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ARTIFICIAL NEURAL NETWORKS IN ARCHAEOLOGY

1. Introduction

The aim of this paper is to introduce the reader to the use and application of Artificial Intelligence (AI), in particular Artificial Neural Networks (ANN), in the archaeological research. The purpose is to help the reader to understand and familiarize with some of the basic elements of ANN applications and technology. At the same time, this paper will address the issue of applicability of ANN to settlement and landscape archaeology, showing some basic applications and implementation of useful methodological strategies.

2. Archaeological record

Archaeological research, as well as every scientific discipline, is based on the dual intellectual process of observation and description. It is through observation and integration into models that human knowledge is developed.

A specific subject of archaeological research is *material culture*. Of course there are many schools and ways "to do" archaeology. Nevertheless one must agree that the common base for all researchers is the material culture (Gordon Childe 1956). As well as every scientist, archaeologists also have to care about complexity of reality: cultures, societies and civilizations. Therefore, in the specific case of this discipline, the complexity of the material remains.

The understanding of complexity represents one of the key issues for contemporary science (Caws 1963, 158). Nevertheless, for archaeologists (as well as for historians) work conditions are more unfavourable and difficult than those of other disciplines. In fact, usually archaeologists had to deal not only with extremely complex features (i.e. culture, society, states, economy, etc.) but also with very imprecise and heterogeneous records. No matter if one refers to excavation or survey documentation: the inaccuracy, bias and incompleteness of archaeological record remains high. Archaeological data imprecision may be subdivided in three specific areas:

a) The archaeological record is by its own nature incomplete. The complete material transcription of human settlements life is by itself impossible. Even with exceptional conservation conditions walls might be rebuild, tools adapted or modified (Cordell, Upham, Brock 1987, 565-566).
b) The archaeological record is always the result of a conservation process. The fact is that conservation and destruction processes deeply modify remains (Bowers, Bonnichsen, Hoch 1983, 553-554). Environmental conditions and

civilization development processes can damage the conservation of archaeological deposits.
c) The archaeological record is heterogeneous and therefore material culture appears as an extremely complex matter. Cultures and especially human experience are not based on standard repetitive paradigms that reproduce again and again the same material outcome. This condition is aggravated by the fact that conservation can be different in similar archaeological sites.

According to points a), b) and c) archaeological research may appear as a hopeless effort to solve an incomplete puzzle.

3. Archaeology and computer sciences

During the last three decades, archaeology has intensely used computers for data management and data analysis (Gaines, Gaines 1980, 463-466). This activity has been wide and intense. The fact is that today almost every archaeologist uses computers and software to deal with archaeological records.

However, the use of computers is not a straight process. Every archaeologist is forced to manipulate, transform and adapt his own data and information in order to elaborate it with a calculator. This, simply because computers are machines based on a binary Boolean architecture (Craig 1979, 751-763).

The history of computers has determined how things work or should work (Goldstine 1977). In the last years, we have observed the frenetic evolution of computers. But truth is that the core paradigm of computers remains intact with the addition of minimal revolutions like object oriented architectures, the Internet, and Graphical User Interfaces (GUI).

For example, the binary Boolean conditions determined how a database works: its data structure and architecture, queries and so on. In fact, all database software are built and conceptualized under the same abstract schema (Date 1982, 18-29). Past, present and future databases work on the same principles: tuples, tables, queries, etc.

Archaeologists have used the computer paradigm to deal with their own archaeological record. This condition has determined two different situations. The first one is the huge and growing efforts made by archaeologists to improve the use of computers in their different research process. A proof of this is the large number of congresses, workshops and books published specifically for the archaeological community on this matter. The second aspect is the inadequate compelling input of archaeological records into the dual binary/Boolean schema. One may ask: “What’s wrong with that?”

As stated above, archaeological datasets are incomplete, imprecise and heterogeneous. This kind of scientific information hardly fits inside the binary/Boolean paradigm. For example, let us imagine 100 archaeological records of excavation contexts. Moreover, let us suppose that ten of them are incomplete, 20 percent inaccurate and that there appears to be a high level of heterogeneity among them. What might be the concrete outcome and significance of a rigorous query session with this database? Well, the answer is not difficult simply because every archaeologist has to deal with such (or worst) conditions constantly in his professional life.

