Human-Environmental Interactions in Northeastern Jordan

Dissertation

by

Julia Meister

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First Supervisor

Prof. Dr. Brigitta Schütt
Freie Universität Berlin
Department of Earth Sciences
Institute of Geographical Sciences
Malteserstraße 74-100
12249 Berlin
Germany

Second Supervisor

Prof. Dr. Elke Kaiser
Freie Universität Berlin
Department of History and Cultural Studies
Institute of Prehistoric Archaeology
Fabeckstr. 23-25
14195 Berlin
Germany

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To my family

“For a great deal of the history of human occupation in the Badia, it has been a place of freedom and refuge. It has always been a choice to live in the Badia and not an imposition; it has never been a place of exile.”

- Betts and Cropper (2013, p. 190) -

Preface

This thesis is written in the Department of Earth Sciences of the Freie Universität Berlin and within the doctoral program *Landscape Archaeology and Architecture* of the Berlin Graduate School of Ancient Studies. The thesis is imbedded in the archaeological research project 'Arid habitats in the 5th to the early 3rd millennium B.C.: mobile subsistence, communication and key resource use in the Northern Badia (NE-Jordan)' of the German Archaeological Institute (DFG-Az.: MU 3075/1-2). This cooperation project between the German Archaeological Institute (Orient Department) and the Institute of Geographical Sciences of the Freie Universität Berlin is also part of the Research Area A S*patial Environment and conceptual design* of the Cluster of Excellence EXC 264 Topoi - 'The Formation and Transformation of Space and Knowledge in Ancient Civilizations'. Based on an integration of archaeological sciences and geosciences, the central research topic of Research Area A is human-environmental interactions, focusing in particular on questions concerning the spatial implementation of land use strategies as well as the impact of these strategies on the environment. As part of the Research Group A-1 *Ancient colonizations of marginal habitats*, the project A-1-5 *Badia, Jordan* focuses on the investigation of the interrelationships between the natural environment, the cultural acquisition of landscapes, and the development of technical knowledge. This doctoral thesis is a cumulative dissertation, comprising three publications.

Acknowledgements

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I am grateful to all anonymous reviewers for their valuable comments, which greatly improved the individual publications. Moreover, I would like to express great thanks to Will Kennedy, Stephan Breiter and Dr. Katharine Thomas for improving the language of this thesis.

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Furthermore, I am greatly indebted to the German Young Geomorphologists for discussions, friendship and support. Seeing a highly motivated group of young scientists working together with lots of energy and enthusiasm to foster the exchange between early career scientists impressed me deeply and is a great motivation for staying in science. Thank you all!

Many thanks are owed to my friends, in particular to Maria Jahn, Anita Meder and Dr. Thusitha Wagalawatta, for their kind friendship and unlimited support even in times when I was unavailable. Finally, I want to thank my wonderful and beloved family and my partner Sascha for always being there when no one else would. You always gave me inspiration and motivation. I love you! ♥♥♥

Abstract

This study investigates human-environmental interactions in northeastern Jordan since late prehistory. To achieve an integrated study in which ecological, economic and cultural factors are considered together, this thesis presents three landscape archaeological case studies, focusing on different adaptation strategies of past societies.

One research focus is on the food and water supply of the ancient settlement of Jawa—one of the major towns in the Middle East during the 4th millennium BCE—, located in the basalt desert steppe of northeastern Jordan. The major settlement phase of Jawa dates to the Early Bronze Age, starting at about 3500 cal BCE, while a small reoccupation is documented for the Middle Bronze Age. The drinking water supply of the city relied predominantly on an elaborated water distribution and storage system. Besides, recent geoarchaeological surveys have uncovered agricultural terrace systems in the nearby vicinity. The main research questions include: When were these terrace systems built, how did they function in detail and how efficient were they? To answer these questions, geomorphological field and laboratory work was applied. The terrace systems were dated using optically stimulated luminescence (OSL). Efficiency was assessed by applying a crop simulation model for the period from 1983 to 2014, integrating a rainfall-runoff model. The main findings of this study show that ancient terrace agriculture was practiced on slopes, small plateaus, and valleys close to Jawa usually through the use of surface canals which collected and diverted floodwater from nearby wadis or runoff from adjacent slopes. Terracing the fields naturally caused retention and collection of water and sediments. The fields were commonly arranged in cascades, enabling an easy distribution of water onto the fields. Increased phytolith concentrations in terrace fills, as compared to samples from non-terrace deposits nearby, indicate increased plant growth within the terraces. The terrace fills investigated yielded OSL ages of around 5300 ± 300 a (1σ), indicating that the terraces were constructed in the Early Bronze Age I. Moreover, the study shows that the runoff irrigated terrace systems were effective. On average the simulated crop yields of irrigated wheat, barley and lentils were increased by 1.5 to 6 times compared to rainfed agriculture. The number of crop failures dropped by c. 70 %.

Furthermore, this thesis investigates pastoral mobility in northeastern Jordan. Mobile pastoralism was already introduced to the region during the Early Late Neolithic. Today it is one of the few remaining regions in the Middle East where pastoral nomadism is still practiced as an adapted land use strategy. A dense distribution of agglomerations of sub-circular enclosures ('clustered enclosures') in the basaltic *harra* can be associated with pastoral groups. They are used by herders to corral flocks and for domestic activities. Archaeological surveys indicate that these remains were already used during the Late Neolithic. After construction, these structures were commonly reused in later periods. In order to investigate their spatial distribution as well as the relation between these pastoral camps and their natural environment, clustered enclosures were systematically recorded in the basaltic region of northeastern Jordan based on satellite imagery. Altogether, 9118 clustered enclosures were mapped. In order to investigate potential migration routes and the grazing lands of former pastoralists, point pattern analyses were conducted and integrated with the geomorphometric and geomorphological site properties. The locations and distribution of these structures are strongly related to the availability of water and thus grazing opportunities. Besides, the overall distribution seems to be related to the traditional pastoral migration cycle of the modern Bedouin Ahl al-Jebel tribe. Based on written and archaeological evidence it can be assumed that this cycle of seasonal migration has already been followed in a similar form in earlier times. Overall, the results demonstrate that the observed spatial distribution of clustered enclosures is influenced locally by natural characteristics and regionally by cultural practices.

The results of this thesis demonstrate how the development of different lifestyles, the application of water harvesting techniques as well as the integration of different forms of subsistence successfully enabled the habitation of the northeastern Jordanian desert. It becomes clear that in order to gain a comprehensive understanding of prehistoric and historical human-environmental interactions, different methodological approaches have to be integrated within an interdisciplinary research framework.

Zusammenfassung

Im Rahmen dieser Dissertation werden Mensch-Umwelt Interaktionen in der Wüstenregion Nordostjordaniens seit der späten Prähistorie untersucht. Um eine integrierte Studie zu ermöglichen, in welcher ökologische, ökonomische und kulturelle Besonderheiten berücksichtigt werden, stellt diese Arbeit drei landschaftsarchäologische Fallstudien vor, die sich auf verschiedene Anpassungsstrategien früherer Gesellschaften konzentrieren.

Ein Schwerpunkt der Untersuchungen liegt auf der frühbronzezeitlichen Siedlung Jawa, gelegen in der Basaltwüste Nordostjordaniens. Jawa wurde 3500 kal. BCE gegründet und war eine der größten Städte im Mittleren Osten während des 4. Jahrtausend BCE. Eine kleinere Nachbesiedlung ist für die Mittelbronzezeit belegt. Die Umgebung der Stadt ist durch ein ausgeklügeltes Wasserspeicher- und verteilungssystem gekennzeichnet. Neuere Untersuchungen erbrachten zudem Nachweise über landwirtschaftliche Terrassensysteme. Die zentrale Fragestellungen dieser Fallstudie sind: Wann wurden die landwirtschaftlichen Systeme errichtet, wie haben sie funktioniert und wie effizient waren sie? Zur Beantwortung dieser Fragen wurden neben geomorphologischen Feld- und Laboruntersuchungen, optisch stimulierte Lumineszenz (OSL) Datierungen vorgenommen, sowie eine Ernteertragsmodellierung, unter Anwendung eines Niederschlags-Abfluss-Modells, durchgeführt. Dabei wurde festgestellt, dass die Terrassensysteme in hydrologischen Gunstlagen, z.B. auf Hängen, Plateaus und kleinen Tälern, angelegt und durch Kanäle bewässert wurden. Letztere haben entweder Oberflächenabflusswasser gesammelt oder Gerinneabfluss aus benachbarten Wadis abgeleitet. Die Terrassierung der einzelnen Felder ermöglichte die Speicherung von Wasser und Sedimenten. Durch eine meist kaskadenartige Anordnung der Terrassenfelder konnte das Wasser auf die einzelnen Felder verteilt werden. In den untersuchten Sedimentprofilen der landwirtschaftlichen Terrassen wurden erhöhte Phytolithgehalte nachgewiesen, welche auf erhöhtes Pflanzenwachstum hindeuten. Die Datierungsergebnisse ergaben ein Alter von 5300 $\pm$ 300 a (1σ) und deuten auf eine frühbronzezeitliche Nutzung der landwirtschaftlichen Systeme hin. Die Abflussbewässerung der Terrassen hatte ferner einen

starken Einfluss auf die Ernteerträge: unter Bewässerung stiegen die modellierten Erträge von Weizen, Gerste und Linsen um das 1.5- bis 6-fache im Vergleich zu Regenfeldbau. Die Anzahl der Ernteausfälle wurde um ca. 70 % reduziert.

Darüber hinaus wird in dieser Arbeit die pastorale Mobilität im Nordosten Jordaniens untersucht. Mobiler Pastoralismus wurde in dieser Region bereits während des frühen Spätneolithikums eingeführt. Heute ist es eine der wenigen verbliebenen Regionen im Mittleren Osten, in der mobile Viehwirtschaft, als angepasste Landnutzungsstrategie, noch praktiziert wird. In der Basaltregion Nordostjordaniens gibt es eine große Anzahl archäologischer Überreste, die pastoralen Gruppen zugeordnet werden können. Diese Agglomerationen rundlicher Strukturen, die aus Steinen und Blöcken von lokal verfügbarem Basalt errichtet wurden, werden von Viehhirten als Viehpferche oder für häusliche Tätigkeiten genutzt. Anhand einer satellitenbildgestützten Kartierung wurde deren räumliche Verteilung sowie deren Beziehung zur natürlichen Umwelt untersucht. Um potentielle Migrationswege und Weideflächen ehemaliger Viehzüchter auszumachen, wurden Punktmuster-Analysen unter Einbeziehung hydrologischer und geomorphologischer Standorteigenschaften durchgeführt. Insgesamt wurden 9118 dieser Strukturen kartiert. Auf lokaler Ebene konnte dabei eine starke Verbindung zu periodisch verfügbaren Wasserressourcen und Weidegründen festgestellt werden. Das regionale Verteilungsmuster der kartierten Strukturen scheint sich demgegenüber an dem traditionellen Migrationszyklus des modernen Ahl al-Jebel Beduinen Klans zu orientieren. Auf Basis historischer Textquellen sowie archäologischen Befunden kann davon ausgegangen werden, dass dieser saisonale Wanderungszyklus schon in früheren Zeiten in ähnlicher Form praktiziert wurde.

Die Ergebnisse dieser Arbeit zeigen, dass die Entwicklung verschiedener Lebensweisen, die Anwendung von Wasserbautechniken, sowie die Integration verschiedener Subsistenzstrategien eine Besiedlung der nordostjordanischen Wüste ermöglichten. Dabei konnte demonstriert werden, dass eine interdisziplinäre Zusammenarbeit und die Integration unterschiedlicher Methoden ein umfassendes Bild prähistorischer und historischer Mensch-Umwelt Interaktionen liefern.

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CHAPTER 1

Introduction

Northeastern Jordan is climatically classified as a hot desert climate (Kottek et al., 2006) characterized by marked seasonal variations, with hot, dry summers and cool, moist winters (Allison et al., 2000). Average annual precipitation ranges from more than 150 mm in the northwest, to less than 50 mm in the south along the border with Saudi Arabia (Tansey, 1999). With regard to the arid environmental conditions it was assumed that the area has not been extensively used by humans in the past. Therefore, archaeological research paid little attention to the region for a long time (Akkermans et al., 2014). Starting in the 1970s, the number of expeditions to this area increased (Betts, 1993)—a trend that has been growing ever since. To date, several archaeological surveys and excavations as well as intensive analyses of satellite imagery and aerial photography have shown that the desert of northeastern Jordan is a 'landscape of preservation', i.e. archaeological remains are remarkably well preserved (Wilkinson, 2003). Overall, some tens of thousands of human-made structures, rock paintings and inscriptions have been noted (Kennedy, 2011), displaying extensive human activities during distinct late prehistoric and historical periods (cf. Akkermans et al., 2014; Akkermans and Huigens, in press; Betts et al., 2013; Betts, 1998; Betts and Helms, 1986; Macdonald, 1992; Müller-Neuhof, 2014a; Kempe and Al-Malabeh, 2013; Kennedy, 2011; Rollefson et al., 2014a; Rowan et al., 2015b).

