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Archaeonics - (Geo)archaeological studies in Anthropogenic Dark Earths (ADE) as an example for future-oriented studies of the past

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A R T I C L E I N F O

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A B S T R A C T

This review paper examines the potential of (geo)archaeological data of past human-environment systems to contribute to the development of sustainable land use and soil management strategies. Looking at past land use systems and their socio-economic background extends our understanding of the slow processes and low frequency events that appear to be the key in deciding whether land use systems lead to sustainability or to collapse. As an example, the paper focuses on so-called Anthropogenic Dark Earths (ADE). These highly fertile soils were managed or actively created by ancient cultures in different regions of the world. Since they are rich in humic matter and carbon, and are highly stable to biochemical oxidation, they appear very relevant both as a model for sustainable soil and land management systems and as a tool for climate change mitigation on different scales - local as well as global. The paper argues in favor of a historical perspective to learn about risks and possibilities of land use strategies. We propose a co-adaptive transdisciplinary problem-solving approach ("Archaeonics"), which includes the study of the past as well as respective technical and social implications for the future.

1. Introduction: facing the challenge of food insecurity, climate change and energy demand?

The world is currently facing one of the biggest challenges in human history. By the year 2050, the world population may increase to almost 10 billion inhabitants in view of current projections (FAO, 2017). The pressure on agricultural soils and the need for freshwater will continuously increase. To feed this growing population, harvest yields will have to rise by 30% by 2030, and by as much as 70% by 2050. However, several 100.000 km^2 of agricultural land are currently lost by degrading through soil erosion, soil salinization, soil acidification and soil compaction every year. The opening of new land by conversion of natural ecosystems to cultivated lands causes approximately one quarter of the global, anthropogenic CO2 emissions (Houghton, 2003). Exacerbating the environmental impact of intensive agriculture, an additional burden on the soils will arise due to the increasing competition of energy crops and the effects of climate change, thereby leading to further problems in resource protection and to unpredictable challenges in food security and energy demand (WBGU, 2009).

During the last 100 years yields have been increased by intensifying land use, which was made possible by investing an increasing amount of fossil energy used for fertilizers, pesticides and machines (Foley et al., 2005; Uekötter, 2010). In contrast, pre-modern agriculture had to be based on “green energy” as well as on closed material cycles. Based on small, structured field systems and associated small scale nutrient cycles have been transformed into a highly organized industrial food production with large fields and high energy consumption. Presumably former subsistence land use systems were therefore closer to the idea of sustainable agriculture than modern systems are.

The current situation requires new types of ecologically and socio-economically sustainable agro-ecosystems, adapted for high production efficiency. Such systems should contribute to soil conservation, soil amelioration, humic formation, reduced water consumption, long-term carbon sequestration, nutrient retention, contaminant binding, and to biodiversity (FAO, 2017; Millennium Ecosystem Assessment, 2005), thereby presenting a huge challenge to all disciplines ranging from the humanities to natural sciences and engineering.

This article begins with a short overview of the scientific background and methodological challenges met in archaeology when it comes to reconstructing long-term effects of land use and climate on the landscape and human-environmental feedbacks contained within it. For the analysis of long-term processes we discuss the use of resilience theory, the linked adaptive cycle metaphor and the panarchy concept which has developed from it. These concepts include trajectory and

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attractor analyses providing a heuristic approach to describe processes, patterns and mechanisms in past human-environment systems. An example of how the knowledge on past land-use systems can be applied in modern land use systems will be demonstrated with the Anthropogenic Dark Earth (ADE). These black colored and highly fertile soils can be found at many ancient settlement and farming sites worldwide. Understanding how ADEs were formed and managed provides helpful information to develop innovative adaptation strategies and techniques for modern sustainable land use systems.

1.1. Applied archaeology

In the last decade there have been several pleads and attempts to use the experience of the past in order to develop a sustainable future (Diamond, 2013; Dearing et al., 2015), mainly coming from geosciences. Exploration of past soil management techniques like horticulture or irrigation systems holds considerable potential for a better understanding of how sustainability can be achieved. It addresses technical systems and circulation oriented managing of water, waste, energy and resources in ancient, advanced, agrarian societies, which probably possessed elaborated land management and market systems to supply a considerable urban and nonagricultural population. Such ancient systems with high adaptation potentials can be found for example in (i) Raised Fields systems in the Amazon Basin and the Andes (Denevan, 2001), (ii) Floating Gardens in Central America (Arco and Abrams, 2006) or Bangladesh (Irfanullah et al., 2008), (iii) Agroforestry in the Andes (Chepstow-Lusty and Winfield, 2000), or (iv) the Anthropogenic Dark Earth in the Amazon basin (Glaser, 2007) or in Central Europe (Eckmeier et al., 2007). In recent years, several authors have argued that such research on past land use systems is relevant for the present. For example, Bürgi (2008) presented a case study on litter collecting in traditional forest use in Central Europe and claimed historical ecology as a concept for a) preserving the cultural heritage in ecosystems and landscapes, b) understanding historical trajectories of patterns and processes in ecosystems and landscapes, and c) enhancing ecosystem and landscape management. Another approach which received some attention is the attempt to expand Long Term Ecological Research into Long Term Socio-Ecological Research LSTER (Collins et al., 2010; Haberl et al., 2006; Singh et al., 2013). Also, Casado and de Molina (2009) presented a strong case for studying pre-industrial land use systems in order to learn for and augment current organic farming methods.

Important impact came from the rather popular publications of Jared Diamond, who caught attention for collapse (Diamond, 2006) and the role of traditional knowledge (Diamond, 2013). Diamond highlighted the role of vulnerability to climate change, environmental maladaptation or a mixture of both. In reaction various publications by historians and archaeologists showed several inconsistencies in Diamonds' examples (e.g. McAnany and Yoffee, 2010). They made clear, that an adequate assessment of past situations requires detailed historical and archaeological studies. As a consequence the contribution of archaeology for present and future development became a matter of debate.