However should we expect that this might be forever the natural circumstances of application of computer sciences to the archaeological research? Would an alternative approach be possible?

Advances in computer sciences have introduced (not so new) computational paradigms (ROSENBLAT 1958); schemes that appear more adequate to the natural features of archaeological records and information; computing strategies that are widely recognized among AI (DOYLE 1996, 656).

4. ARTIFICIAL NEURAL NETWORKS: FOUNDATIONS AND PRINCIPLES

ANN are based on an abstract analogy with brain's architecture and functionality. For many aspects ANN are another case of technological emulation of nature-biological strategies. This kind of software applications is basically based on the functional process of the brain (ABDI, VALENTIN, EDELMAN 1999, 1-6).

But how the brain works? Even if some things remain still a mystery, there are fundamental theories that had explained at least some aspects of this biological process. Paradoxically, it will be more easily to comprehend the nature of the human brain if one first understands the characteristics of an ANN.

The basic components of an ANN are units and connections just like the neurons and their synapses. The synapses are branched connections specialized on electrochemical transmission (or outputs). On the other side of the neuron cell, dendrites represent the specialized section for signal receiving (or inputs). Therefore, it is clear that neurons are cells specialized for reciprocal interconnection. Each neuron can transmit to other cells through its synapses and receive information from its dendrites. For this reason we might argue that a neuron is basically an input/output processes specialized cell (ANDERSON, MCNEILL 1992, 2-3).

The key factor for ANN development and application, as well as for the brain, is *interconnectivity*. The broadness of interconnectivity determines the ability of the ANN to adapt itself to learning patterns. Due to their structure, ANN are based on a different kind of logic: basically a fuzzy logic paradigm. Therefore, ANN can become an extremely flexible tool; something that traditional Boolean based algorithms would never become.

Adaptiveness means also that a specific portion of the brain can become specialized in some activities: colour, sound, smells recognition. ANN are like a software simulation of a very small piece of brain that can be used for computational processes. "Very small" means just few cells.

Just take a minute to think on how the brain performs some basic operations: for example how does an observer recognize an apple. An apple is not always the same. It changes in size, shape, colour and conditions (half apple, maturation, deterioration, etc.). However, even if an observer has not seen all the existing, existed and transformed apples he will be able to recognize it. He may also recognize a smashed apple or even an artificially flavoured apple candy. How is it possible? Is a fact that the brain works with fuzzy logic principles and rules. Otherwise (i.e. a Boolean logic structure), the brain would be able to distinguish specific and particular items and unable to recognize categories or classes of objects (Posner, Carr 1992, 1-2)

ANN do not have to match an exact pattern to recognize it. When the image of an apple reaches the retina, it is encoded and then transmitted through the optical nerve to the brain. The impulse is spread on a vast network of neurons. The specialization of these cells makes it possible that the impulses reach and activate that small portion of our brain where the significance of the idea "apple" is recorded.

5. The structure of an ANN

ANN are adaptive models (Abdi, Valentin, Edelman 1999, 1). In other words, this means that they can learn. It is for this reason that this kind of technology is accounted among the AI techniques. ANN can self adapt its functionality in a learning process. It would be more correct to say that ANN can be trained because the learning process requires some level of consciousness that obviously artificial software as well as machines do not have. In any case, the adaptiveness of an ANN is used on a specific training process in which the user trains the network using a training pattern.

The training pattern contains and describes arbitrary relationships between output and input signals. The use of the word "arbitrary" means that the given pattern does not explain to the network how to transform a specific input into a definite output. In analogy with a human brain, it is like teaching a child a lesson on good and bad actions. It would be like saying, «help the elderly (input) is a good action (output) » without explaining the child the ethics and social principles that determine that the assistance to aged individuals of his own specie is a good thing.

