be also an indicator for the transport of artefacts and fossils towards the toe slopes. This hypothesis was then investigated with the TN approach.

Figure 4. shows the resulting spatial distribution of the modelled occurrence probabilities for all archaeological sites (N=99). Shown in dark blue are the areas that have the highest probabilities. The highest probabilities are related to lower areas where runoff concentrates. Since the Maxent model takes into account tectonic activities as well (altitude above stream channel), paleosurfaces can be detected showing a much more complex topography as the present day digital elevation model provides. The results presented in *Figure 4.* reveal potential areas where further sites may be located. These sites with high probability values will be preferentially screened during the next field stages in 2011.

Figure 4: **Selected predictor variables**



Note: upper left: DEM; upper right: slope; lower left: TWI, lower right: NDVI.

Treenet Modeling

The results and hypothesis derived from the Maxent simulation can be summarized as follows: i) the distribution of sites is related to certain environmental variables; ii) these environmental variables clearly show a strong influence of runoff processes; iii) the poor performance of the Maxent model may be related to the fact that there are sites with artefacts only, sites with fossils only and mixed sites where both kinds of specimens were observed. Thus, our hypothesis for the TN modelling is that the specialized classes are characterized by differing parameter combinations and hence, processes that explain the spatial distribution of the respective specimens. The TN model was consequently used to decipher the responsible variables and processes related to the classes.

Figure 5. shows the ROC curves with the AUC values (ROC integral). The performance of the model is excellent to outstanding. The model is able to discriminate with high precision between positives and negatives. However, the small number of cases especially for the fossil find category must be taken into account as shown by the poor results of the V-fold cross validation with AUC values of 0.65 for fossil sites; 0.56 for artefact sites and 0.56 for fossils and artefact sites. The poor validation results may be due to the small amount of cases per class and are expected to improve with increasing number of cases.

The relative variable importance tables *(Table 1.)* given by Treenet illustrates the overall importance of the curvature classification. The parameter describes terrain elements with dissipation characteristics or accumulation characteristics as a proxy and thus erosion and deposition processes. However, the next two parameters differ between artefact and fossil bearing sites and are very interesting to characterize find-specific processes in relation to the sites.

In case of fossil sites these parameters are the Aster spectral bands 4 and 3. These bands identify the colour differences between Upper and Lower Manyara Beds, thus reflect a stratigraphic impact. This corresponds well to the known stratigraphic distribution of fossils *(Figure 6.)* and is apparently robust towards taphonomic processes of deposition which differ among Upper and Lower Manyara Beds despite the small number of samples. The findings on the fossil sites are also stressed by the prediction of site probabilities *(Figure 7.)*. The highest probabilities for a fossil site are highlighted in red and follow the boundary between upper and lower Manyara beds. Moreover the highest probabilities spatially correlate with the former lake boundary.

Figure 5: **Modelled probabilities for paleontological sites in the Makuyuni area (sites in red)**

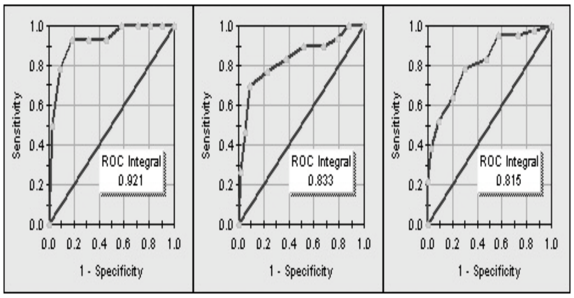
Table 1.

Variable importance for the fossil sites (above) and the artefact sites (below)

Variable	Fossils
CURVATURE_CLASSIFICATION	100,00
PRO_ASTE4_TIF	33,88
PRO_ASTE3_TIF	31,26
CONVERGENCE_INDEX	29,68
FILLED_DEM_SGRD	25,97
PROFILE_CURVATURE	22,48
ASPECT	22,21
NDVI_TIF	22,18
PLAN_CURVATURE	22,13
PRO_ASTE2_TIF	19,64
STREAM_POWER	19,63
CHANNEL_NETWORK_BASE_LEVEL	17,75
CATCHMENT_AREA	15,55
LS_FACTOR	13,28
ALT_ABOVE_CHANNEL_NETWORK	12,87
PRO_ASTE1A_TIF	7,99
SLOPE	7,19
WETNESS_INDEX	4,45
CURVATURE	1,09
CHANNEL_NETWORK	0,00