In order to describe, interpret, and understand the development of human exploitation in desert environments, as well as the environmental aspects of that exploitation, it is necessary to ask:

- What kind of adaptation strategies and techniques were developed to cope with these arid environmental conditions?

- How does the cultural landscape relate to the natural environment? Specifically, how do they interact?

The aim of this thesis is to contribute to a better understanding of the human-landscape relationships in northeastern Jordan from late prehistoric times until today. In consequence, the main goal of this thesis is to evaluate interrelations between the natural environment and human land use strategies. To do so, this thesis presents three landscape archaeological case studies, focusing on different adaptation strategies of past societies, which can provide valuable information to address these questions. The aim is to achieve an integrated study in which ecological, economic and cultural features are considered together to provide a broad picture of human-environment relationships in northeastern Jordan over time.

A major research focus is on the food and water supply of one of the major towns in the Middle East during the 4th millennium BCE, located in the basalt desert steppe of northeastern Jordan—the Early Bronze Age settlement of Jawa. The fortified ancient settlement of Jawa covered approximately ten hectares and is located on a plateau along the Wadi Rajil, situated about 7 km south of the present-day border to Syria (Helms, 1981). The major settlement phase of Jawa dates to the Early Bronze Age I, starting between 3500 and 3400 cal BCE (Müller-Neuhof et al., 2015), while a small reoccupation is documented for the Middle Bronze Age at around 2000 BCE (Helms, 1989, 1981). During the earlier phase, ancient Jawa had its largest extent and may have been inhabited by up to 3400 to 5000 people (Helms, 1981) who relied on a mixed herding and farming subsistence strategy, supported by hunting activities (Köhler, 1981).

Water supply is crucial to settlements in dry regions because of the need for drinking water and irrigation water for crops (Wilkinson, 2003). According to this, the location of Jawa in an ecologically marginal region is somewhat surprising. Today, the annual rainfall at the site is about 100 mm and paleoenvironmental records indicate that the climate conditions during the Early Bronze Age were—at least to a certain extent—similar to the present-day conditions. Moreover, it is most likely that there was a lack of perennial water sources. In consequence, Jawa's inhabitants had to apply various water management strategies to secure their food and water supply. This is apparent from the existence of a highly elaborated water distribution and storage system, consisting of a series of diversion canals, water reservoirs and small areas of arable land utilizing surface and floodwater runoff—a hydraulic system which appears to be one of the earliest of its kind (Helms, 1981; Roberts, 1977; Viollet, 2007; Whitehead et al., 2008). In addition, the well-preserved remains of several abandoned agricultural terrace systems were recently discovered by geoarchaeological surveys in the direct vicinity of Jawa (Müller-Neuhof, 2014a,b, 2012). Under the current conditions of low rainfall rates and erratic rainfall distribution agriculture is risky for those who depend upon subsistence. How was it possible to practice farming in this desert environment? As yet, it is largely unknown when these agricultural systems were built, how they functioned in detail, how efficient they were and how many people could have been supplied by the crop production. Therefore, one major aim of this thesis is to characterize agricultural activities at the ancient city of Jawa by investigating the ancient built and natural environment of Jawa under different objectives; as published within two research papers:

- **'Desert agricultural systems at EBA Jawa (Jordan): Integrating archaeological and paleoenvironmental records'** by Meister, J.; Krause, J.; Müller-Neuhof, B.; Portillo, M.; Reimann, T.; Schütt, B. (2017, *Quaternary International*; own contribution 85 %).
  In order to investigate the layout and functioning of the agricultural terrace systems at Jawa, in this study four of such systems were investigated by detailed mapping. Additionally, 13 sediment profiles from inside and outside the terrace systems were recorded and sampled to supply information on the environmental and depositional conditions by analyzing the bulk chemistry, texture, phytoliths, diatoms, and dung spherulites. To set up a chronology, the terrace systems were dated using optically stimulated luminescence (OSL) dating.

- **'Ancient runoff agriculture at EBA Jawa (Jordan): Water availability, efficiency and food supply capacity'** by Meister, J.; Rettig, R.; Schütt, B. (in press, *Journal of Archaeological Science: Reports*; own contribution 85 %).
  This paper investigates the impact of the applied water management strategies on harvest yields and the scale of the 'on-site'crop production at Jawa by applying a crop simulation model (CropSyst). Simulations for the cultivation of winter barley, winter wheat and lentils were performed for the period from 1983 to 2014. To simulate the different runoff irrigation schemes, a curve-number-based rainfall-runoff model was applied. To estimate the number of people that could have been supplied by local food production, simple calculations based on metabolic calorie requirements and agricultural and pastoral production rates were conducted.

Furthermore, this thesis aims to investigate pastoral mobility in northeastern Jordan as it seems likely that mobile pastoralism was already introduced to the area during the Early Late Neolithic (Rollefson et al., 2014a). Today, it is one of the few remaining regions in the Middle East where pastoral nomadism is still practiced (Tansey, 1999) as another adapted land use strategy to cope with low rainfall rates, great seasonal and annual rainfall variations and thus heterogeneous vegetation and water availability. Fortunately, there is a dense distribution of archaeological remains in the basaltic *harra* of Jordan which can be associated to pastoral groups due to the herders' ancient practice of building agglomerations of sub-circular enclosures ('clustered enclosures') made of basalt boulders for corralling their flocks and domestic activities. The resulting features provide an excellent opportunity to investigate the relation between pastoral camps and their environment in a landscape that has been frequently used by herders during the last eight to nine millennia. Therefore, clustered enclosures and their spatial distribution were investigated within a research article:

- **'A pastoral landscape for millennia: Investigating pastoral mobility in northeastern Jordan using quantitative spatial analyses'** by Meister, J.; Knitter, D.; Krause J.; Müller-Neuhof, B.; Schütt, B. (in press, *Quaternary International*; own contribution 75 %).
  In this study, clustered enclosures were systematically recorded in the basaltic region of northeastern Jordan based on satellite imagery. In order to investigate potential migration routes and the grazing lands of former pastoralists, their first- and second-order characteristics using distance and density based approaches of point pattern analyses were examined by integrating geomorphometric and geomorphological site properties. The results of this spatial analysis were combined with available archaeological data and a review on traditional herding practices in northeastern Jordan.

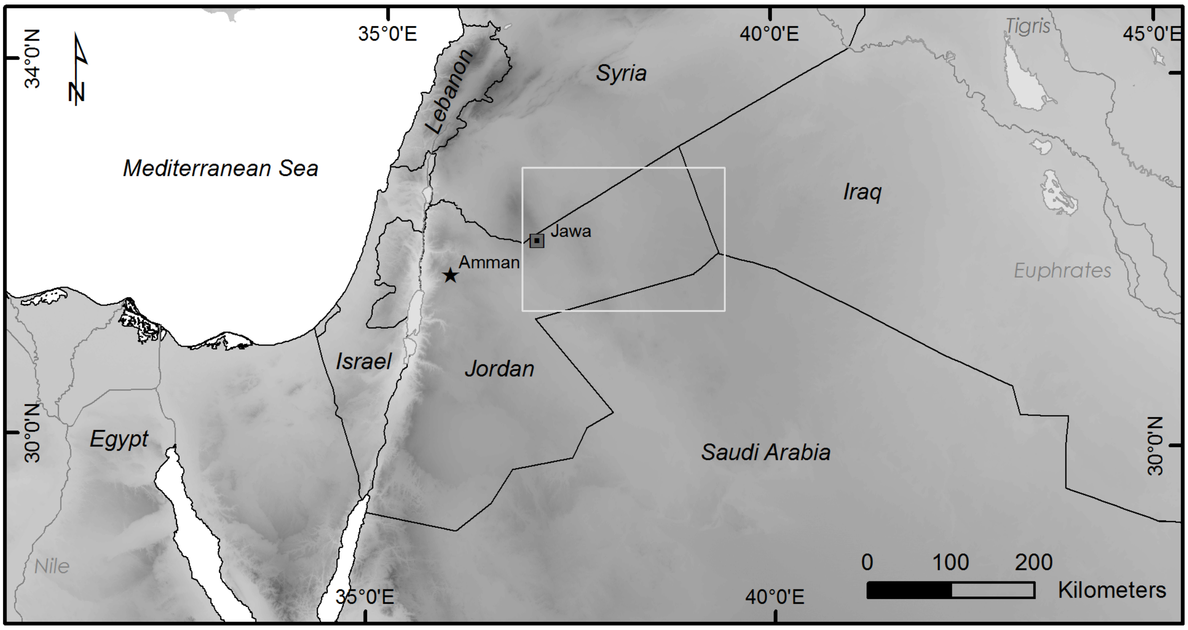

Figure 1.1.: Location of Jordan and the study area (white rectangle) within the Middle East.

To gain a comprehensive overview on the human-environmental interactions in northeastern Jordan the three publications (chapters 5–7) are framed by an overview of landscape- and geoarchaeological studies in Jordan (chapter 2.1) and the research history in northeastern Jordan (chapter 2.2), a detailed description of the study area (chapter 3) and the methodological framework of this study (chapter 4). The final chapter (chapter 8) concludes the achievements of this thesis and sets them in a more general context.

CHAPTER 2

State of the art

2.1. Landscape- and geoarchaeological investigations in Jordan

Over the last decades, Jordan has been investigated by many scholars of various disciplines dealing with landscape- and geoarchaeological questions. Although most of these studies focus on paleoenvironmental reconstructions at archaeological sites, e.g. by analyzing sedimentary sequences, pollen, and various other proxies, a large number of studies cover a broad array of subjects related to the fields of landscape- and geoarchaeology. To give a broad overview of these research activities previous studies, among others, are listed below according to their study areas (Fig. 2.1).

1. To reconstruct the paleolandscape of Wadi Ziqlab in northern Jordan, a study of Maher (2011) integrated geomorphological and micromorphological data with the settlement history from the Middle Paleolithic to recent times.

   To assess the impact of prehistoric sites on their local environment, Ullah (2011) developed a GIS-based model using the pastoral economy of the Late Neolithic period in Wadi Ziqlab as a test case. The model of Late Neolithic herding economy and ecology combines data e.g. from archeology, botanical geography, agronomy, and ethnohistory.

2. A study by Cordova (2008) investigated a Mid-Holocene cycle of stream aggradation and incision in Wadi al-Wala and Wadi ash-Shallalah in western Jordan. In the context of available local and regional evidence, this study discusses the relation between Early Bronze Age settlement activities and stream degradation.

3. A research project by Zielhofer et al. (2012) focused on the early Holocene decline of the Pre-Pottery Neolithic mega-site of ‘Ain Ghazal, situated along the Zarqa River. Based on

sedimentological analyses the aim of this study was to determine whether corresponding earth-surface processes at ‘Ain Ghazal were climatically driven, and whether the decline of the site was linked to a geomorphological (catastrophic) event.

4. In order to examine spatial patterns of prehistoric sites in relation to landforms, alluvial fills, and soil development in the uplands and valleys of the Madaba and Dhiban Plateaus of Jordan, Cordova et al. (2005) investigated a sequence of allostratigraphic units, paleosols, and terraces to reconstruct phases of fluvial aggradation and stream incision during the past 20,000 years.

5. To investigate prehistoric settlement patterns and palaeoenvironmental change in the Wadi el-Hasa in west-central Jordan, Schuldenrein and Clark (1994, 2001) conducted geomorphological investigations as well as sedimentological analyses of cultural and geological deposits. Moreover, Hill (2000) applied spatial statistics on archaeological sites located in the Wadi el-Hasa clarifying which factors potentially led people to degrade their environment and how people responded to degradation.