Input and output concepts can be used to explain another important aspect of ANN. Most common ANN are based on three layers: input, hidden and output layer (Anderson, McNeill 1992, 7-8). Each layer is based on a certain number of units, which usually interconnects from the input to the hidden and from the hidden to the output (Fig. 1). The training pattern teaches

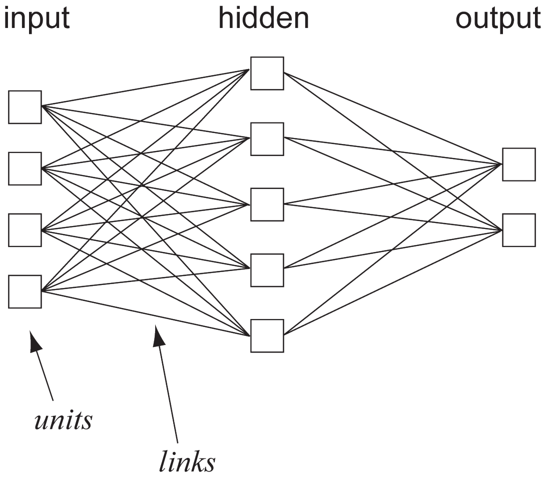

Fig. 1 – ANN are based on a multilayer structure: input, hidden and output layers. Each layer is based on a set of units that are interconnected with a series of weighted links.

the ANN how to adapt itself to obtain a specific output with a certain input. Interconnections represent the basic functional element of this technology. In fact, the adaptive process is based on the modifications of the weights of each connection. This is how information flows inside the ANN.

However, units are not only based on a simple flowing process. They are also based on a logic paradigm that depends on units. Each unit has a specific threshold value. When the sum of inputs from the incoming connections overcomes the unit threshold, it activates itself and let the information flow and get through to the next interconnected units. Even if this may appear as a very primitive law, this solution represents an excellent strategy for fuzzy logic devices. The software interaction within input, hidden and output layer is known as multilayer-perceptrons. Originally, the perceptron was the first basic prototype of network.

The training process is based on the recurring feed of the training pattern to the ANN until the weight of the connections reaches a specific combination that allows the user to obtain an output with a specific input.

Once the ANN is trained, the user can present as inputs instances not included in the training pattern. The result will be that even if the artificial neural network was not trained with the full set of possible examples, eventually, outputs will be extremely accurate. In other words, depending on the quality of the training process, the ANN will present the "best estimate" for every possible input combination, even for instances not included in the training pattern.

6. ANN AND ITS AREAS OF APPLICATION TO THE ARCHAEOLOGICAL RESEARCH

What has all this got to do with archaeology? As stated before, the archaeological record is incomplete, inexact and heterogeneous and do not fit well in traditional (Boolean logic based) computing paradigms. No matter how many methodological advances could come, archaeological datasets structures and architecture, for example, would not change significantly.

The fact is that archaeological data can be better used and fully exploited with the use of AI. To perform a certain analysis, the archaeologist does not have to worry about completeness of records. In fact, for a well trained ANN, incomplete archaeological records may be read as a new combination of variables that may be used to produce an output.

One of the most important characteristics of ANN is their flexibility to be conformed and adapted to most different applications. In fact, ANN can be applied to almost every possible scientific area because their structure is based on simple primitive parts and their functionality of a basic principle. ANN units of the input layer can be used as abstract, physical or quantitative inputs. It is for this reason that input units can be adapted to every possible application. Theoretically, one might use as much inputs as needed to simulate the retina. The output can be very articulated as well. Similarly to human thoughts, ANN output layers are based on abstract principles and this facilitates the application to almost every possible scientific field.

It is for this reason that ANN might eventually be applied to a broad number of archaeological areas. There are however some obvious subjects where ANN can be used immediately. They can be classified in three distinct areas:

a) *Spatial Analysis and GIS*. Probably the most important area of interest, and eventually the most intuitive field would be GIS applications (DUCKE 2003). This depends on the fact that GIS raster model can easily be adapted to the input-output paradigm of ANN. In fact, this attribute of the raster model had for a long time been used to make quantitative models in GIS platforms. Every single raster layer can be conceived as an input unit. But also outputs can be translated into raster. The application of ANN will allow the archaeologist to develop extremely accurate predictive models.
b) *Artifact and object recognition*. Archaeology is mostly based on recognition and identification of taxonomic attributes (BARCELÓ, PIJOAN-LOPEZ 2004) applied to tools and artefacts. The comparison within artefacts is mostly based on human work. In order to determine whether a sample matches a certain category, there is a process that requires an intelligent agent. In any case such activity would be possible with traditional computing. With trained ANN, however capable to recognize the different characteristics of a certain tool, the user would be able to use in order to query large databases.
c) *Database querying and analysis*. Another potentially foreseeable field of