Basically the contribution of Erickson (1998) emphasized for the first time the potential of archaeological data to develop strategies for the future. He introduced the term "Applied Archaeology", which he defined – in contrast to some different application of the term referring mainly to professional practice - as the anthropologically informed study of the human past, primarily through material remains, with a goal of employing the knowledge gained from this research to improve (Erickson, 1998, 34f.). His own work was based in the Andes, where he developed his ideas related to raised field agriculture. Rather occasionally his field work resulted in a successful rehabilitation of pre-Columbian agrarian techniques. Mainly based on his work, Guttmann-Bond (2010) sketched in her article on "Sustainability out of the past: How archaeology can save the planet" this new research area. Besides the raised fields in Southern America she also dealt with the "rainwater harvesting" in the Negev desert and the terra preta phenomenon. In the meantime there are even some more projects promoting learning from the past. When the first raised fields were recreated successfully in the framework of single families, soon their neighbors and finally several NGOs voluntarily took over the raised field agriculture which was promoted as traditional agriculture despite of the fact that there was no continuity. The fields were abandoned at the end of the 1st millennium AD and as there was no detailed information on their land management, it was rather experimental archaeology. Some years later, many of the projects of rehabilitation failed, just a few are still working. Within a review of these projects Bandy (2005) concluded that a major factor of the failure was based in the social organization. Whereas modern NGOs promoted common land within cooperatives, the historical framework was that of a central state probably involving slavery. In more details Erickson (Erickson, 2006, 326) referred to a couple of social reasons as the competition for labour and questions of land property, but also to some changes in the land use practices- Modern farmers transferred their traditional cycles of long-term fallow on the raised fields, which in consequence decayed. Furthermore modern farmers were not able to go back to the genetically adapted plants of precolumbian times, which have been lost (Khalaf, 2014).

When the state of Israel was founded after WWII most immigrants had few agricultural experiences, especially not in the semi-arid climate of the region. However since the Middle Ages travellers recognised fossil field systems indicating the possibility of farming even in unsuitable conditions. Already in the 19th century ancient irrigation systems close to Jerusalem were reactivated (Khalaf, 2014) and therefore it was obvious to study also the traces of past land use in the Northern Negev desert. Close to the Byzantine desert towns there are various traces of past agriculture also including ADE (Bruins and Van der Plicht, 2017). Field systems within the wadis were related with complex stone structures used to catch rain water during the few rains (Schreg, 2017). A special research program dealt with the archaeological traces and experimented with the recreation of that system (Evenari et al., 1971). These experiences were later used for developing agricultural strategies in Africa (Bruins et al., 1986). Nowadays however, modern agriculture in the Negev region is based on fossil water, which is extracted with a high energy input and results in the risk of salination.

Other projects of applied archaeology also deal with water management. There are several archaeological projects around the world, indicating an increasing interests of archaeologists in 'understanding the past to help the future" (Kaptijn, 2018, 2). In Tanzania for example the "Engineers without borders" apply traditional knowledge for a project providing clean water cisterns (Ingenieure ohne Grenzen e.V. 2017). Guertler et al. (2015) refer to this project in order to emphasize the role of an archaeology-inspired design: "In the presented case study of the cistern project in Tanzania, the identified archaeological solutions provide robust and affordable cistern designs suitable for the modern context factors in Tanzania. They demand low requirements for the training of local workers, building technics and the availability of materials." There is little information how this transfer was realized, but obviously many practical problems as for example the regular cleaning of the cisterns benefited from the analysis of Roman and Punic cisterns and wells in Northern Africa.

All these examples were engaged with green technologies aiming for sustainable land use strategies avoiding the traps of modern industrial agriculture. A German citizen science project, however, shows some more potential. Based on a rescue excavation, which revealed the remains of a Bronze Age wall of wattle and daub, they experimentally reconstructed a multilayer construction with thermal insulation. Thermal efficiency of this wall was able to compete with modern solutions (Staeves, 2007). Whereas this research did not direct to an applied archaeology, research on Roman concrete found some technical aspects of Opus Caementitium which could help to improve modern concrete (Jackson et al., 2013).

Though, besides these technical aspects (geo)archaeological data are important for a risk assessment. Archaeological and historical information on extreme weather events in the 14th century challenge modern flood protection, as they show, that there is the possibility of flooding far over the water levels of the last few centuries. Similarly the assessment of the Basel earthquake in 1356 (Fäh et al., 2009) provides interesting data for the risks of nuclear plants in Switzerland and Alsace. Regarding the question of sustainable land-use, (geo)archaeological research helps to identify long-term risks, but also to gain some experience about the societal preconditions for dealing with agrarian landscapes. A project dealing with African agriculture in Northwest Kenia aimed not only to reconstruct and reuse old irrigation systems, but also to develop some recommendations for action for development aid (Davies, 2012). They included for example to grant the local people regional flexibility, as this was an important strategy in the past to deal with climatic and economic challenges. Instability at the local scale proved to be a precondition of long-term stability at the scale of regional society. Davies understood this research as part of “useable” or “applied archaeology”, which did not aim for specific technical solutions. Instead he aimed to show, that an analysis of long-term changes within local socio-economic systems can help to current topics of food safety, sustainability and future development.

Applied archaeology therefore comprises exploratory knowledge, risk assessment as well as technical developments based on experiences from the past.

Archaeologist Guttmann-Bond (2010) argued that some of past agricultural techniques “are not only more sustainable than modern technologies, but more resilient in the face of environmental extremes. Ancient engineering and agricultural methods are often more appropriate for developing countries than modern technologies based on fossil fuel and imported materials.” Erica Gutmann-Bond as well as Eva Kaptijn (2018) emphasized the potential of past data and the role of the archaeologists. Kaptijn especially referred to the long-term perspective provided by archaeology.

However, their optimistic view is not common opinion within archaeology. Eggert (2006, 257) emphasizes, that it is not the task of archaeology “to participate in public discourse or coping with problems of the future. He stressed that archaeology is of no use to teach us for life, because in general archaeology “provides neither a sufficiently detailed database nor qualified information about the social contexts“ (Eggert, 2006, 257).

Regarding the challenges of the future and an increasing pressure by the public and by politicians on the humanities to show their relevance the trend towards an applied archaeology will continue. We therefore need to discuss methods and standards to cope with the emerging responsibility. On the one hand we need to reflect the preconditions and consequences regarding our ideas of historical specificity and anthropological structures. On the other hand we need to reflect the way, how an applied archaeology has to be integrated into a transdisciplinary research program.