   Arıkan (2012) developed a GIS-based approach to model past human-environment interactions and landscape changes in the Wadi el-Hasa. The model combines a wide variety of spatial data such as climatic, geological, and cultural to estimate how long-term interactions among these factors contribute to the evolution of natural environment and anthropogenic landscapes. Additionally, the model allows the visualization of the anthropogenic impacts of extensive agropastoralism on landscapes. Another study by Contreras et al. (2014) investigated a floodplain surface in the Wadi el-Hasa that was occupied from the 7th to the 8th century cal CE. To examine evidence of soil formation and anthropogenic influences, including the potential of cultivation activity, the authors applied a multi-proxy analysis that incorporated geomorphological, geochemical, and paleobotanical analyses.

6. In order to study ancient field systems and to construct the landscape development for the past 10,000 years in the Wadi Faynan in southern Jordan, Barker et al. (1997, 1998, 1999, 2000) conducted several seasons of fieldwork integrating geomorphological-, palaeoecological-, archaeological and hydrological aspects. Moreover, the early-Holocene environments in the Wadi Faynan were investigated by Hunt et al. (2004) by analyzing pollen, plant macrofossils and molluscs from sediment deposits. To examine the design and main hydraulic features of an ancient irrigated field system in the Wadi Faynan, Crook (2009) applied a theoretical runoff model based on ground conditions and historical climate reconstructions.

   A geoarchaeological research project by Pyatt et al. (2000) has focused on the ancient and continuing environmental impacts of Khirbet Faynan—one of the major mining and smelting centers of the ancient world—situated in the Wadi Faynan, by analyzing the metal content of plants, animals and sediments in the vicinity of the site. A similar but more extensive study on this issue was undertaken by Grattan et al. (2007). Ancient mining-waste/spoil deposits found in the Wadi Khalid near Khirbat Faynan were geochemically studied by Grattan et al. (2014). In order to investigate palaeoenvironmental changes and the impact of copper mining throughout the Holocene in the Wadi Faynan and the Wadi Dana in southern Jordan, Hunt et al. (2007) investigated sedimentary deposits, geomorphological processes, pollen, palynofacies, and charcoal.

Witten et al. (2000) conducted geophysical investigations at a series of Neolithic and Bronze Age sites in order to identify specific areas within the Wadi Fidan for future excavations. Thereby, three geophysical techniques were used to locate buried architectural and industrial features remaining from early mining and metallurgical activities.

7. Environmental change and human history in the Jabal Harun area, situated close to the ancient site of Petra in southern Jordan, were investigated by Kouki (2006) by examining wadi terraces based on sedimentological analyses and optically stimulated luminescence (OSL) dating. Agricultural terrace systems in the Petra region were dated by Beckers et al. (2013b) by applying OSL and radiocarbon dating techniques.

8. To reconstruct the Upper Pleistocene landscape evolution, terrestrial sedimentary deposits around archaeological sites in the Wadi Sabra in south-central Jordan were geoarchaeologically investigated by Bertrams et al. (2012b,a).

9. A geoarchaeological project by Niemi and Smith (1999) conducted an archaeological survey and geologic investigations along the southeast of Wadi Araba in order to reconstruct paleoenvironmental conditions. Thereby, they focused on the analysis of sediments and soil development at archaeological sites and the interpretation of aerial photographs.

10. A study by Allison and Niemi (2010) investigated the Holocene paleoenvironmental conditions in the vicinity of Early Roman/Nabataean to Byzantine archaeological sites in Aqaba in southern Jordan, utilizing sediment analyses of several sediment cores. Rhodius et al. (2015) applied OSL dating to determine the construction age of ancient irrigation systems at Tell Hujayrat al-Ghuzlan near Aqaba.

11. To place Lower Paleolithic sites at ‘Ayoun Qedim within an environmental context, Rech et al. (2007) investigated the geology and geomorphology of this region.

12. A detailed landscape reconstruction throughout the Middle and Late Pleistocene was provided by Ames and Cordova (2013, 2015) and Cordova et al. (2013) based on in-depth stratigraphic and sedimentological analyses from several profiles in the Greater Azraq Oasis Area in northeastern Jordan. To reconstruct paleoenvironmental conditions at the Late Epipaleolithic and Neolithic sites of Wadi el-Jilat and Uwaynid situated in the Azraq basin, Garrard et al. (1988a) investigated sedimentary profiles.

13. Athanassas et al. (2015) applied OSL dating to date ancient stone structures in northeastern Jordan. Moreover, the authors conducted a spatial analysis of the specific 'wheel' structures in this region.

14. A comprehensive overview of climate change, cultural development and human-induced landscape transformations in Jordan through prehistoric and historical times is given by Cordova (2007).

There are widespread research activities in Jordan aiming to get a deeper understanding of past human-environmental interactions. This thesis complements these activities by integrating knowledge on this issue for northeastern Jordan—an area which hitherto has rarely been the focus of landscape- and geoarchaeological research.

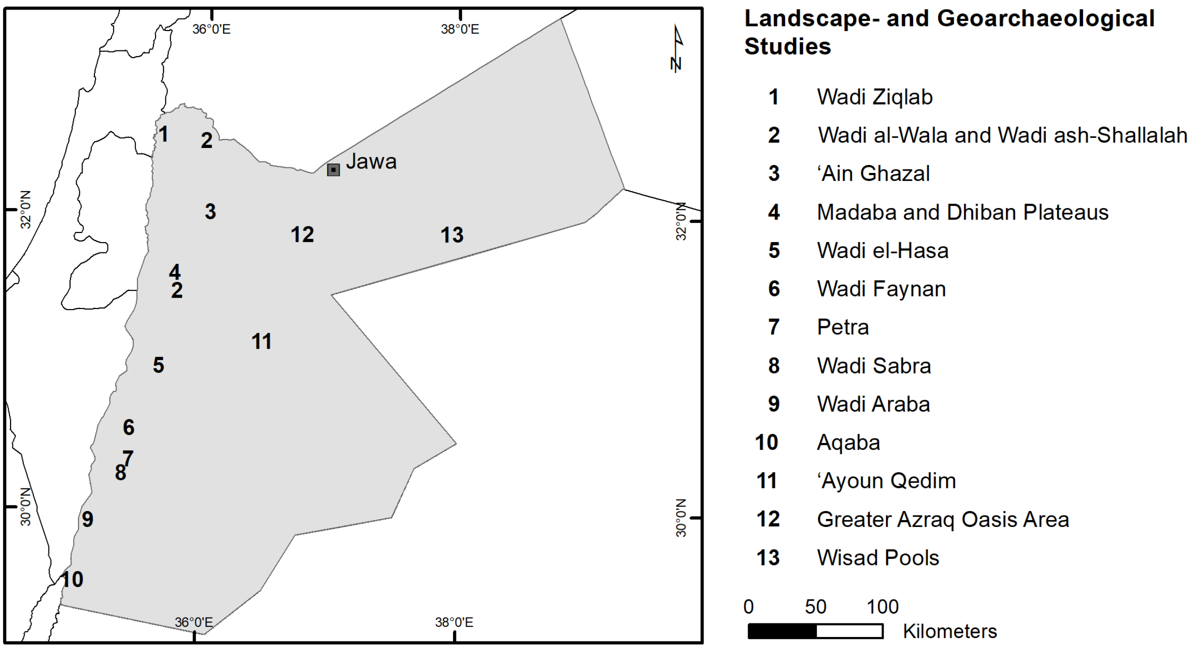

Figure 2.1.: Addressed landscape- and geoarchaeological study sites in Jordan.

2.2. Research history in northeastern Jordan

The northeast of Jordan is divided into two distinctive zones: the basaltic region of the *harra* (also called 'Black Desert') to the west and the limestone region of the *hamad* to the east, both forming the northern Badia. Within the last century, this region has been investigated by many scholars of various disciplines (see Fig. 2.2 for the study locations addressed).

2.2.1. Archaeological research

With regard to prehistoric archaeological research, the northern Badia received first attention from the reports of the Royal Air Force pilots in the 1920s who described visible archaeological features such as walls and corrals after they crossed the desert on the airmail route from Cairo to Baghdad (Maitland, 1927; Rees, 1929). During the 1930s two prehistoric sites close to Azraq were investigated by Waechter and Seton-Williams (1938). Until the 1970s the prehistory of northeastern Jordan was almost unexplored. It was only in the 1980s that the number of expeditions to this area increased substantially.

The basalt desert of the *harra* was investigated by Helms, carrying out a survey in 1966. Between 1972 and 1976, he partly excavated the Bronze Age site of Jawa (Helms, 1973, 1975, 1976, 1977, 1981, 1989; Betts, 1991). More recently, the ancient water supply systems of Jawa were simulated by Whitehead et al. (2008), while Müller-Neuhof et al. (2015) provided the first radiocarbon dates for the site.

The first systematic surveys of prehistoric sites in the Azraq basin were conducted by Garrard and Stanley Price (1975). A few years later, Garrad also started a major survey and excavation program in Azraq and Wadi Jilat (e.g. Garrard et al., 1986, 1987, 1988b,a; Garrard and Byrd, 1992; Garrard et al., 1994; Baird et al., 1992).

With the Black Desert Survey Project in the *harra* and the Burqu'/Ruweishid Project in the *hamad*—associated with extensive surveys and excavations in the northern Badia during the period between 1979 and 1996—a vast body of knowledge on the Epipaleolithic, Neolithic and Chalcolithic exploitation of this area has been built up by Betts and her colleagues (e.g. Betts, 1982b, 1983, 1984, 1985, 1987, 1988, 1989, 1990; Betts et al., 1991; Betts, 1992b,a, 1993, 1998; Betts et al., 2013).

More recently, the Neolithic sites at Wisad Pools and the mesas in the Wadi al-Qattafi region in the *harra* have been investigated by the northern Badia Archaeological Project, carried out by Rollefson, Rowan, Wasse and colleagues (e.g. Wasse et al., 2012; Rollefson et al., 2011b,a, 2013, 2014a,b,c, 2016; Rowan et al., 2011, 2015b,a; Athanassas et al., 2015).

The Chalcolithic/Early Bronze Age period has been investigated by extensive surveys in the eastern hinterland of Jawa by Müller-Neuhof between 2006 and 2016. Müller-Neuhof revealed abundant traces of socio-economic activities, including the exploitation of large flint mines in the *hamad*, as well as the practice of ancient pastoralism and irrigation agriculture in the *harra*. Müller-Neuhof also investigated the Chalcolithic/Early Bronze Age sites of Tulul al-Ghusayn and Khirbet Abu al-Husayn, both located east of Jawa (e.g. Müller-Neuhof, 2006, 2012, 2013b; Müller-Neuhof et al., 2013; Müller-Neuhof, 2013a, 2014b,a).

Important insights into the nature and distribution of prehistoric and historical sites, particularly within the Jordanian deserts, were given by the Aerial Archaeology in Jordan (AAJ) Project and the Aerial Photographic Archive for Archaeology in the Middle East (APAAME); both long-term research projects directed by Kennedy and Bewley. The projects discover archaeological sites and structures through aerial photography and the investigation of high resolution satellite imagery on Google Earth (e.g. Kennedy, 2012, 2011; Kennedy and Bewley, 2009; Kennedy, 1998). Moreover, Athanassas et al. (2015) as well as Kempe and Al-Malabeh (2013, 2010b) also used satellite imagery in order to identify and examine archaeological sites and structures within northeastern Jordan.

The historical periods have also been investigated in recent years, although much smaller in scope than compared with prehistoric research. Several epigraphical surveys of rock inscriptions were conducted for instance by Macdonald (1982, 1983, 1992, 1993). Sites of the Roman, Byzantine and Islamic periods were investigated by King (1983) and Helms (1991a), among others.

The Jebel Qurma Archaeological Landscape Project focuses on the occupation history of both the late prehistoric and historical periods in the Jebel Qurma region. Starting in 2012, intensive surveys and excavations have been carried out by Akkermans, Huigens and colleagues (e.g. Akkermans et al., 2014; Huigens, 2015; Akkermans and Huigens, in press).