application will be database management. In fact, most of the archaeological task is based on database examination and match. But, as stated before, archaeological records do not have the same level of homogeneousness. As a result, the outcome of an archaeological database query may in most cases be inexact, no matter how accurately the logic structure is formulated. ANN may be used to formulate within traditional databases fuzzy and complex query not achievable with traditional SQL languages.

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7. THE ANALYSIS PROCESS

Usually, the tools needed for the application of ANN to spatial analysis processes are a GIS platform, a neural networks simulator and specific utilities that allow the user to connect these two environments.

The first application of ANN implemented by the ASIAA lab (Laboratorio di Analisi Spaziale e Informatica Applicata all'Archeologia: http://www.archeogr.unisi.it/asiaa/) was in the field of spatial analysis. It is for this reason that we started the development of different software applications to cover the entire quantitative process. Our first case study was the settlement pattern of medieval castles in Tuscany.

Castles may be imagined as entities located in a certain territory and every single settlement may be conceived as characterized by the variables of the territory where it stands. These can be environmental variables like elevation, slope, distance from watersheds, etc. There are however other kinds of variables, like distance from other settlements (i.e. towns, farms) or from raw materials. Thus, every single variable that characterizes a fortified village may be considered as an input for the ANN. It is by means of this specific procedure that an analytical approach, fully integrating not only the characteristics of settlement but also the features of its natural and cultural environment, can be performed. At the same time the output can be conceived as areas where a castle "may" or "may not" be settled. These two concepts allow the user to train the network in order to recognize variables that identify "existing castles" excluding areas with "no castles".

The problem of negative areas (or pixels) may be easily solved once the location of most of the castles is known; therefore the probability of picking randomly an actual site is very low. On the other hand, it is also true that the structure itself of neural networks has a high noise resistance capability that avoids most of the effects of this kind of issues.

8. THE STUTTGART NEURAL NETWORK SIMULATOR

The ANN simulator used for the study of medieval villages is SNNS (Stuttgart Neural Network Simulator). The choice was based on different motivations. It is an open-source software that allows the use of various types of architectures with different training options. It is also portable on almost every operating system and it has a user-friendly GUI.

However, adapting SNNS for archaeological analyses involves some software development. In this effort a great advantage is that all files used by SNNS are open format documents with a very simple structure. Moreover, SNNS includes a utility, snns2c, which allows for the conversion of a trained network into a C code function.

Using SNNS is very simple and permits a graphical design of the network: layers units, and connections. Once the network is created, it can be trained by feeding it with a training pattern file formed by input and desired output values. In this manner links weights will change (training) and the user can supervise the level of associated error on a graphical diagram. Once the network is well trained, it can be saved and fed with new patterns.

9. The GIS platform

Initially the GIS platform used for these analyses was ESRI ArcGIS. This software, used for a long time in our archaeology department, allows performing all the necessary tasks like creating rasters, filling point patterns tables with raster data values, etc. ArcGIS has a user-friendly GUI and it is used by many archaeologists. Very important is the recent addition of ArcToolbox that integrate in the GUI most of the powerful ArcInfo command-line tools.

Since the aim of this project was to implement a methodology applicable on different operating systems, and therefore with different GIS software, we decided to utilize standard file formats that allow performing this procedure on almost every platform.

To accomplish this task, it was decided to choose a file format functional on most common GIS applications: the choice was the ESRI ASCII grid file format. This is a simple text file composed by a header with the metadata, and a body that contains the actual data. ASCII rasters are also fully supported by GRASS.

10. GIS and Artificial Neural Networks

Beside "applications and formats", it was necessary to develop specific utilities able to join GIS functionalities (in particular the raster algorithms) and an ANN developed inside the SNNS simulator.