2. How can we learn from the past?

There is however little understanding and experience, how we can learn from the past. This is not the place to get into the philosophical debate whether humanity is able to learn from historical experiences (e.g. Nietzsche, 1994). Regarding the challenge of developing a sustainable future we rather face the methodological questions, how we could practically gain useful data, how we can identify past land-use strategies, how we can reconstruct them detailed enough to recreate them and how we can assess their sustainability in the past as well as in the present situation. This approach of an “applied research on the past” could be labeled as “Archaeonics”, somewhat analogue to bionics. It aims to provide possible implementations to develop modern sustainable land use systems to mitigate the environmental problems of today and in the future.

The challenge to understand the relationship between ancient human and natural systems over the long term in order to develop a more sustainable approach to human-environment interactions in the future has prompted several international research initiatives like IHOPE (Costanza et al., 2007), IGBP-PAGES Focus 4 – (Dearing et al., 2006b) or the Global Human Ecodynamics Alliance (GHEA, 2018). The overall general research questions and goals of these initiatives can be summarized as follows:

- What are the complex and interacting mechanisms and processes resulting in the emergence, sustainability, or collapse of coupled human and natural systems?
- Which data, models and frameworks are feasible to analyze pathways and process patterns of coupled human and natural systems?
- How can we utilize the results of this research for practical problem solving that contributes to a more sustainable and livable future?

By now, there are very few successful examples demonstrating how the study of the past can be applied to modern ecological land-use systems (Schreg, 2016). Researchers from the humanities are very skeptical with regard to the possibility of learning from the past, because in their eyes, historical situations are too complex and unique. Interpretations of the past emphasizing natural and ecological factors are often labeled as deterministic or ahistoric, because generally, they do not take human agency and social behavior into account. Indeed, modern societies are much more complex and modern technological possibilities are more elaborate. However, past societies had no better ecological ethics and the sustainable and ecological way of life of indigenous people is a myth in most cases, although some societies were certainly able to maintain their way of life and culture over many centuries or generations. Furthermore we may still underestimate the ecological effects of pre-industrial land use. Medieval agrarian history for example, which still today is primarily seen as a story of technical progress and technical improvement of food production, may have been an important factor of the 14th century crisis as the cultural landscape became vulnerable against heavy weather events and may have backed the spread of epidemics among rodents, husbandry and humans (Campbell, 2016).

To learn from the past, it is neither possible nor sufficient to just copy past strategies. The value of a historical approach lies in understanding more about the long-term risks resulting either from the internal development of agro ecosystems or from external factors such as climate, extreme weather events or other natural catastrophes.

We therefore need some methodological guidelines, which help to transfer data from the past to action for the future. From an engineer perspective Guertler et al., 2015 sketched six methodological Steps towards an application of archaeological knowledge (Table 1).

From their perspective the search for archaeological analogies – based on publications and personal communication with experts – results in a similarity matrix (Fig. 1) which systematically compares the modern technical problem and the solution concept identified in the archaeological record. It especially considers among other criteria the specific function and context of the archaeological evidence, which they compared with the modern technical requirements.

Table 1
Six methodological Steps towards an application of archaeological knowledge (after Guertler et al., 2015).

1	Analyze a modern engineering problem
2	Create a problem model
3	Search for archaeological analogies
4	Identify archaeological solution concepts
5	Transfer and adapt solution concepts
6	Select a technical solution.

Table 2
Possible criteria for studies in applied archaeology (Davies, 2012).

1. Long-term analysis of the human environment dynamic
a. Analysis of changing land-use patterns; identification and dating of landscape features such as field boundaries, agricultural terraces, irrigation channels, wells, etc.
b. Analysis of ongoing long-term demographic trends; settlement patterns, population sizes and population densities, etc.
c. Analysis of anthropogenically modified soils and vegetation (including improvement and degradation)
d. Analysis of past crop/animal varieties, combinations and novel management strategies
e. Analysis of ongoing regional networks of production, exchange and support acting within and beyond the community level
f. Analysis of cultural systems of access to land (tenure) and inheritance
g. Analysis of ongoing climatic trends and reciprocal human impacts/responses
h. Assessment of past vulnerability to climate change
2.Assessment of environmental narratives
a. Challenging current (and past) environmental narratives (especially those used in development discourse) using archaeological data
b. Providing long-term environmental data-sets to compliment or critique short-term experimental data
c. Developing critical approaches based on long-term data to widely used concepts of adaptation/maladaptation, sustainability, resilience, optimality, 'pristine/natural' environments, stasis/equilibrium etc.
3. Rehabilitation and Indigenous knowledge
a. Rehabilitation of past land management strategies
b. Archaeological analysis of past or ongoing environmental practices/technologies and knowledge and their assessment as possible solutions to modern problems
c. Recovery of past indigenous knowledge (IK) as novel contributions to stores of environmental knowledge
4. Recursivity and scale in socionatural systems
a. General elucidation of long-term continuity and change in socionatural systems with reference to concepts of non-equilibrium, sustainability and resilience
b. Analysis of the temporal and spatial scales of socionatural phenomena especially quantification of rates of change (constant, accelerating, decelerating, scalar) and modes of fluctuation (i.e., linear, scalar, cyclical)
5. Memory and risk management
a. Analysis of community inscription of environmental risks through heritage and memory making
b. Analogous analysis of community impacts and responses to environmental risk in the past

In order to identify valuable archaeological data some solid criteria are needed. A first approach is provided by the study mentioned in chapter 1.1 above on agriculture in Kenia, where a list of possible criteria has been developed (Davies, 2012) (Table 2):

A crucial point within these suggestions is the fact that we need to know whether the archaeologically identified strategy or technique was finally successful. Archaeology on the one hand can trace long-term processes, but on the other hand there is the challenge of assessing cause and effects. Furthermore the definition of sustainability becomes more difficult, as we need to consider or more clearly define environmental, social, economic, and cultural dimensions on different spatial and temporal scales.