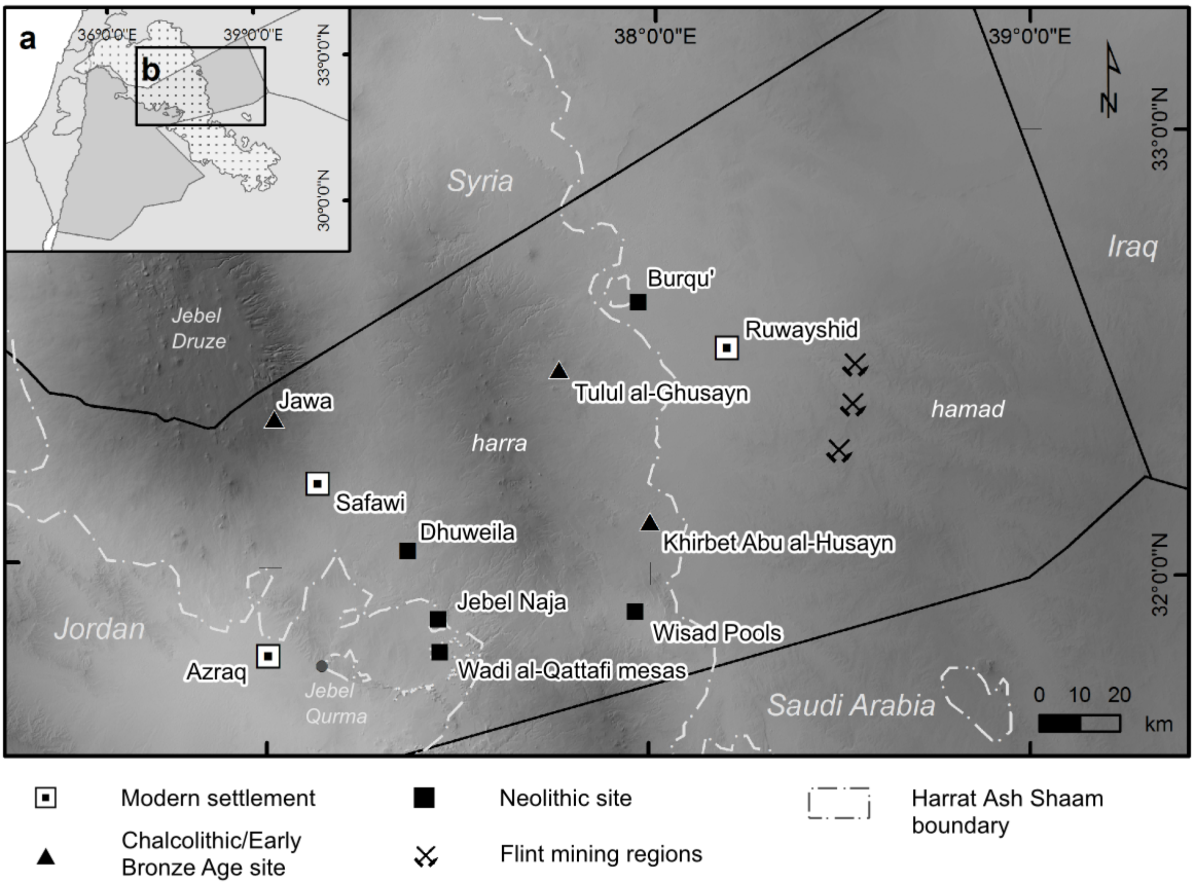

Figure 2.2.: 2a: Location of the 'Harrat Ash Shaam' basaltic region within Jordan and neighboring countries. 2b: Addressed archaeological sites (after Betts 1998; Akkermans et al. 2014; Müller-Neuhof 2014b; Rollefson et al. 2014a) in northeastern Jordan.

2.2.2. Environmental and socio-economic research

The first detailed geological surveys in Jordan were conducted by Bender and his team in the 1950s and 1960s, publishing a compendium (Bender, 1968, 1974) and a series of geological maps (Bender et al., 1968). Regarding the geology, geomorphology, hydrology and physical resources in northeastern Jordan a large number of research projects were supported by the Jordan Badia Research and Development Program (BRDP; Al-Homoud et al., 1995, 1996, 1998; Dutton et al., 1998; Dottridge and Abu Jaber, 1999; Allison et al., 2000). The BRDP was set up in 1992 to address the problems of land degradation in the basaltic *harra*, also dealing with socio-economic and socio-environmental aspects of pastoralism and livestock keeping. Within the framework of this program Tansey and colleagues monitored and modeled the surface moisture using satellite imaging radar data within the project area (Tansey, 1999; Tansey et al., 1999). In addition, Edwards et al. (1999) analyzed the grazing resources of the region, using remote sensing. Focusing on the western part of northern Jordan, Millington et al. (1999) investigated population dynamics, socio-economic change and land colonization, while Al-Adamat et al. (2004) examined the land use change associated with irrigated agriculture. In order to estimate how population growth and socio-economic influences affects the soil quality within this area, Al-Hussein (2000) developed a GIS-based erosion model to predict annual soil loss. A paper by Findlay and Maani (1999) presented population projections for the entire region covered by the Badia Research and Development Project and evaluated the economic and social implications of these projections in the future. Regarding socio-economic aspects, Spicer (1999) investigated pastoral mobility, sedentarization and the accessibility of health services in the northern Jordanian Badia. Moreover, Rowe (1999) studied the recent socio-economic developments, using Bedouin livestock herding as a case study of a pastoral system in transition, whereas Roe (2000) analyzed the changes concerning the role and function of livestock. A more recent study of Al-Tabini et al. (2012) investigated the traditional and local knowledge of Bedouin communities in the Badia region with regard to livestock production, medicinal plant use and rangeland management.

To date only a few paleoenvironmental/paleoclimatic studies have been carried out within northeastern Jordan. Late Pleistocene records from the Qa'a Selma in northern Jordan have been investigated by Al-Tawash (2007) and Al-Tawash and Al-Qudah (2008), while Frumkin et al. (2008) explored the environmental conditions of the basalt plateau during the Holocene and the mid-late Pleistocene by investigating calcite speleothems from a lava tube.

The present-day climate of Jordan was analyzed by Tarawneh and Kadıoğlu (2003), studying precipitation records from all over Jordan and their spatial characteristics.

CHAPTER 3

Study area

3.1. Regional scale: northeastern Jordan

3.1.1. Location

The Hashemite Kingdom of Jordan is located in Western Asia, bordered by Saudi Arabia to the east and south, Iraq to the northeast, Syria to the north, Israel, Palestine and the Dead Sea to the west. The study area of this thesis comprises the northeastern part of Jordan, bounded by the Azraq basin and the political borders of Syria, Iraq and Saudi Arabia (Fig. 1.1). Due to its environmental setting the region is also called the 'northern Badia'; the term Badia is described as arid, desert environment with little or no vegetation cover, low precipitation rates and periodic surface water (Allison et al., 2000).

3.1.2. Geotectonic setting

Jordan is located within the convergence of three tectonic plates, affecting the geology of the country (Fig. 3.1). A north-south rift system formed by the Dead Sea-Gulf of Aqaba Rift and the Suez Rift mark the boundaries of the African Plate, the Arabian Plate and the Levantine Plate. Probably already since the Precambrian tectonic activities along this rift system are influencing the crystalline basement of Jordan (Bender, 1968; Cordova, 2007).

The north-south graben that separates the Levantine Plate from the Arabian Plate developed through a bifurcation of the Red Sea Rift at the beginning of the Miocene. This graben forms the depression which is covered today by the Jordan river, the Dead Sea and the Wadi Araba (Cordova, 2007). A complex system of faults that run vertical or diagonal to the rift developed through tectonic activities. Faults also reach eastern Jordan, where tectonic forces led to the formation of the Azraq- and Al-Jafr basins and volcanic activity in the northwestern plateau (Bender, 1968; Cordova, 2007, Fig. 3.2). Nowadays, little tectonic activities are found throughout Jordan; only the Rift Valley is tectonically highly active as demonstrated by active faulting and the frequent occurrence of earthquakes (Cordova, 2007).

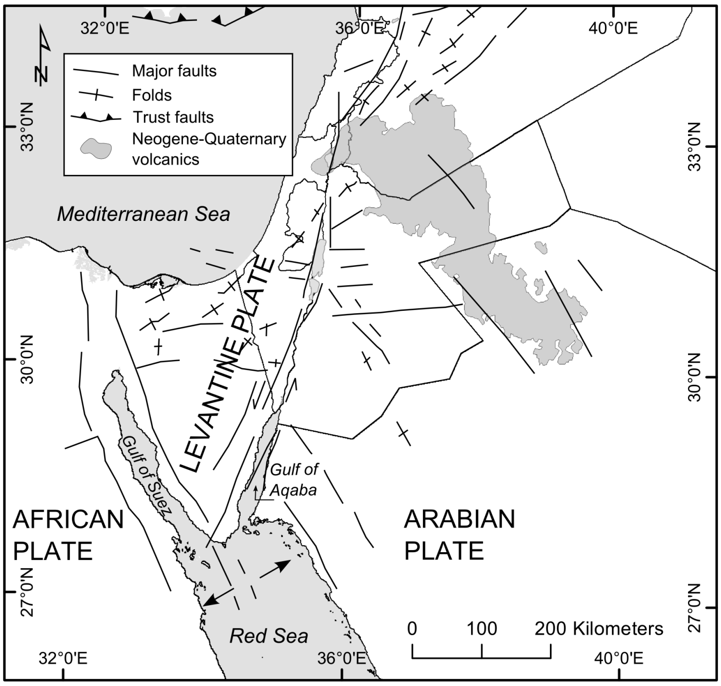

Figure 3.1: Jordan in the context of the regional tectonics of the Middle East; modified after Cordova (2007).

3.1.3. Geology

Jordan is almost completely covered by sedimentary rocks. Exceptions are some Precambrian igneous and metamorphic rocks in the southwest of the country and the Neogene-Quaternary basalts of northeastern Jordan. In between, several sedimentary formations of terrestrial and marine origin become progressively younger towards the northeast (Bender, 1968; Cordova, 2007, Fig. 3.3).

Northeastern Jordan can be divided geologically into two main areas (Fig. 3.3): (1) In the east, the so-called *hamad*, is composed of limestone of cretaceous and tertiary age, covered by a significant amount of chert gravels (Bender, 1968, Fig. 3.6). (2) In the west follows the northeastern Jordanian basalt plateau, called *harra* (Fig. 3.5). The *harra* is part of the North Arabian Volcanic Province ‘Harrat Ash Shaam’ that extends from southern Syria to Saudi Arabia. It consists of several Quaternary and Neogene volcanic basalt lava flows that extruded from widely-distributed volcanic centers (Allison et al., 2000; Bender, 1968; Taqieddin et al., 1995, Fig. 3.1). Overall, the ‘Harrat Ash Shaam’ basaltic supergroup is composed of one pyroclastic group and four basaltic subgroups; three are of Neogene age and one is of Quaternary age (Taqieddin et al., 1995). The basaltic area within Jordan covers about 11,000 km^2, with ages ranging from 13.7 Ma to less than 0.5 Ma. Some of the unexposed flows are dated at 23 Ma (Al-Homoud et al., 1995). The whole area is characterized by major faulting systems and numerous ground surface lineaments, as well as basalt dykes which lie along distinct linear zones (Al-Homoud et al., 1995), following three major structural trends: east to west, north-west to south-east, and east-north-east to west-south-west (Allison et al., 2000). Ground surfaces are generally covered by basalt stones of various sizes and shapes due to weathering of the volcanic rocks, forming extensive stone pavements. These pavements are merely missing in areas where topographic depressions have been filled with sediments or where stones have been manually removed (Allison et al., 2000). In the Azraq region the basalts are replaced by older sedimentary limestone and marls (Fig. 3.3).