However our first "ArcGIS approach" led us to the creation of the first tool developed by the ASIAA lab: ArcANN, a user-friendly ArcGIS plug-in that allows the user to create SNNS pattern files directly from ArcMap. ArcANN was also able to convert different raster maps into one "data matrix file" for

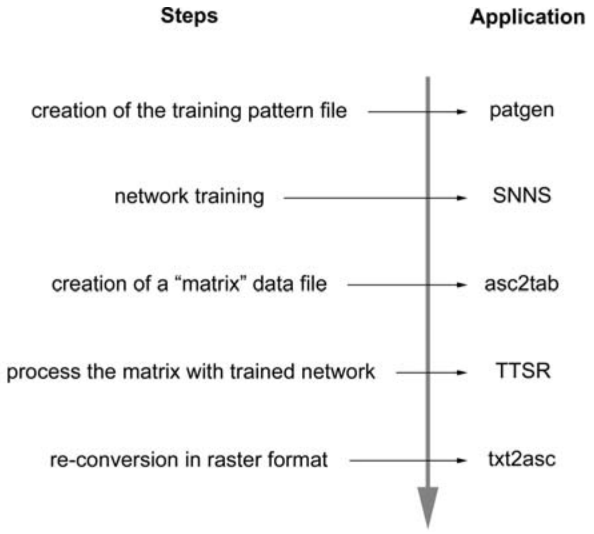

Fig. 2 – The analysis process is based on a 5 steps process. For most of them, specific applications where developed.

SNNS processing procedures. The utility was developed through ArcObjects, with Microsoft Visual Basic. But alongside the simplicity of VB development there was the issue of performance on huge raster maps and, obviously, another limit was also the portability of the code.

Due to all this concerns we started to develop stand-alone utilities written in C programming language, compiled both for Windows and Linux environments. Today these are simple command-line programs that allow the user to cover the entire processing task from GIS to neural networks and vice-versa.

This entire process is achieved via software and nowadays is based on 5 steps:

1) creation of the training pattern file;
2) network training;
3) creation of a "matrix" data file containing input values;
4) processing the matrix with trained network;
5) re-conversion of the processed data in a format readable by the GIS platform.

Each one of the five-step process described uses and is performed through different specific utilities (Fig. 2).

Patgen is a command line utility that allows the user to compile a SNNS training pattern file using those input variables that characterize the attributes of the settlement. Patgen has to be feed with two tab-delimited text files containing respectively input and desired output values. In practice all the variables employed in the network training, and hence embedded inside the pattern file, are taken from different raster layers. The output of a Patgen session is a .pat file that can be used to perform the network training on SNNS. Once the network is trained, the user can convert it to a fully C function with snns2c.

After the network training, a dedicated utility, asc2tab, will compile into a single tab multicolumn file several raster maps in ASCII. Asc2tab also reclassify raster values from -1 and 1 in order to comply and fulfil SNNS input signals requirements.

The third step is based on the TTSR utility. It reads and processes along with the code produced by snns2c utility the file produced by asc2tab. The output of the TTSR utility is a single column text file that the user can convert to an ASCII raster map with the txt2asc utility. In this way the user is able to view the results of the analysis directly georeferenced into his favourite GIS software.

11. Landscapes analysis

The analysis of archaeological landscapes is more than analysing "the territory"; this is especially true for Middle Ages simply because on that period the landscape was deeply correlated to settlement patterns (Ginatempo, Francovich 2000). The theories on this subject have reached a high level of complexity so that we must consider new methods that, integrated with archaeological data, may be useful for the understanding of ancient societies (Reeler 1996).

In this effort, spatial analysis represents a useful mean: in fact it can guarantee a high level of objectivity and synthesis (O'Sullivan, Unwin 2003). Traditional quantitative methods can offer many insights on ancient settlements patterns and their relationships with natural resources, their role in economy, structure of political powers, etc. Much has been written on early and late medieval settlement in Tuscany and a large number of quantitative methods and models were applied to this problem but unfortunately so complex arguments can be only partially understood with "classical" statistical methods (Macchi 2000a, 2001b, 2001c).