2.1. Understanding long term human-environment interactions - scientific and methodological challenges of an applied research on the past

Exploring the processes and linkages of human-environment interactions is perhaps one of the most complex challenges in science. While recent processes can be directly monitored, historical data are generally fragmentary and hard to acquire. Long-term socio-ecological systems can be studied at different time scales, from decadal to millennial (Costanza et al., 2007). Depending on the studied time scale, completely different sources (archaeological, written, pictorial, or oral) and methods need to be employed – and the approaches vary accordingly. Despite these problems, the benefits of investigating past systems can be of enormous value for revealing slow processes and low frequency events that ultimately appear to be the key to system resilience. Only on a long time scale, from centennial to millennial, is it possible to detect thresholds, legacy effects and historical dependencies of the background processes in human–environment systems. Seen in this light, the paradigm of sustainability may become distinct spatial, temporal and societal points of view. For example, on a decadal timescale a particular system may be sustainable but on a longer term it produces „risk spirals" – runaway processes with a repetitive pattern of problem-solving that create new problems with increased risk – a pattern which can be observed throughout human history (Sieferle, 2006; Sieferle and Müller-Herold, 1997). Hence, human-environment systems should be analyzed from a number of alternative perspectives of durability, stability, robustness and resilience. Computer modeling, especially agent-based modeling (Johnson et al., 2005) may provide a powerful tool, because it allows the integration of human agency (in particular decision-making) into models as active contributory factors (Axtell et al., 2002; Bankes, 2002).

Previous and current research on past human-environment systems has mostly been carried out by correlating archaeological data, historic

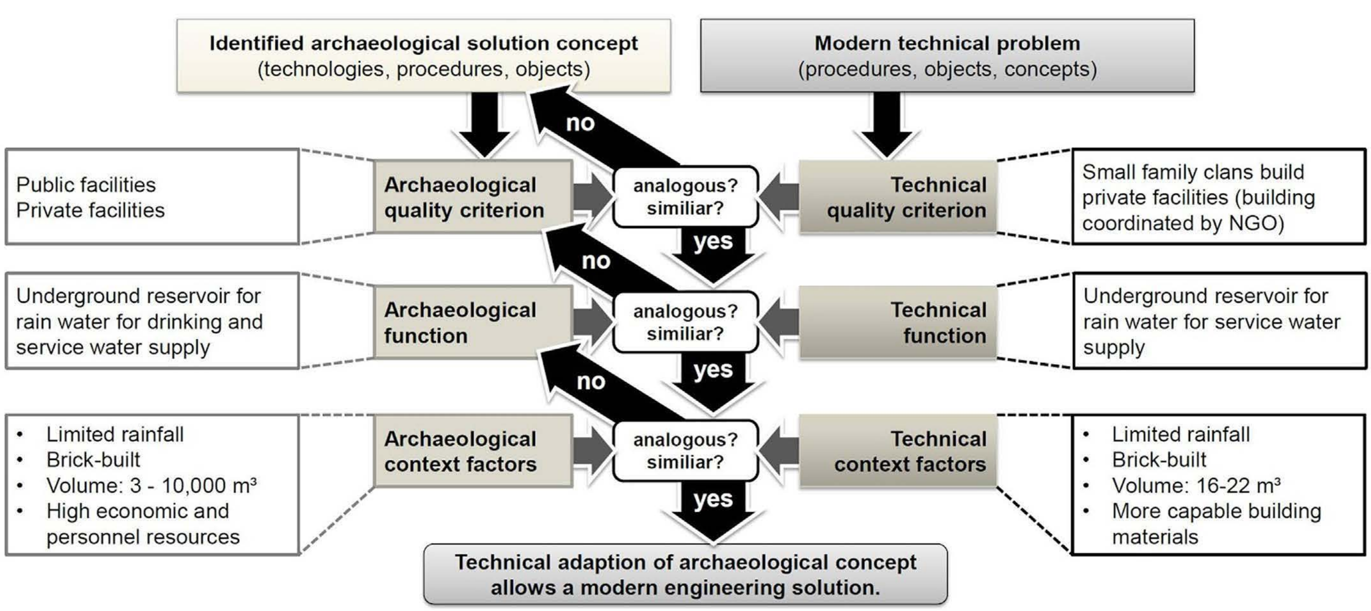

Fig. 1. Similarity Matrix in the Archaeonic approach (adopted from Guertler et al., 2015).

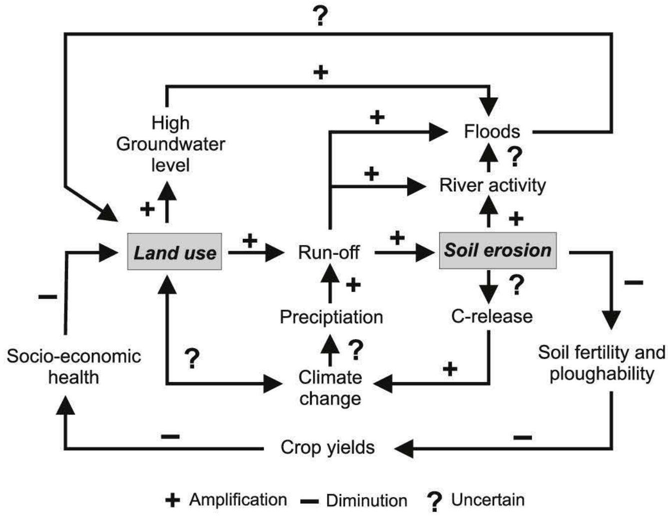

Fig. 2. Short-term and long-term human-impact interactions between land-use and soil erosion. The evolving system will change over time, causing positive and negative feedback loops (Dotterweich, 2008).