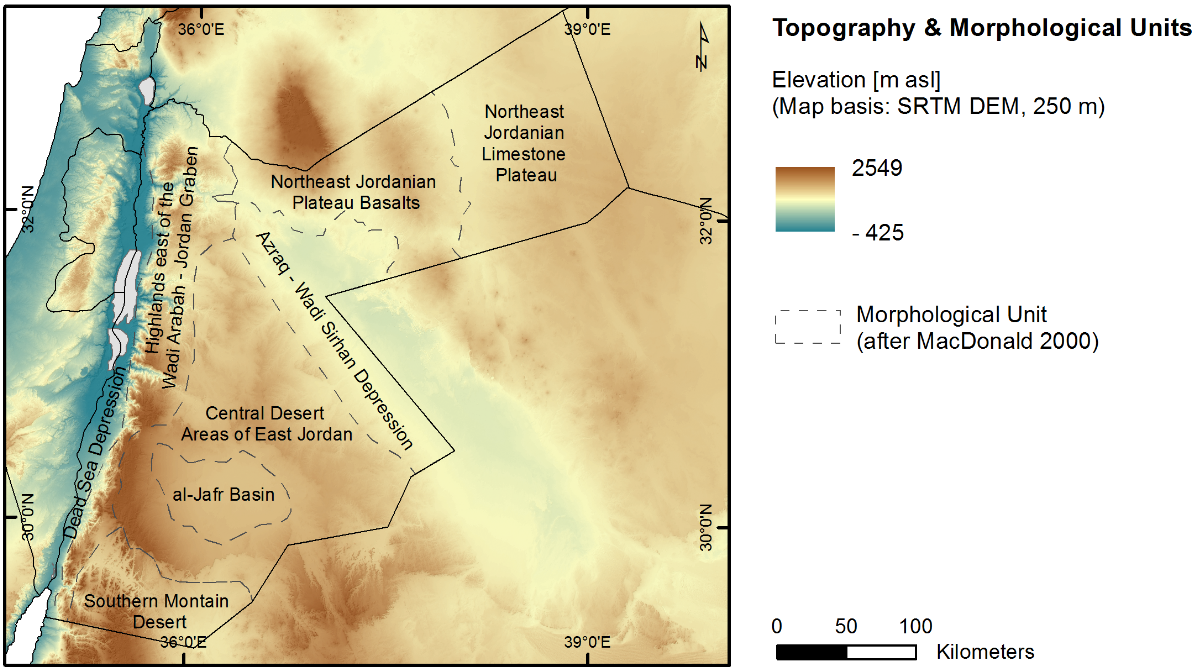

Figure 3.2.: The topography of Jordan and major morphological units; modified after MacDonald (2000).

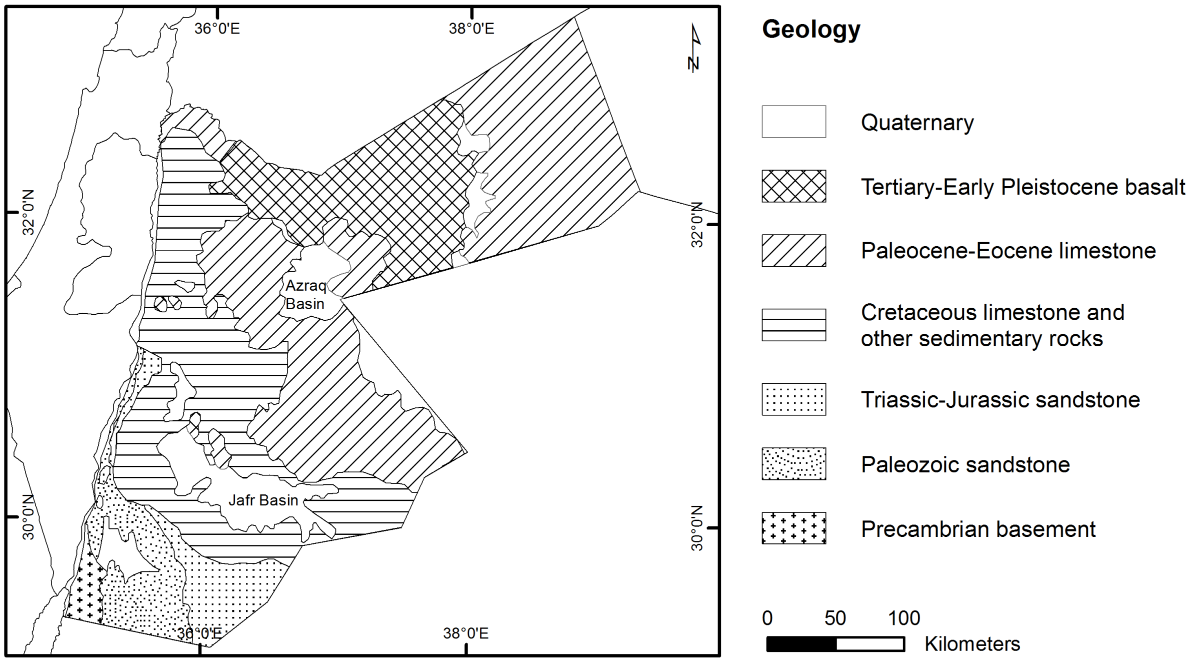

Figure 3.3.: Major lithological groups in Jordan; modified after Cordova (2007).

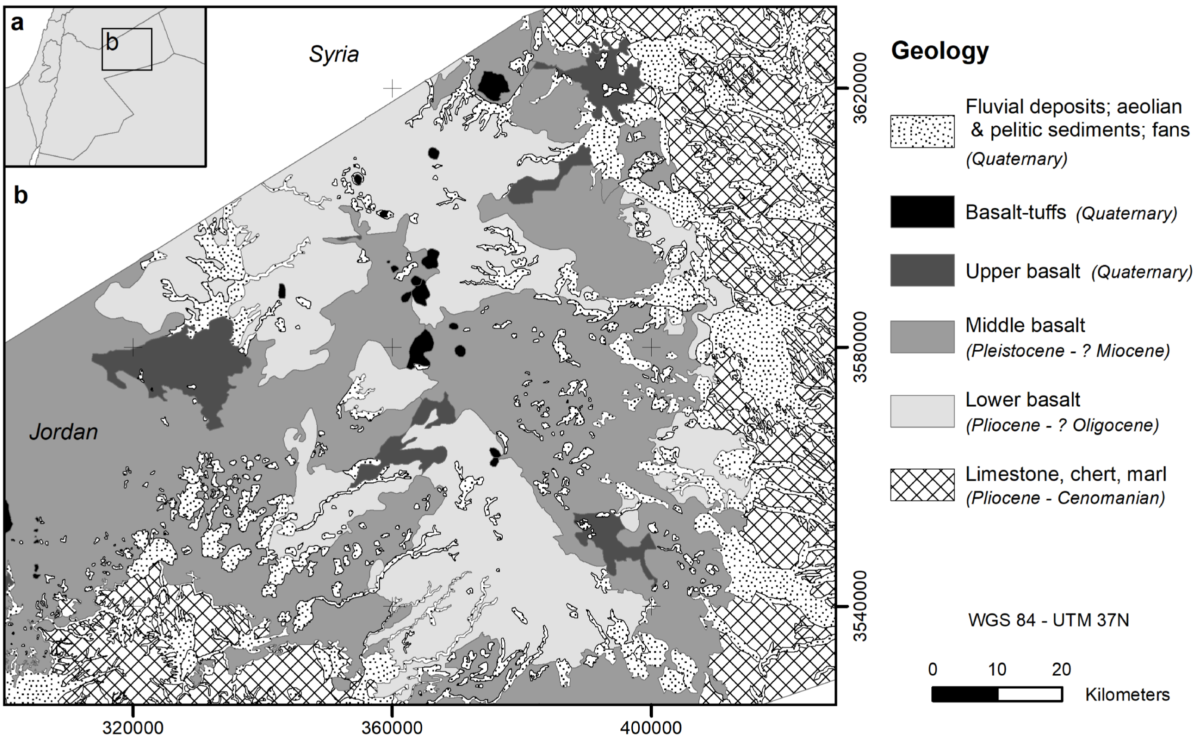

Figure 3.4.: Geological map of the *harra* and neighboring areas; modified after Bender et al. (1968).

Figure 3.5.: Photograph of a typical *harra* landscape. (© J. Krause, 2013)

Figure 3.6.: Photograph of a typical *hamad* landscape. (© J. Krause, 2013)

3.1.4. Climate

3.1.4.1. Present-day climate

Climatically, the northern Badia is located in the transition zone between the Mediterranean environment along the Jordan valley and the fully arid zone of the Syrian Desert (Al-Homoud et al., 1996). Following the Köppen-Geiger classification the area corresponds to a hot desert climate (BWh; Kottek et al., 2006, Fig. 3.7), characterized by marked seasonal variations, with hot, dry summers and cool, moist winters (Allison et al., 2000). Rainfall averages about 100 mm and occurs mainly between November and March. In the northwest of the study area, average rainfall rates exceed 150 mm due to the westerly location and orographic effects at the Jebel Druze. Towards the south and east rainfall rates decline, reaching less than 50 mm in the southern regions close to the political border with Saudi Arabia (Tansey, 1999). Potential evaporation rates are high, ranging between 1500 mm*a^{-1} and 2000 mm*a^{-1} (Allison et al., 2000). The mean annual temperature in Safawi is about 18.9 °C (Meister et al., 2017, Fig. 3.8). The mean annual maximum temperatures reach 35 to 38 °C in summer and mean annual minimum temperatures range from 2 to 9 °C during winter (Allison et al., 2000). Strong winds occur frequently, in the summer coming mostly from the northwest and in the winter prevailing from the northeast (Al-Homoud et al., 1996).

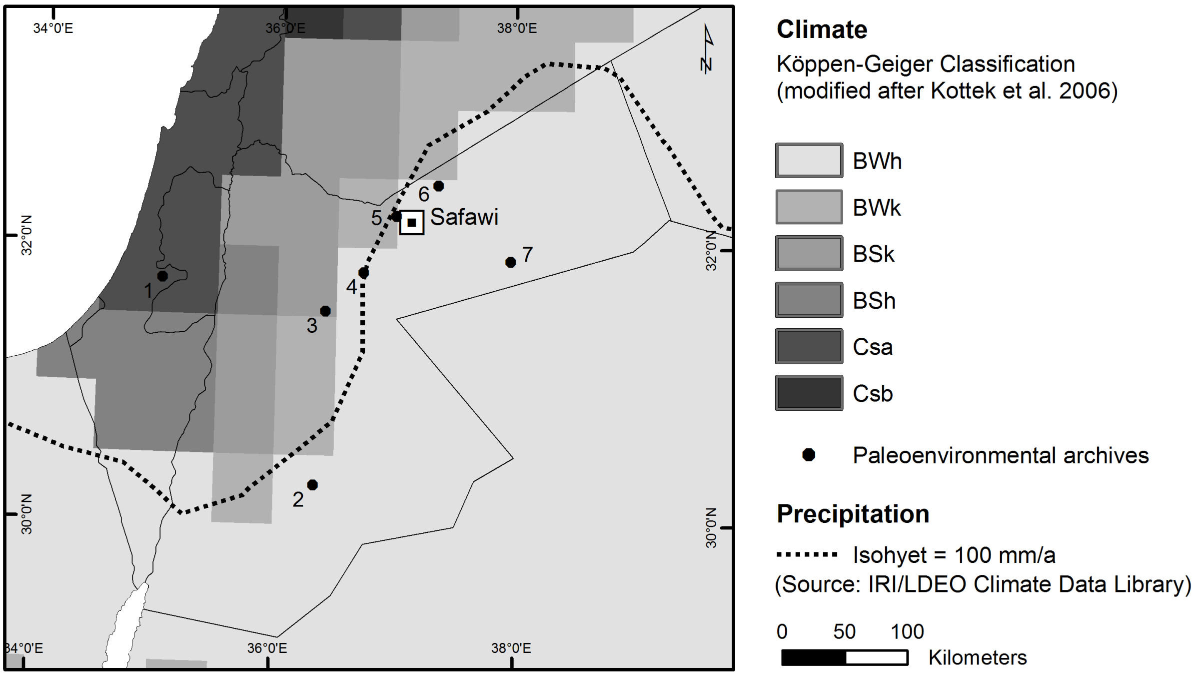

Figure 3.7.: Climate zones of Jordan and neighboring states (after Kottek et al. 2006), and paleoenvironmental studies addressed in this thesis (1 = Soreq caves; 2 = Qa'el-Jafr; 3 = Wadi el-Jilat; 4 = Wadi el-Uwaynid; 5 = Khsheifa Cave; 6 = Qa'a Selma, 7 = Wisad Pools).