In the last years new methodologies and more specifically AI techniques had spread on the archaeological community. Certainly these methods can help the archaeologist on the process of archaeological data analysis from new perspectives. One of the most popular methods (maybe for its effectiveness and simplicity) are ANN.

ANN can combine a basic level of abstraction keeping all the characteristics of a standard quantitative approach. In fact one of the strong points of this method is that ANN can learn how to solve a certain problem by observing some examples. This procedure is at the base of the training phase and allows using sample data making ANN very useful for archaeological purposes. So it is important to feed networks with the most correct data as possible.

The application of ANN allows identifying with a high level of accuracy relationships and links between the settlement and its territory in a certain historical period. Moreover, it is possible to visualize the evolution of the settlement systems observing and comparing results in time-line.

12. ANN APPLICATION TO MEDIEVAL SETTLEMENT PATTERN ANALYSIS: PRELIMINARY RESULTS

Medieval fortified villages in Tuscany had been among the most important topics for the Archaeology Department at University of Siena (FRANCOVICH, MILANESE 1989). Medieval castles are still today object of quantitative analyses that have produced a vast amount of new information, and more specifically the characteristics of their spatial structure and organization (MACCHI 2001b).

The first attempts to apply ANN to the study of medieval villages' settlement pattern were made on small areas (about few square kilometres) and with few input values in order to improve software reliability.

Subsequently we selected the area of interest for analyses choosing the south-eastern part of Tuscany formed by the Provinces of Grosseto, Siena and Arezzo (Fig. 3). Among the first steps was the calculation and revision of the necessary rasters. This operation requires a long lapse of time due the fact that resolution is fundamental for a better and significant analysis outcome. It would be desirable to use, when possible, the highest resolution available.

The first examples were made with 50 and then with 10 meters pixels resolution only for a smaller territory portion. One of the problems, using huge raster maps, is the issue of performance, but yet on a mid-high scale we noticed the great precision increasing when using 10 instead of 50 meters pixels.

An important step forward is based on the assumption that not only the site location is important but also the values of surrounding areas. We can take these values simply performing a raster shift of desired meters. Almost every single value like height, slope, geology, etc. can be statistically integrated into a model that deals also with the surrounding areas. For medieval settlements, as well as for other periods in time, the characteristics of surroundings represent a primary piece of information simply because every rural settlement is not only a residence for human population but also a productive unit highly integrated with the territory. If it is true that settlement location is affected by geo-morphologic and primary resources variables, it is also true that hidden links, which can substantially determine settlements choices, do exist.

Looking at results of analyses performed using surrounding values, and comparing them with the previous ones, it can be noticed a remarkable increase of the predictive precision level. In Fig. 4 we can see differences between the

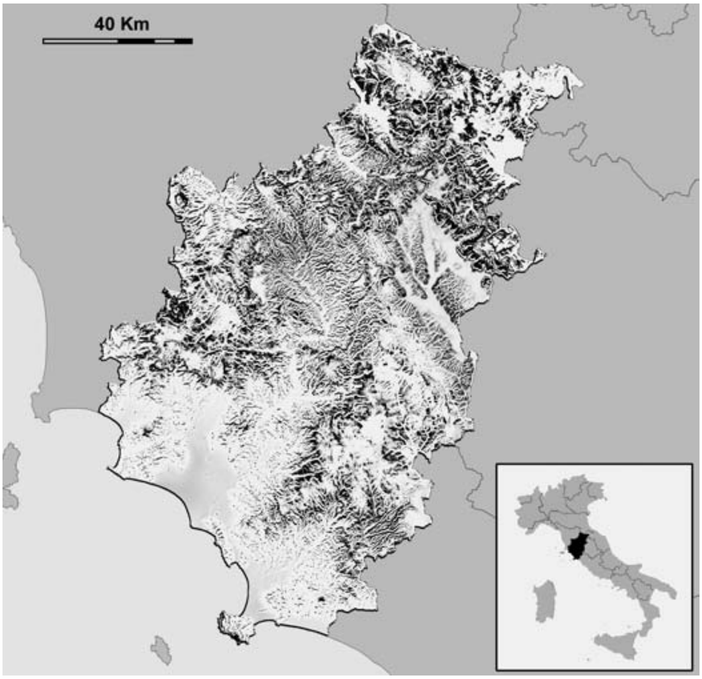

Fig. 3 – The analysis area: south-eastern Tuscany including the Provinces of Grosseto, Siena and Arezzo. This specific analysis was achieved with 14 input variables: cost distance from watersheds and from towns, slope, elevation (DTM) and the relatives 300 meters shifts (North, North-East, East...), their mean and standard deviation.