records and palaeoecological reconstructions. For example, case studies on the development of soil, relief and river systems led to a better understanding about the long-term effects of land use and climate on the landscape. The majority of these studies indicate that in humid regions sediment fluxes are highly sensitive to changes in local land use, while climatic changes only play a secondary role. On the other hand, peaks of soil erosion can be shown to be linked to phases of high land-use intensity and extreme rainfall events set off by rapid climate change (Bork et al., 1998; Dotterweich 2008, 2013). These studies also show that the long-term effects of past land use trigger renewed activity of river systems and manifestation of flooding (Hoffmann et al., 2011). However, too little is known about the feedback mechanism of land-use changes to society (Fraser, 2010) and climate (Kaplan et al., 2010; Ruddiman and Ellis, 2009). Most recent studies combine and correlate different time series, assuming causality and neglecting the legacy of past forcings and responses as well as human (re)action. Human-environment systems must be understood as complex systems (Fig. 2). They exhibit self-organization in the form of emergent phenomena: forms and structures that have evolved only through a network of process interaction within a set of boundary conditions (Hergarten, 2002). Future approaches have to be developed further to be able to distinguish proximate from ultimate causes more reliably, delivering a new understanding of the behavioral nature of complex systems. In the field of historical socio-ecological research, discussion about human-environment interactions started about 50 years ago. In order to achieve more general insights and to understand ecosystems in considerable detail, it has been necessary to draw analogies from the past and apply them to the present and vice versa. This requires a comparative approach and large scale „macro-theories". For many colleagues working within the research traditions of history – and to some degree of the humanities more on the whole – such generalizing theories do not seem to be adequate to analyze human societies or historical situations. As a result, models trying to explain cultural and ecological changes are rare (Butzer, 1982; Sieferle, 2008b; Sieferle and Müller-Herold, 1997). Many social scientists, historians and archaeologists trained in the past 50 years are critically aware of discourse and context, making any grand explanatory theory for something like "the rise and fall of civilization" or "how society is vulnerable to climate change" wildly unpopular (Fraser, 2010). As a consequence, implementing the „Archaeonics" concept seeks to integrate quite different perspectives to provide a unified conceptual framework acceptable in different disciplines from the humanities to the natural sciences. However, any approach aiming to contribute to the solution of current ecological problems needs a transdisciplinary basis that is able to support and promote the transfer of methods and concepts into other, more practical disciplines such as eco-engineering. Therefore a first requirement for an Archaeonic approach is an adequate theoretical framework, which we suggest should be a system theoretical concept that enables an analysis of processes and trajectory patterns of change according to the dynamics and feedback-mechanisms between land use and vegetation, soil, water, energy, and climate. Secondly, to avoid a deterministic ahistorical understanding we need to integrate an agent's perspective into this model to understand specific historical situations. In particular, this human dimension recognizes how the environment influences the preferences and decisions taken with regard to adaptive strategies, risk minimization and innovation by past societies.

However, this approach is far from trivial and research is needed how to implement the agent's perspective into an applied research on the past. Finally, we need to know as many details as possible of past land use practices to enable the modeling (rather than reconstruction) of former land use strategies which can then be applied to modern socio-economic ecosystems.

2.2. Binding together theories and data in natural sciences and humanities

As a framework for these theoretical needs, we propose to use a time-sensible ecosystem approach. To understand the processes of systems change, the Panarchy concept seems to be adequate. Panarchy theory explains the changes of complex systems based on their complexity (connectedness), their potential and stability (resilience versus vulnerability) (Gunderson and Holling, 2001; Liu et al., 2007; Redman and Kinzig, 2003) (∞-figure in Fig. 3). Resilience theory and the linked adaptive cycle provide an effective way to illustrate the interconnections between climatic, environmental and social trajectories. The Panarchy concept describes the process of (1) exploitation, characterized by rapid seizing of recently disturbed areas or resources [r-phase] (2) conservation, described by slow accumulation and storage of energy

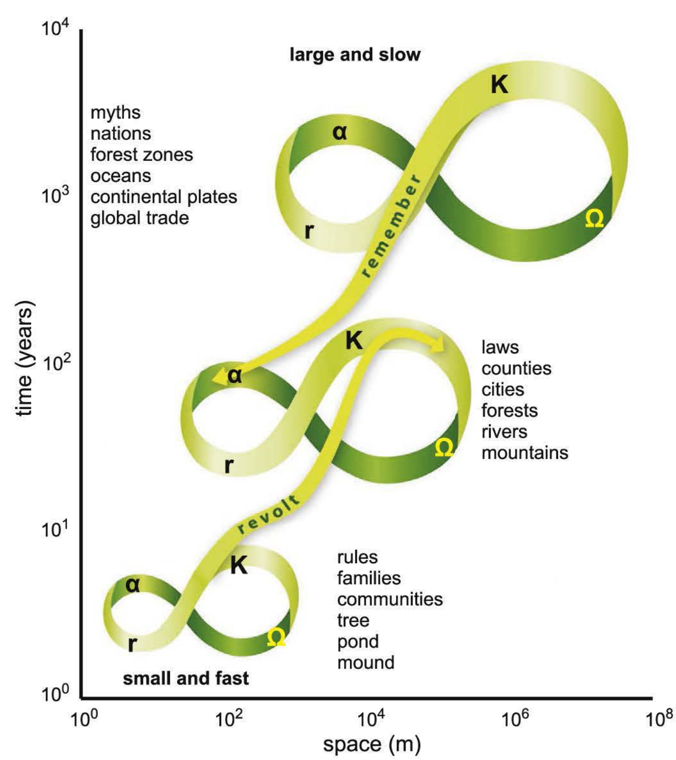

Fig. 3. The Panarchy metatheory composes nested adaptive cycles demonstrating the interplay between fast and slow variables operating at different spatial scales (Gunderson and Holling, 2001, modified).

and material [k-phase], (3) release, during which tightly bound accumulated mass becomes increasingly fragile until it is suddenly released by external agents [Ω-phase], and (4) reorganization, in which resources are reorganized into a new system [α-phase]. Derived from studies of “natural” ecosystems such as lakes (Gunderson et al., 2002), there have been also some studies of human ecosystems, showing their fruitful contribution reconsidering the sustainability of human societies (Schreg, 2011). However, based on the adaptive cycle, the Panarchy concept transforms the adaptive cycle concept to a metatheory (Fig. 3). Panarchy theory assumes the existence of countless systems of different scales in time and space as well as of different character (biological, socio-economic, institutional, etc.), interacting with each other by permitting transitions to other cycles and the changing and reorganization of cycles at different connected, hierarchical levels (Gunderson and Holling, 2001). This framework provides a holistic integration of archaeological, palaeoecological and historical data over long time scales. It allows another perspective on already well-known phenomena and processes, thereby helping to distinguish proximate from ultimate causes and additionally, it drives the creation of new hypotheses.