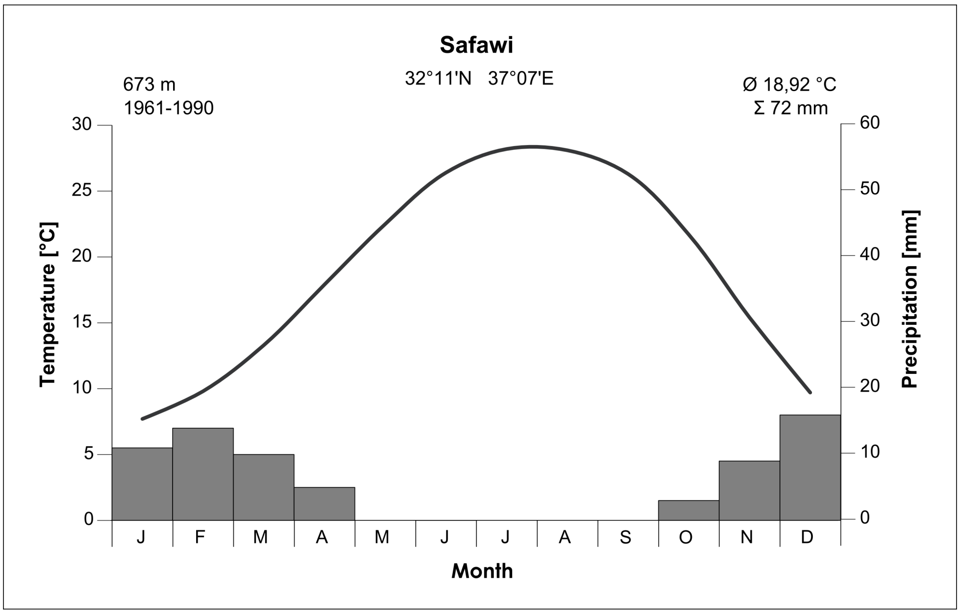

Figure 3.8.: Climate diagram of the Safawi weather station (Data source: FAO 2001).

3.1.4.2. Late Quaternary climate development of the Southern Levant

Palaeoenvironmental research in the Southern Levant (modern Israel, Palestinian territories and Jordan; Rambeau 2010) and neighboring countries is based on a series of paleoenvironmental proxies, such as:

- pollen records from lakes, e.g. Lake Ghab in northwest Syria (e.g. Niklewski and Van Zeist, 1970; Yasuda et al., 2000), Birkat Rum in the Golan Heights (Schwab et al., 2004) and Lake Hula in northern Israel (e.g. Baruch, 1994; Baruch and Bottema, 1999);
- geomorphological evidences derived from soil-sequences (e.g. Gvirtzman and Wieder, 2001), sediment sequences or fluvial terraces (e.g. Cordova, 2000; Goldberg, 1994; Hunt et al., 2004; Rosen, 1991);
- Dead Sea lake levels (e.g. Bookman et al., 2004; Enzel et al., 2003; Kagan et al., 2015) and sedimentary records (e.g. Migowski et al., 2006; Neev and Emery, 1967; Neugebauer et al., 2015);
- stable isotope records from lake- and marine sediment cores (e.g. Kroon et al., 1998; Schilman et al., 2002), snail shells from the Negev desert (e.g. Goodfriend, 1991, 1999) and speleothems from caves in Galilee (Geyh, 1994) and central Israel (e.g. Bar-Matthews et al., 1997, 1998, 1999; Frumkin et al., 1999a,b).

Due to dating limitations and potentially different interpretations of the various proxies it is often challenging to reconstruct paleoenvironmental conditions. Moreover, most of the high-resolution climate archives are located in regions north and west of the Dead Sea and the Jordan Valley, characterized by wetter environment conditions compared to the regions in the east and south (Rambeau, 2010).

The following section will mainly focus on the isotopic evidence from the Soreq cave records. More comprehensive compilations on the climate variability in the Southern Levant and the Eastern Mediterranean during this periods (or parts thereof) were published e.g. by Cordova (2007); Finné et al. (2011); Mithen and Black (2011); Rambeau (2010) and Rosen (2007). Regarding the climatic evolution throughout the late Pleistocene and Holocene in the eastern parts of Jordan, a more detailed description of the available evidence is given in chapter 3.1.4.3.

Isotope records are probably the most important proxies for understanding climatic evolution (Rosen, 2007). With respect to the late Quaternary climate development in the Southern Levant, the most continuous and high-resolution isotopic records are the speleothems of the Soreq caves in central Israel (e.g. Bar-Matthews et al., 1997, 1998, 1999; Bar-Matthews and Ayalon, 2004, 2011, Fig. 3.7). The measured isotope ratios for oxygen (δ^{18}O) and carbon (δ^{13}C) provide valuable information on past rainfall and temperature patterns (Bar-Matthews et al., 1999, Fig. 3.9). Based on ^{230}Th/U dating, the speleothem records cover the past 60,000 years, thus the periods from the late Pleistocene to the Holocene. Nowadays, this area receives a mean annual precipitation of 500-550 mm. The cave temperatures typically range from 18 to 20 °C. The $\delta^{13}C$ values of modern speleothems vary between −11 to −12‰, while the $\delta^{18}O$ values reach an average of about −5.4‰ (Bar-Matthews et al., 1999). In order to interpret the significance of past isotopic variations, Bar-Matthews et al. (1997) have developed a model for estimating mean annual rainfall rates based on the assumption that the modern relationship between average annual rainfall amounts, its $\delta^{18}O$ composition and $\delta^{18}O$ values for the cave water have not changed since the late Pleistocene (Fig. 3.10).

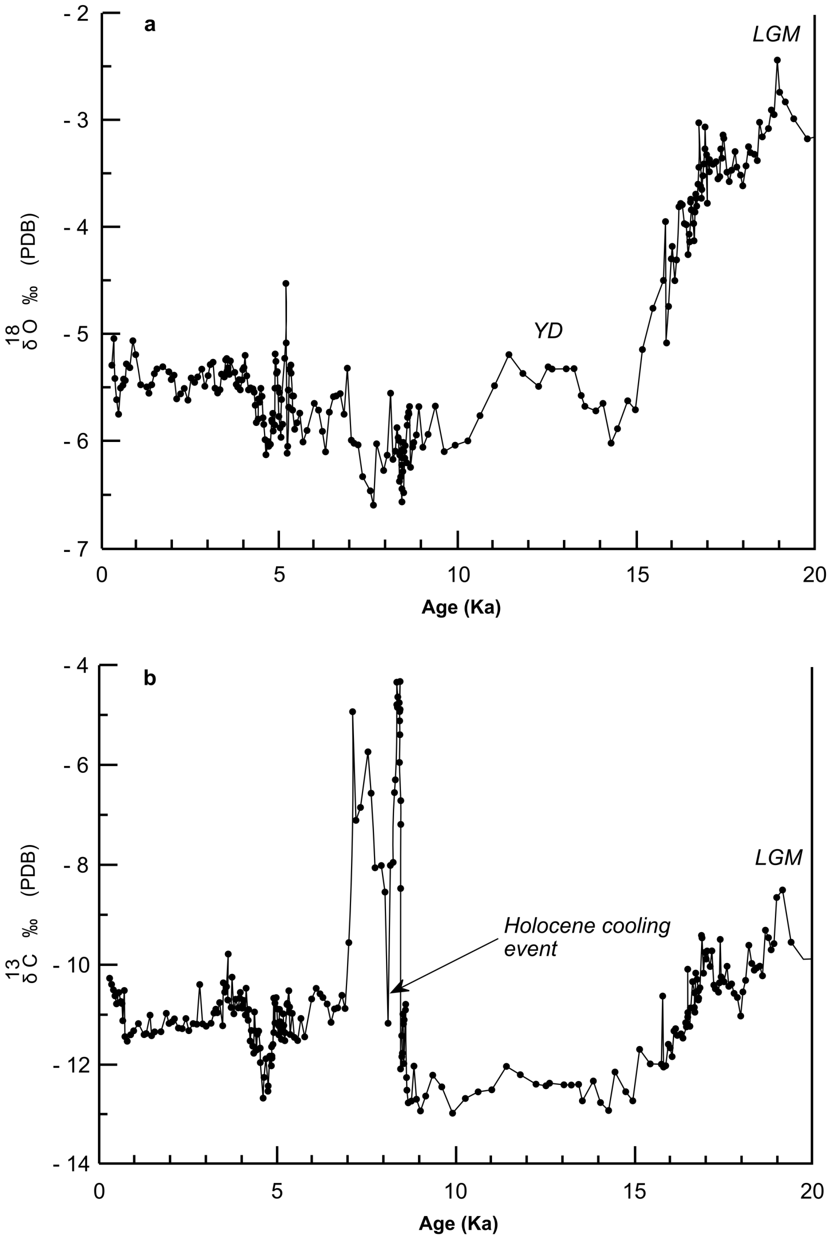

Figure 3.9: $\delta^{18}O$ (a) and $\delta^{13}C$ (b) values of speleothems deposited in the Soreq caves during the last 20 ka, showing: (1) highest $\delta^{18}O$ and $\delta^{13}C$ values during the end of the last glacial maximum (LGM) at 19 ka; (2) a sharp drop in the isotopic values during deglaciation (~17 to 15 ka); (3) an increase during the Younger Dryas (YD) (13.2 to 11.4 ka); (4) the Holocene optimum with the lowest $\delta^{18}O$ and highest $\delta^{13}C$ values 8.5 to 7 ka; (5) a sharp decrease in $\delta^{13}C$ values during the Holocene cooling event at 8.1 ka; (6) many small isotopic fluctuations observed since ~7 ka. The $\delta^{18}O$ and $\delta^{13}C$ values reach the isotopic values of present-day speleothems at ~4 ka.; modified after Bar-Matthews et al. (1999).

According to the isotopic profile of the Soreq cave speleothems over the past 20,000 years (Fig. 3.9), the peaks of δ^{18}O and δ^{13}C at 19 ka are probably related to the last glacial maximum (LGM)—a period when it was extremely cold causing the largest expansion of ice sheets over northern Europe (Bar-Matthews et al., 1999). A sharp drop in both curves between 17.0 and 14.0 ka corresponds with increasing temperatures and the melting of glaciers during the deglaciation. From 13.2 to 11.4 ka the values in both δ^{18}O and δ^{13}C increase clearly, corresponding to the dry and cool global climatic event of the Younger Dryas (YD) at the end of the Pleistocene (Bar-Matthews et al., 1999).

The Holocene started about 11.5 ka. During the Early Holocene, lasting from about 11.5 ka (after Rosen 2007) to 7.0 ka (after Bar-Matthews and Ayalon 2011), the oxygen and carbon isotope records show a clear drop from c. 11.0 to 8.5 ka, indicating a nearly steady trend towards warmer and wetter climatic conditions (Bar-Matthews et al., 1999, Fig. 3.9). The period between 8.5 and 7 ka shows a combination of very low oxygen isotopic values and very high carbon isotopic values—a case which is unique in the isotope record of the Soreq caves. This episode corresponds to the Holocene climatic optimum, which is characterized by a marked increase in rainfall (Bar-Matthews et al., 1999). The climatic optimum is only shortly interrupted by the so-called 8.2 ka Holocene cooling event, when between 8.2 and 8.0 ka δ^{13}C values considerably decrease while δ^{18}O values rise only marginally (Bar-Matthews et al., 1999). According to the isotope evidence from the Soreq caves the Holocene climatic optimum ended at 7.0 ka (Bar-Matthews et al., 1999, Fig. 3.9).

Overall, the climatic optimum led to an increase of winter rains as a result of increasing temperatures and the intensification of the Mediterranean cyclogenesis, as well as the Indian monsoon (Cordova, 2007). Although these changes potentially led to an increase of summer rains in the Arabian peninsula, Egypt and the southern Levant (cf. Fontugne et al., 1994; Blanchet et al., 1997; Bar-Matthews et al., 1999), for Jordan there is no evidence for the occurrence of summer rains during that time. While some records indicate moister conditions, there are no indications for rain seasonality (Cordova, 2007).

After 7.0 ka the δ^{18}O and δ^{13}C curves attained similar values to those of the present, indicating climatic conditions in the Eastern Mediterranean region that are similar to those of today (Bar-Matthews et al., 1999, Fig. 3.9). Considering the rainfall estimates of Bar-Matthews et al. (1998, Fig. 3.10) for the last 7 ka, the period of the Middle Holocene (~7.0–4.0 ka; after Bar-Matthews and Ayalon 2011) is characterized by small fluctuations between wetter and drier climate phases (see also Bar-Matthews and Ayalon, 2004, 2011). After the Early Holocene moist phase a drier phase prevailed which was followed by moister climatic conditions starting at c. 6.5 ka at the beginning of the Chalcolithic period. During the Early Bronze Age I moister conditions alternated with drier periods. A short but distinct dry climatic event occurred at the end of the Early Bronze Age I at about 5.2 ka which was followed by small fluctuations until about 4.0 ka (Bar-Matthews et al., 1998, Fig. 3.10, see also Table 3.1, p. 43, for the chronology of the Southern Levant).