two analyses performed on castles settled before 1150 A.D.: the first one was made with a simple training pattern containing just morphological values. The second one was based instead on 14 input variables, including cost distance from watersheds and from towns, slope, elevation (DTM) and the relatives 300 meters shifts (North, North-East, East, etc.), their mean and standard deviation. In other words a wider description with values that represent in a much comprehensive way quality and features of each archaeological site.

Comparing the two results it can be noticed how the morphology of the site and the proximity to main resources (water, raw materials, etc.) are certainly very important for every kind of settlement. By means of this comparison it is possible to identify the hilltops where the largest set of fortified villages are located.

Another important aspect is the measurement of significance of this approach. Fig. 5 represents, for example, the sequence of ordered values for each castle taken from three different output raster surfaces (examples 1, 2 and 3). Each one of these lines represents the outcome of a different trained network.

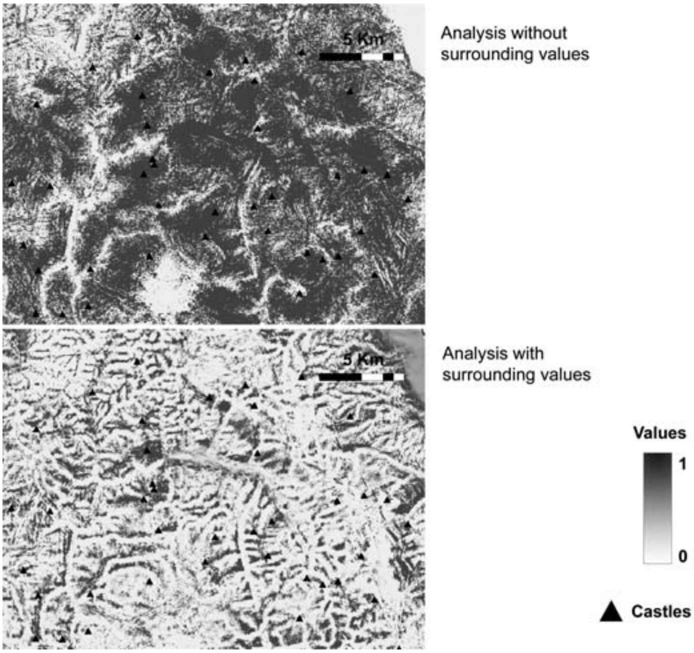

Fig. 4 – Differences between analyses performed without and with surroundings values. Areas with high values are smaller in the second screenshot, highlighting the increased precision of the analysis.

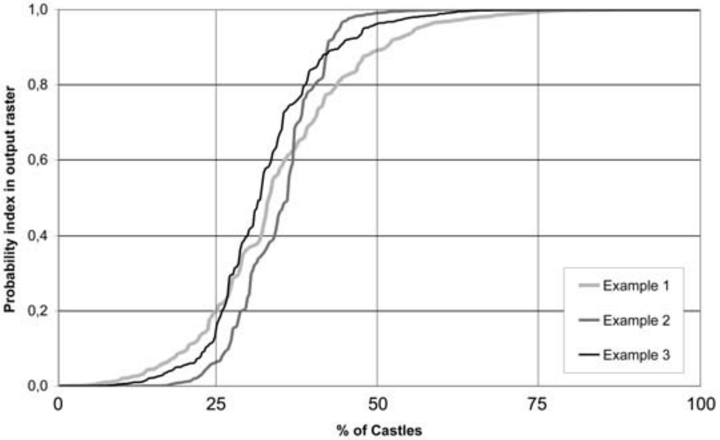

Fig. 5 – Comparison of analyses results using a line chart. Each line represents the sequence of ordered values for each castle taken from three different output raster surfaces (examples 1, 2 and 3). By some aspects this chart may be used as a significance measurement for different networks.