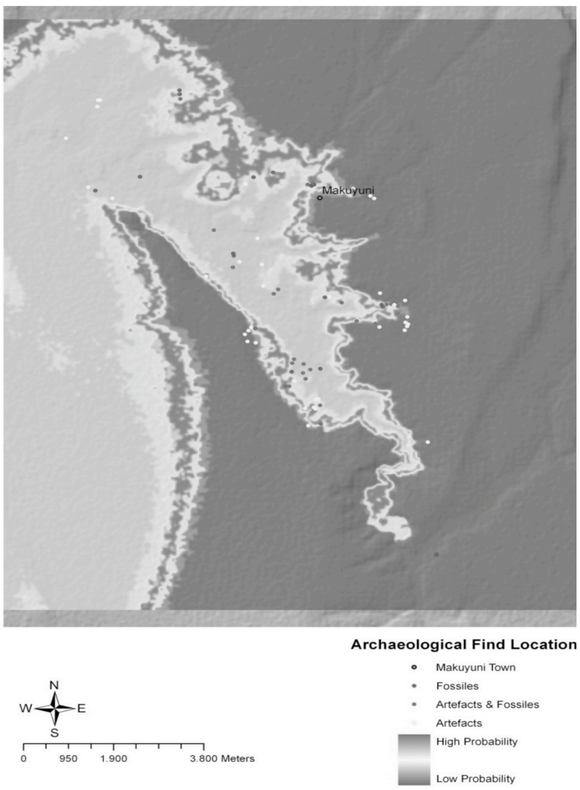
Variable	Artefacts
CURVATURE_CLASSIFICATION	100,00
STREAM_POWER	47,07
WETNESS_INDEX	45,30
PRO_ASTE4_TIF	42,04
PROFILE_CURVATURE	38,87
PRO_ASTE2_TIF	35,86
CURVATURE	28,85
PRO_ASTE3_TIF	27,91
SLOPE	27,63
LS_FACTOR	26,72
CATCHMENT_AREA	26,48
FILLED_DEM_SGRD	26,13
PRO_ASTE1A_TIF	25,19
PLAN_CURVATURE	24,16
NDVI_TIF	23,58
CHANNEL_NETWORK_BASE_LEVEL	21,99
ASPECT	21,45
CONVERGENCE_INDEX	20,83
ALTI_ABOVE_CHANNEL_NETWORK	18,64
CHANNEL_NETWORK	0,00

Figure 6: **ROC diagrams of the TN modelling**



Note: left: fossil sites; middle: artefact sites; right: artefact and fossil sites.

Figure 7: **Regionalization of the Treenet results for the fossil sites**



Note: in red high probabilities for a fossil site, in blue low probability for a fossil site.

The variable importance for the artefact category reveals two parameters that are mainly related to water flow and erosion processes, namely the stream power index and the wetness index. These two indices indicate an influence of runoff processes on the deposition.

Thus, the analysis lead us to a new hypothesis concerning the processes related to the find locations and find classes: i) artefacts are mainly transported by water, whereas ii) fossils rather correlate with the stratigraphy and are not transported in a similar way. These hypotheses need further investigations and will be focus of the next field stage in Tanzania.

CONCLUSIONS

The study presents a first attempt to detect the occurrence of paleontological sites (fossils & artefacts) in relation to environmental information. Moreover, we further examined the importance of a set of variables with respect to specific site categories. We found the fossil sites to be dominated by the stratigraphical setting whereas the deposition of artefacts illustrates a clear influence of transport processes. Thus, besides the fact that all sites are located in the vicinity of the former lake boundary (Lower/Upper Manyara Beds boundary), the artefacts seems to be transported by overland flow. Unlike artefacts, fossils seem not to be transported or at least only over short distances. These hypotheses are part of a forthcoming research project characterizing the present day hydrological dynamics in order to reconstruct paleo-process dynamics.

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