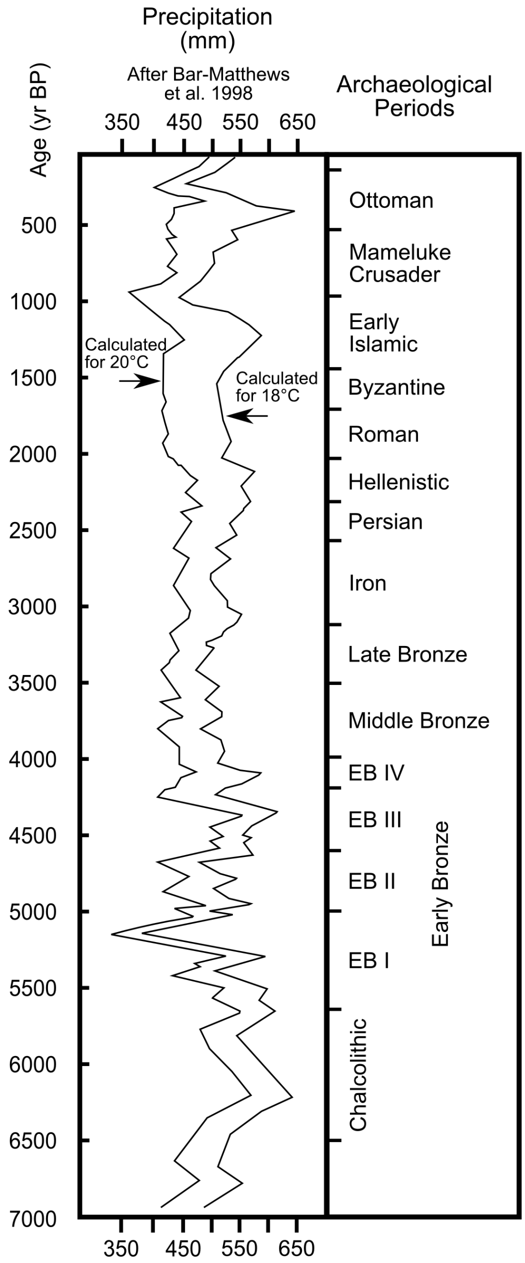

Figure 3.10.: Paleorainfall (based on δ^{18}O data) during the Holocene derived from the Soreq caves after Bar-Matthews et al. (1998), correlated with archaeological periods; modified after Cordova (2007).

Since the beginning of the Late Holocene at around 4.0 ka the climatic conditions are generally characterized by low rainfall amounts, being similar to today or even below (Bar-Matthews et al., 1998; Bar-Matthews and Ayalon, 2004). The sole exception was the period from c. 0.6 to 0.4 ka, where rainfall rates were higher than the current average (Fig. 3.10, Bar-Matthews and Ayalon 2004).

3.1.4.3. Late Quaternary climate development of the eastern Jordan deserts

Even though the western part of the Southern Levant has been well studied, the evidence on climatic changes during the Late Pleistocene–Holocene period are fragmented when it comes to the eastern regions of the Dead Sea and the Jordan Valley (Rambeau, 2010). Especially the eastern Jordan deserts, which are less influenced by the seas compared to the coastal areas of the Levant (Cordova, 2007), are lacking high-resolution palaeoenvironmental records that would allow to understand the climatic development during these periods as well as compare them with the palaeoenvironmental data generated in the Dead Sea area (Rambeau, 2010). The resulting trend of interpolating climatic conditions for these areas from proxy data of the neighboring regions seems problematic (Cordova, 2007), since it is not clear that the climatic evolutions in both regions were similar, either in timing or in intensity (Rambeau, 2010). Under the assumption that rainfall gradients, similar to those of the present or even more pronounced, existed already during the Late Pleistocene/Holocene in the Southern Levant a wet phase during the Early Holocene would have had only little impact on the environments of these regions (Rambeau, 2010; Enzel et al., 2008). This is also demonstrated by a study of Enzel et al. (2008) showing that the southern Negev has probably been hyper-arid during the entire Holocene.

The little evidence that is available from paleoenvironmental records for the eastern parts of Jordan also point to generally arid conditions during the Holocene, as will be described below.

The analysis of a 31 m sediment core from the Qa'el-Jafr basin in southern Jordan revealed evidence for several significant changes in the climate regime of the Quaternary for the Jordan Plateau (Davies, 2005, Fig.3.7). The upper sediments, characterized by a mixture of reworked aeolian and alluvial sediments, however, seem to lack a Holocene sequence as indicated by the very old sediment ages recorded near the surface. The lack of a depositional Holocene record is interpreted as the result of deflation processes caused by increased aeolian activity (Davies, 2005).

A similar observation was made by Al-Tawash (2007) who investigated a 3.5 m sediment core from the Qa'a Selma located in northeastern Jordan (Fig. 3.7). The sediment sequence analyzed for radiometric chronology (^{14}C) and stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) provides a Late Pleistocene record, again lacking Holocene depositions. Variations in $\delta^{13}C$ and $\delta^{18}O$ values reveal changes in environmental conditions induced by climate change. Accordingly, most of the Late Pleistocene record of the Qa'a shows arid climatic conditions except for two wet phases dating to periods between 37–32 ka and 15.5–13.9 ka (Al-Tawash, 2007).

Frumkin et al. (2008) investigated calcite speleothems from a lava tube (Khsheifa Cave) of the basaltic region of northeastern Jordan in order to explore the environmental conditions during the Pleistocene and Holocene periods (Fig. 3.7). Based on U-Th dating, the speleothem depositions could be dated to the periods from 250–220 ka and 80–70 ka lacking speleothems dating to the Late Pleistocene and Holocene. The available evidence indicates general aridity of the basaltic desert region during most of the mid-late Quaternary. This was interrupted by short wetter periods which resulted from the intensification of Mediterranean cyclonic systems that penetrated the north Arabian Desert (Frumkin et al., 2008). Frumkin et al. (2008) argue that the termination of speleothem deposition during the Late Pleistocene can be linked only to a lack of water as the availability of carbonate dust grows with time. In contrast, the absence of speleothem deposition during the Holocene is most likely related to enhanced aridity caused by increased heat and associated evaporation. Consequently, during the Holocene the climate in northeastern Jordan was arid, although small-scale fluctuations in rainfall intensity can not be excluded (Frumkin et al., 2008).

Due to the obvious lack of continuous, long-term paleoclimate records, archaeological data and associated geomorphological studies are important sources of paleoenvironmental information for the Jordan deserts (Davies, 2005). With regard to northeastern Jordan, Garrard et al. (1988a) investigated sediment profiles at dated sites in Wadi el-Jilat and Uwaynid (Fig. 3.7). Based on the finding of developed soils that are indicative for higher groundwater levels and a dense vegetation it could be demonstrated that the climate was a little wetter than today during the time between c. 23,000 (Uwaynid 18) and c. 15,000 BP (Jilat 6). The observation that Late Epipaleolithic and Neolithic sites (post 15,000 BP) are found in aeolian sediments point to climatic conditions similar to those of today (Garrard et al., 1988a).

Excavations at Wisad Pools have uncovered reddish-brown sediments with a thickness of 35 to 40 cm underneath two Late Neolithic structures that were interpreted as possible topsoils (Rowan et al., 2015b; Rollefson et al., 2016, Fig. 3.7). Moreover, scattered pieces of charcoal from deciduous oak and tamarisk were recovered from two hearths in a building dated to c. 6500 cal BCE (Rowan et al., 2015b), indicating that climate conditions during the Late Neolithic were probably less arid than today (Rollefson et al., 2016).

3.1.5. Hydrology and geomorphology

The drainage system of northeastern Jordan is sub-divided into three major basins, namely the Azraq basin in the west, the *hamad* basin in the east, and the Wadi Serhan basin in the south (Fig. 3.11). The wadi systems which drain each basin are extensive (Tansey, 1999, Fig. 3.12). However, besides basin delineation, there is a lack of information about the characteristics of each region (Al-Homoud et al., 1995).

Groundwater is available from three aquifers. The lower aquifer is found at depths of 1.3 to 3.4 kilometers. The upper aquifer, today's most important water resource (Dottridge and Abu Jaber, 1999), is located at depth of 450 to 50 meters (Allison et al., 2000)—making it inaccessible to human communities until the most recent past (Dottridge and Abu Jaber, 1999).

Within the *harra* the altitude gradual declines from north to south, with elevations ranging from around 1200 to 400 meters (Al-Homoud et al., 1995; Allison et al., 2000). The topography is gently undulating and dominated by low hills; many slopes are slightly inclined and show

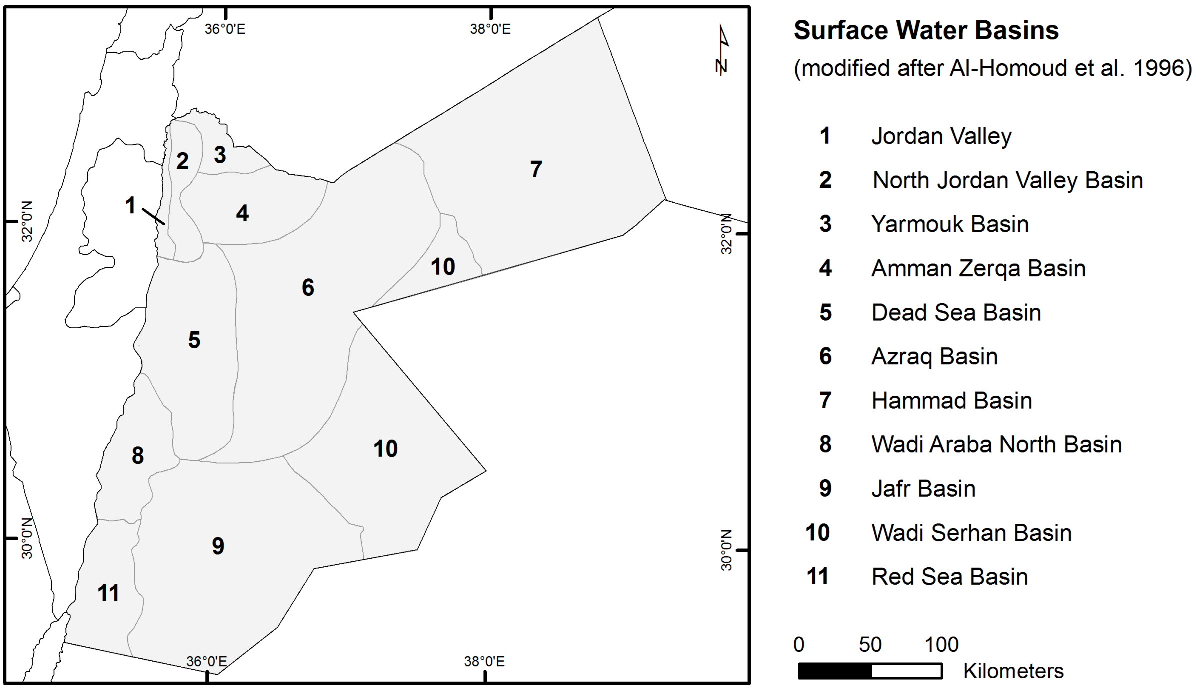

Figure 3.11.: The main surface water drainage basins in Jordan; modified after Al-Homoud et al. (1996).

a concavo-convex profile curvature (Al-Homoud et al., 1995). Generally, the distribution of basalt flows plays an important role since the age of the lava flows significantly determines ground surface topography, landform development and drainage network connectivity (Allison et al., 2000, Fig. 3.4). On the older flows the landscape is more rounded and characterized by well-developed drainage patterns. The most recent basalt flows feature rugged topography with poorly linked surface drainage and many small silt-filled depressions (Al-Homoud et al., 1996; Allison et al., 2000). Fine-grained sediments occur in depressions, located between the basalt hills (Al-Homoud et al., 1996). These locally called 'Qa'a' are flat mudpans and similar to playas due to their endorheic character (Tansey, 1999); in contrast to most playa lake deposits (Schütt, 2004), sediments deposited in these mudpans of the Badia are seldom saline (Tansey, 1999). The largest qa'a depressions are located along the *harra/hamad* boundary, often extending over 10 km in length and 1 km in width (Bender, 1968). Besides, another geomorphological feature that is locally called 'marab' refers to depressions with a well-defined inflow and outflow, normally in the form of a wadi channel (Tansey, 1999).