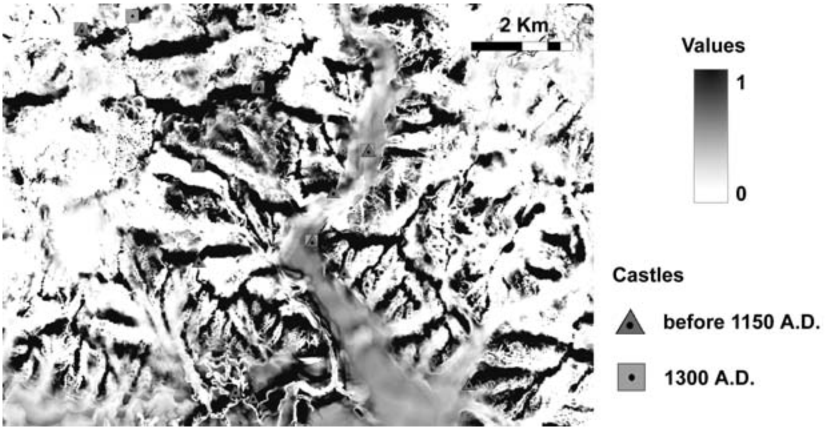

Fig. 6 – Detail of the analysis. Darker areas show a higher probability of castles presence even if the ANN is trained only on castles prior to 1150 A.D.

The three cases present differences in network structures (specially number of inputs) and training strategies (mostly number of cycles). For instance «example 1» was trained with less input values. As the chart points out, only 25% of castles present in the output raster pixel values equal to 1.0. At the same time «example 2» represents the outcome of a more complex network. In this case almost 50% of castles reach the highest level of probability (1.0). It is important also to notice that in all the three examples presented in Fig. 5 more than the 65% of castles had probability values higher than 0.5.

13. FINAL CONSIDERATIONS

We can assume that the real possibilities of the use of ANN in the archaeological research process are certainly still distant. At the same time, however, we may consider this experience and the specific results in a positive way. There is no doubt that there are numerous gaps both on what concerns the choice of variables and their utilization, and also for network structures and training algorithms which will give archaeologists a large number of possibilities to perform these analyses.

By means of ANN we can also examine relationships between castles of other periods. In Fig. 6 there is a detail of an area showing the results on early medieval castles, used in the training step, and the others of a later time, in this case XIII century.

The development of this procedure let us head to different aims: by application of ANN methodology it is possible to detect variables that apparently characterize the underlying invisible relationships between territory and settlement patterns in a synchronic way. By formal observation with the support of a GIS archaeologists may define the rules functional for training a network on a certain territory. Afterward, ANN may be used as a numerical model that may be applied in another territory in order to measure the similarities or differences between two settlement patterns. What is most important is that the link or association between the two archaeological areas will be based on a fully integrated model of the settlement system with his specific environment.

Furthermore, the numerical model will allow researchers to observe and compare results on the time-line. In fact a single model might help to understand the evolution of the settlement systems by identifying continuity, transformation or eventually interruption of settlement patterns trend and adaptation to the natural environment.

L.D.

LUCA DERAVIGNONE, GIANCARLO MACCHI JÁNICA
Laboratorio di Analisi Spaziale
e Informatica Applicata all'Archeologia
Dipartimento di Archeologia e Storia delle Arti
Università degli Studi di Siena

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ABSTRACT

Artificial neural networks are adaptive models that can be used for classification and pattern recognition purposes. ANNs do not differ from standard statistical models. The main difference between ANNs and traditional statistical models is their construction and definition process. In fact ANNs are adaptive in the sense that they can learn. Landscape Archaeology is a research area where the application of ANNs can be very useful. ANNs can be used for Landscape pattern recognition and Settlement systems modeling. This paper illustrate some aspects of the development of new tools and the application of ANNs in a raster GIS environment for archaeological predictive modeling purposes.