For example, to map these process patterns in detail, biophysical, archaeological, and historical data and proxies need to be built into each phase space. The resulting bivariate or multivariate plots show a temporal sequence of points as a trajectory. Fig. 4, for instance, shows the relationship between land use and soil erosion in lake basin catchments in SW-China over the past 3000 years (Dearing, 2008). The trajectory starts from a non-degraded „steady state“ through a transition period leading to the modern degraded „steady state“. It also includes the capacity to show possible future trajectories of landscape recovery. In other systems, such a trajectory can be described verbally, graphically as well as deterministically. Hence, this method permits (i) the combination and integration of data, proxies or realistic assumptions from socio-economic processes, climate, weather, settlement history, and land use history into a single coherent model, (ii) the description of behavior patterns of past processes and (iii) a tool to estimate the probabilistic conditions of future coherent behaviors (Dearing, 2008). The amalgamation of trajectory analyses into the adaptive cycle provides the basis for examination of legacy effects, time dependency, thresholds, slow processes, and low frequency events. Therefore it provides new insights into the long-term processes of human-environment systems (Dearing, 2008; Gunderson and Holling, 2001; Holling, 2001; Redman, 2005). These models are extremely valuable since they provide a better understanding of the creation of sustainability or the reasons for failure of particular systems. The evaluation of probabilistic conditions of coherent behaviors yet to be seen

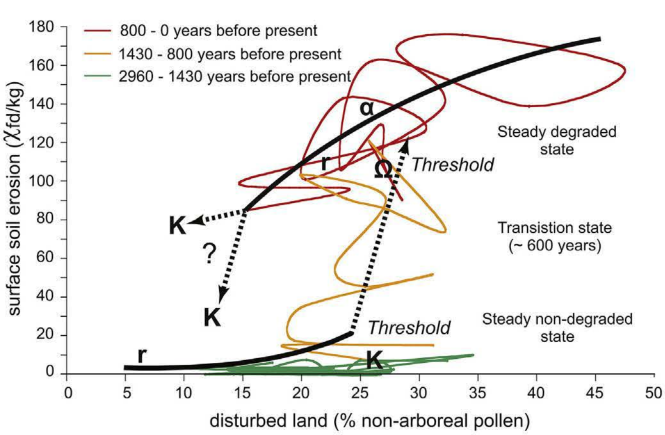

Fig. 4. Bivariate plotting of trajectories displays the patterns of stability and transition processes in an adaptive cycle and allows the detection of legacy effects, time dependency, thresholds, slow processes, and low frequency events (Dearing, 2008, modified).

contributes to the evaluation of sustainable land use policies in the future.

2.2.1. *From the past to the future - lessons from the anthropogenic dark earth (ADE)*

Bringing together studies on long-term human-environment interactions focusing on land use and soil management strategies for the development of modern sustainable land use schemes, this example examines the phenomenon of the Anthropogenic Dark Earth (ADE). The most prominent and well investigated example of an ADE is the Terra Preta do Indio which occurs in small patches up to 20 ha in the Amazon basin (Glaser, 2007). These black colored anthrosols were managed by the Amerindian populations in pre-Columbian times approximately 500–2500 years ago (Glaser, 2007). They are very fertile and particularly resistant to biogeochemical oxidation (Glaser and Woods, 2004; Woods et al., 2009). Compared to the surrounding tropical soils, Terra Preta soils have, on average, a three times higher content of soil organic matter, higher nutrient levels, a markedly high cation exchange capacity and a significantly greater water retention capacity. Terra Preta soils contain exceptionally large amounts of pottery fragments and a high content of charcoal and stable organic matter as a result of biomass charring. Charcoal and black carbon improve the retention of all nutrients due to a greater cation exchange capacity and present a habitat for fungi and bacteria. The nutrients derive from excremental material, bones, ash residues, and plant biomass. Despite numerous biogeochemical and archaeological investigations, it is still unclear whether the Terra Preta is the result of accidental accumulation of organic matter or whether it was formed by an intentional enrichment aimed at supporting intensive semi-permanent agriculture (Arroyo-Kalin, 2009; Glaser et al., 2004).

Despite of groundbreaking success of archaeological research in recognizing pre-columbian settlement pattern and field structures in the Amazon basin (Heckenberger et al. 2003, 2007; Denevan, 2001) we still have little information about the socio-economic structures of the past societies. Despite of previous ideas of a low carrying capacity of the Amazonian rain forest, archaeology developed a new model that suggests complex regional societies, locally dense populations, intensive cultivation, fertile anthropogenic soils, and considerable anthropogenic landscape changes (Denevan, 2012, 17).

There is a high risk to succumb to the myth of the Indians in harmony with nature. A BBC documentation on terra preta (BBC, 2002) for example showed life-like reconstructions depicting the indigenous farmers in an angel like romanticizing style reviving the idea of noble savage. In any case, there is a collapse in the pre-Columbian land use, which has been related by a chronological correlation of the regional series of radiocarbon dates with the arrival of the first Europeans. Whereas the earliest Spanish sources report about flourishing settlement along the Amazon river, later travelers found nearly uninhabited forests. It is a plausible hypothesis, that the first European contact caused devastating epidemics. In any case we don't have information, how an anthropogenic terra preta do Indio may have been integrated into social practice and we also don't know about their long-term sustainability.

2.3. *Using modern anthropogenic dark earth to develop sustainable soil management*

Beside the Terra Preta in the Amazon basin, several other areas with highly fertile, black soil have been described or are in discussion with regard to their anthropogenic formation. Such areas can be found in different regions of Europe, the west coast and near the Black Belt region of the USA, as well as in Guinea, Namibia, and Easter Island (Eckmeier et al., 2007; Fairhead and Leach, 2009; Frei, 1980; Lehmann et al., 2003; Mieth and Bork, 2003, Fraser et al., 2014, Wiedner et al., 2015). Even in many urban areas, buried dark earth layers have been discovered during archaeological excavations (Macphail et al., 2003).

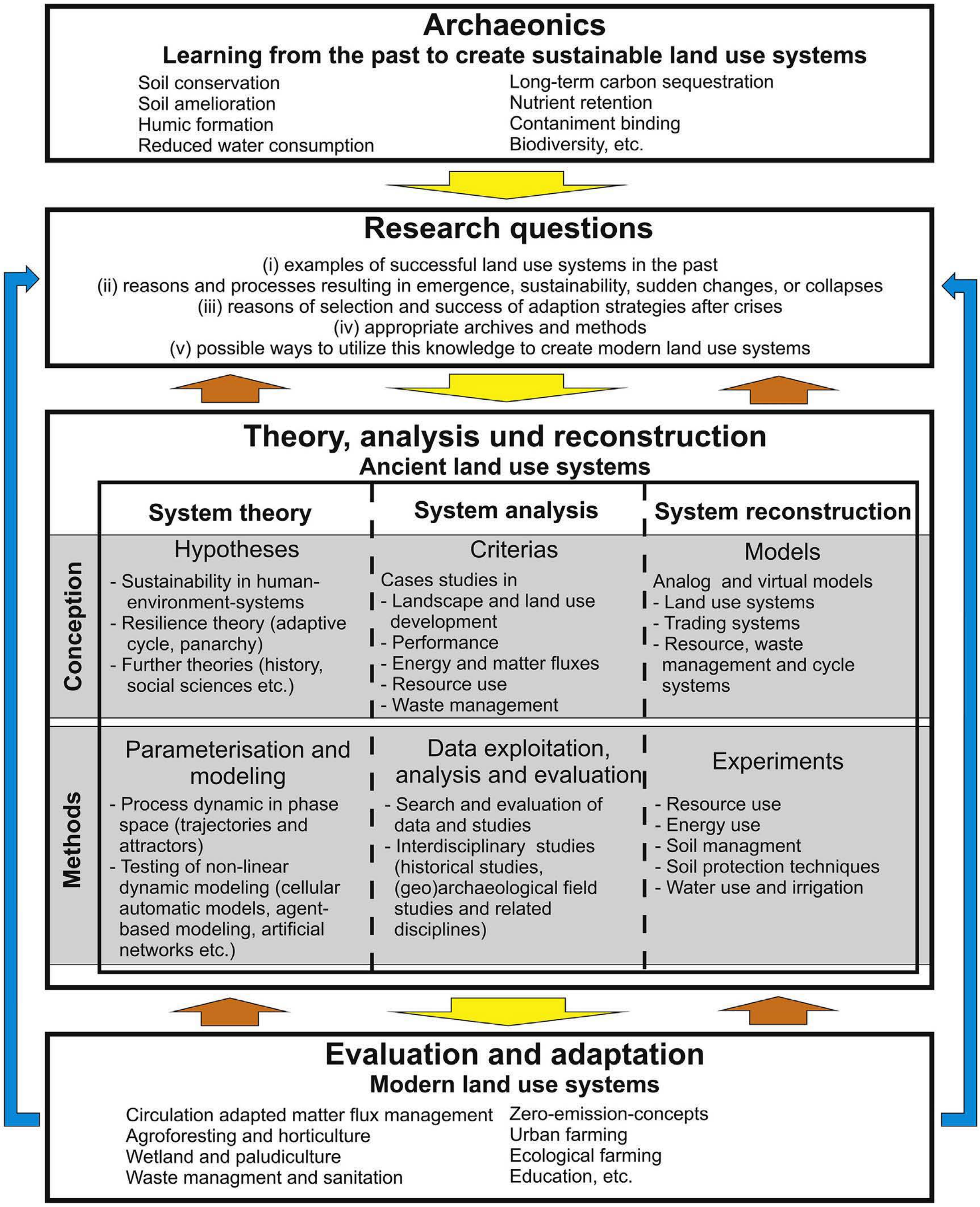

Fig. 5. The Archaeonic framework analyses past land use systems to understand the creation of long-term sustainability in order to provide possible implementations in modern land use systems to mitigate todays and future environmental problems.

Upon closer inspection, these soils were described as deepened topsoils formed due to human influences (Black Earths, Plaggen, or Phaeozems). It was shown that there are huge variations in their composition both across different landscapes as well as between sites. These soils very often occur in areas of intensive land use during the last centuries or millennia where the use of manuring practices was highly developed. Very often, they contain features similar to the Terra Preta do Indio, but because of the lack of cross-sectional interdisciplinary comparisons they are still poorly understood.

Recent developments on the ADE in central Europe permit the use of molecular proxies to investigate the history of soil amendment. Ancient topsoil material that has been preserved (e.g. as pit filling or below colluvial sediments) still contains information concerning its nutritional status and potential traces of fertilizing. Soil amendment methods include the application of manure and burning of vegetation prior to cropping. Fire clears the soil from weed seeds and releases nutrients from burned plant material. Burning and prehistoric agricultural experiments showed that slash-and-burn leads to crop yields of 5000 kg/ha on fertile soils and 1800 kg/ha on less fertile soils, compared to only 2100 kg/ha and 1200 kg/ha, respectively, when the field was not burned before sowing (Ehrmann et al., 2009). This technique allowed prehistoric communities around ca. 4200–4000 BCE to introduce agricultural techniques (cropping) to regions with less fertile soils, like the Baltic Sea or the Alpine foothills (Schier, 2009).

These findings on the ADE raise new questions about the differences and similarities in the development and management of these soils.

Since they are all rich in humic matter and carbon and are highly resistant to biochemical oxidation, they appear distinctly relevant both as a model for sustainable soil and land management systems and as a tool for climate change mitigation by carbon sequestration from a local to global scale.

Rooted in recent findings of the Terra Preta do Indio in the Amazon basin, several concepts on modern land use systems have already been established. The International Biochar Initiative is the most prominent example. It is based on the knowledge of the charcoal effect on soil fertility and nutrient retention of the Terra Preta do Indio (Lehmann and Joseph, 2009; Lehmann et al., 2006; Marris, 2006). The International Biochar Initiative encourages the production of charcoal products by pyrolysis or hydrothermal carbonization of organic waste to increase agronomic efficiency and to sequester carbon in the soil to fight global warming. It is used as a soil amendment material directly, or it can be mixed with compost before using. However, biochar is different to ADE, and the production and the use of biochar has heightened awareness of long term negative environmental effects such as charcoal emissions by dust or soil erosion (BIOFUELWATCH, 2011; Silva et al., 2015; Ravi et al., 2016). A different concept to produce a modern type of ADE has already been established on a commercial level in Germany (Böttcher et al., 2009; Palaterra, 2018). Technical installations transforms the raw mixture of organic waste and pyrolyzed charcoal into a highly fertile organic-rich and oxidation-stable substrate. Here, the main process is alactic-acid fermentation which creates a black earth like substrate within a few weeks. More recently, similar approaches using lactic-acid fermentation but with human excreta were also successfully tested by Andreev et al. (2018).

The production and use of modern types of ADE would be particularly attractive for forestry, agriculture, horticulture, and all types of farming and livestock breeding. All of these and many other activities like households and the food industry produce high outputs of organic wastes, which – while currently scarcely or inefficiently used – can be exploited as raw material input into the creation of ADE within sustainable soil management systems which have small-scale nutrient cycles. However, the production and use of modern types of ADE raise many research questions related to optimization of the substrate output and the assimilation into current land use systems or the development of new systems. However, an integrated and transdisciplinary research on the ancient ADE including a holistic theoretical system approach, field investigations and experiments has not been established yet but it may provide new ideas for a sustainable application of a modern ADE.

3. Discussion: archaeonics – an applied research on the past

The Archaeonic framework focuses towards systemic and technical analyses of past land-use systems to develop modern sustainable land use strategies (Fig. 5). In particular, it concentrates on effective and long-lasting technical and management solutions that have led to ecologically and socio-economically adapted agroecosystems like soil conservation, soil amelioration, humic formation, water consumption, long term carbon sequestration, nutrient retention, contaminant binding, or biodiversity. Consequently, the resulting research questions which are oriented towards problem solving seek to (i) search for examples of successful land use systems in the past, (ii) explain the reasons behind and analyze the processes which have resulted either in the emergence of sustainability, or in sudden changes, even collapses, based on a detailed analysis of the socioeconomic ecosystem, (iii) understand the reasons for the selection and success of certain adaptation strategies after crises using Panarchy concept as one possibility, (iv) look for appropriate archives and methods for further testing, and (v) find possible ways to utilize this knowledge by integrating it into current and future land use management systems. Fundamental to this set of research questions are the conceptual and methodical ideas of system theory, system analyses, and system reconstruction of ancient land use systems. The second part focuses on the evaluation and adaptation of the generated results and their application in the development of modern land use systems. Vice versa, the conception and creation of modern long lasting sustainable land use systems delivers new ideas that can inform research on past land use systems. This will influence the research and working scheme including the research questions themselves. As a result, our approach of the Archaeonic framework is not hierarchical but a co-adaptive research and working scheme.

System theoretical approaches provide a conceptual foundation for the elaboration of hypotheses to explain the creation of sustainability in ancient human-environment systems. Resilience theory, as discussed above, might be a profitable approach but other human-ecological theories should also be discussed and tested. The verbal, graphical or deterministic parameterizations of proxies or realistic assumptions are important to test and evaluate through other hypothetical trajectories or non-linear, agent based models. Such system analyses serve to isolate the principal criteria identified in case and field studies that enable the reconstruction of past landscapes, land use development, and land use techniques, focusing on performance, energy and matter fluxes, resource use, or waste management. To exploit, analyze and evaluate the data requires an interdisciplinary approach by various disciplines from the natural sciences, humanities, and engineering which are working within a historical dimension. The system reconstruction aims to conceptualize analogue or virtual models on land use systems, trading, resource use, waste management and their interconnections. These systems should be tested by experiments. For example, experiments on soil management like slash and burn, irrigation systems or soil protection techniques using ancient methods will demonstrate the effectiveness of past land use systems. The experimental results will also help to measure energy balances or resource productivity of past land use systems in pre-industrial land use systems.

The last step of the framework will evaluate the results for their adaptive potential to inform modern land use systems. The knowledge derived from the system theoretical work, the case studies, and the experimental reconstructions are valuable for the technical installation and management of circulation-orientated matter flux management systems, agroforesting, wetland farms or paludicultures, or waste management and sanitation. It also provides contributions to the development of concepts in zero-emission, urban farming, ecological farming, or education. The Archaeonic framework that has been presented here integrates a wide range of theories and methods which cannot be handled by single scientists or working groups or within a typical research project. Archaeonics should be understood as a coherent framework for transdisciplinary co-operation that brings researchers together to elucidate the problem of understanding long-term sustainability in past land use systems from which innovative responses aimed at mitigating current and future environmental problems might be developed. Many scientists already working on human-ecodynamics in past human-environment systems could easily contribute to or adapt such a framework. Research on the ADE provides a valuable example, showing the potential of a transdisciplinary approach to applied research on the past that might help to create modern sustainable land use systems, although it still lacks on a well developed amalgamation of both worlds.

To achieve this we firstly need to analyze their sustainability and their resilience in the past and then develop the technical and social preconditions for their implementation. This requires an approach that combines a systemic theory perspective looking for long-term changes with specific case studies on land use techniques, which evaluate the driving factors in past human-environment systems. However in a second step, the implementation requires a transdisciplinary research approach and close interdisciplinary cooperation between the humanities, natural sciences, engineering sciences, land managers and farmers. The research should be co-adaptive and transdisciplinary because it includes issues which combine theoretical discussion and practical learning. The presented framework should be understood as a very first attempt to integrate different research initiatives currently exploring long-term human-ecodynamics of past systems and re-directing these towards understanding and developing modern, more sustainable land use systems. In contrast to the above mentioned LSTER concept or Historical Ecology, Archaeonics focuses on ancient socio-ecological land management systems and land management techniques with high transfer potential to modern land use systems.

4. Conclusions

The Archaeonic approach (Fig. 5) is based on a systemic understanding of past agriculture. As the reconstruction of past ecosystems is limited due to the nature of historical and archaeological data, Archaeonics implements analogue and virtual modeling as well as experiments aiming for a sustainability assessment, which is an integrative part of the system analysis. As the experiences regarding raised fields agriculture in Bolivia and Peru show, the integration of these soil management strategies into society is a crucial element of their sustainability. As mentioned above, the reintroduction of raised fields agriculture in the 1990s faced some difficulties. In face of the huge workload of raised field gardening in comparison to conventional agriculture, their advantages of higher yields and less environmental risks were not accepted by all local farmers (Bandy, 2005). However these social settings which made the raised fields agriculture running in the past can't be recreated. Archaeonics don't aim to recreate the past, but to use past agroecosystems for inspiration on the agrarian technologies and for a critical reflection on long-term developments. Archaeological data are used to understand long-term developments, and to a certain degree they may also help to think about the meaning of social integration of these techniques.

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