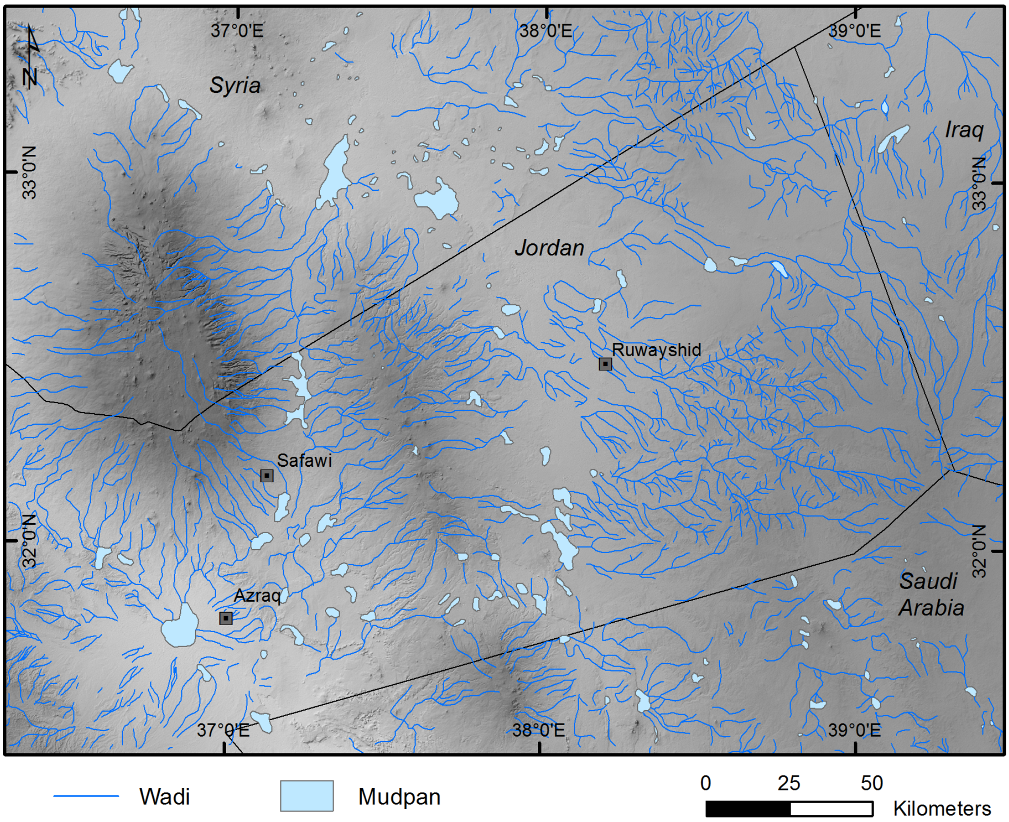

Figure 3.12.: Surface water drainage in northeastern Jordan; modified after ACSAD (1983) (Base map: SRTM 3 DEM).

3.1.6. Soils and vegetation

The modern soils in northeastern Jordan are poorly developed, and thus classified as raw desert soils (Al-Eisawì, 1996, Fig. 3.13). The current natural vegetation cover of northeastern Jordan is classified as part of the Saharo-Arabian plant region (Al-Eisawì, 1996, Fig. 3.14), whose characteristic taxa are *Fabaceae*, *Tamaricaceae*, *Chenopodiaceae*, *Caryophyllaceae*, *Zygophyllaceae* and *Brassicaceae* (Frey and Lösch, 2010). Vegetation is sparse consisting of grasses, herbs, and shrubs and is dominated by chenopod plants such as *Salsola vermiculata* and *Halogeton alopecuroides* (Al-Eisawì, 1996). Vegetation growth is mostly restricted to qa'a, and wadi areas since these are flooded regularly during the winter rainy season and, thus, provide essential moisture reserves (Tansey, 1999). Moreover, the basalt boulders on the surface retain some moisture and are regularly covered by lichens (Al-Eisawì, 1996; Al-Homoud et al., 1996). The availability of grassland fluctuates across the area and depends predominantly on the distribution and timing of rainfall, the soil character and the topography (Rowe, 1999). The vegetation cover of the region has been considerably reduced in recent times due to overgrazing and the destruction of bushes and shrubs for fuel (Betts, 1998).

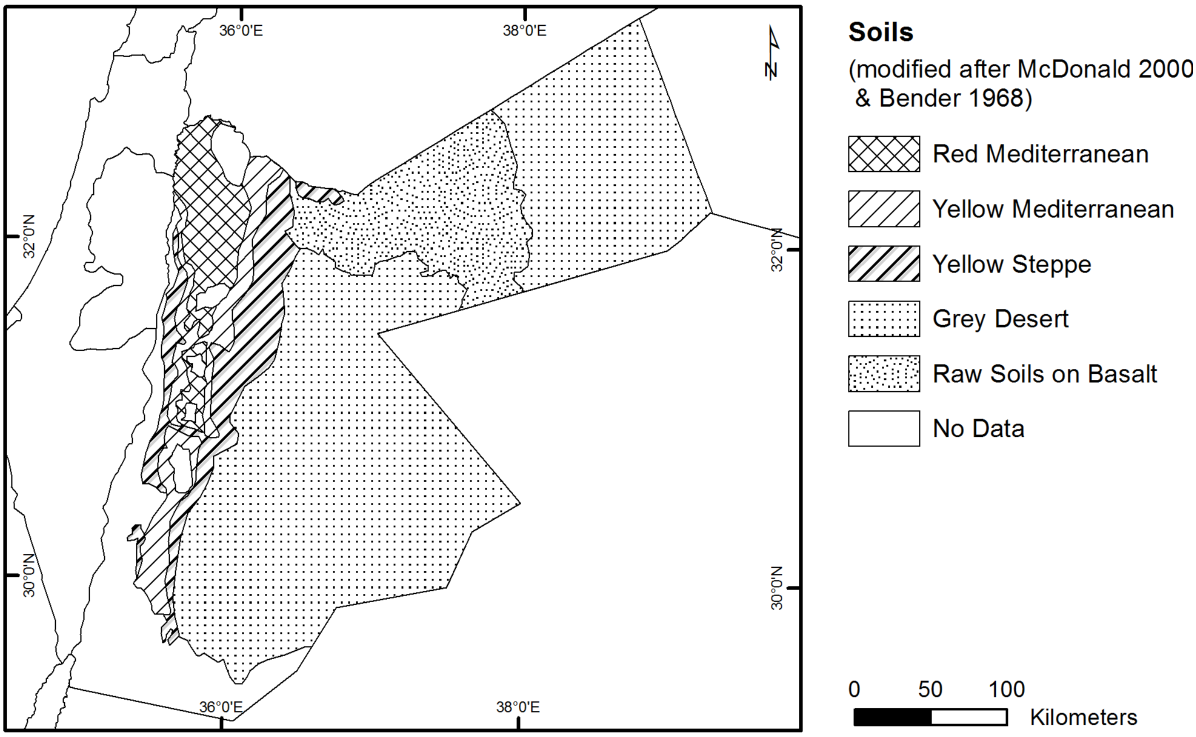

Figure 3.13.: Soil map of Jordan; modified after MacDonald (2000) & Bender (1968).

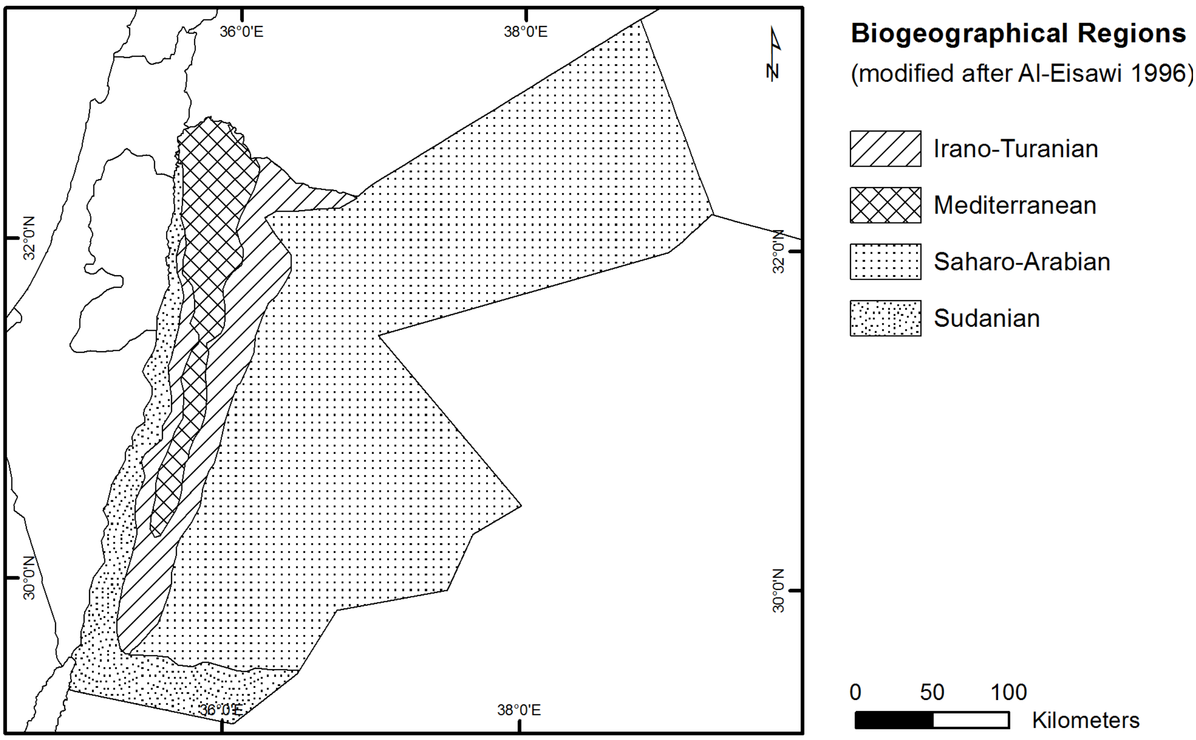

Figure 3.14.: Biogeographical regions of Jordan; modified after Al-Eisawì (1996).

3.1.7. Land use practices

Historically, the northern Badia lies in a ‘transitional zone’ between areas in which cereal agriculture and mobile pastoralism are the dominant economic forms of production (Lewis, 1987). Due to the high aridity in northeastern Jordan the long tradition of rainfed agriculture is mainly confined to the northwestern highlands of the Jebel Druze (Helms, 1981; Tansey, 1999; Roe, 2000). However, in some qa’a and marab areas within the northern Badia, e.g. the Qa’a Shubayka, the environmental settings also support the cultivation of cereal crops (Tansey, 1999). The common cultivated crop is barley, although, in well-watered areas or in especially wet years, occasionally wheat is grown (Roe, 2000).

Within the northern Badia, the present-day form of land use is dominated by mobile pastoralism, mainly based on sheep and goat herding (Betts et al., 2013; Roe, 2000). Thereby, the current population of the northern Badia belongs almost exclusively to the Ahl al-Jebel Bedouin tribe that has resided at the southeastern slopes of the Jebel Druze and within the area of the *harra* for a long time, as documented by oral history and available documents (Roe, 2000). Traditionally, these herders of goats and sheep follow a common pattern of annual migration in the Badia involving two constituent movements which are described as *al tashreeq* (‘the easting’) and *al taghreeb* (‘the westing’) (Roe, 2000, Fig. 3.15). During *al tashreeq* in late autumn (late October and early November) the Ahl al-Jebel Bedouin traditionally move rapidly east towards the *hamad* plains where they scatter across the desert-steppe during the winter and spring months, following the rain and plant growth (Roe, 2000; Betts, 1998). By late spring (from late February onwards), as these pastures are grazed out, *al taghreeb* starts, corresponding to a slow westerly movement back into the *harra* where, owing to the shading of boulder cover and general inaccessibility, perennial plants can be found locally (Roe, 2000). The movement ends at the fringes of the desert-steppe and the settled areas where the herders are based during the summer (Betts, 1998). In order to prevent an early over-exploitation of grazing lands around water sources the herders usually postpone their return to the summer residence sites for as long as possible (Roe, 2000). Traditional summer residence sites in the Badia include the Azraq basin and the southern foothills of the Jebel Druze. Here, the pastoralists co-reside with sedentary agrarian communities, exchanging pastoral products for goods they require (Roe, 2000). The described migration pattern is spatially and temporally variable and depends on the availability of pastures and water, factors which can vary greatly from year to year (Betts, 1998).

With the emergence of The Hashemite Kingdom of Jordan in the 1950s these traditional land use practices started to change significantly. The new international borders separated the northern Badia from the Arabian Peninsula and Syria without consideration of the spatial distribution of tribes, or the existing land use and tenure patterns; which in turn has influenced and changed the economic behavior of their inhabitants (Roe, 2000).

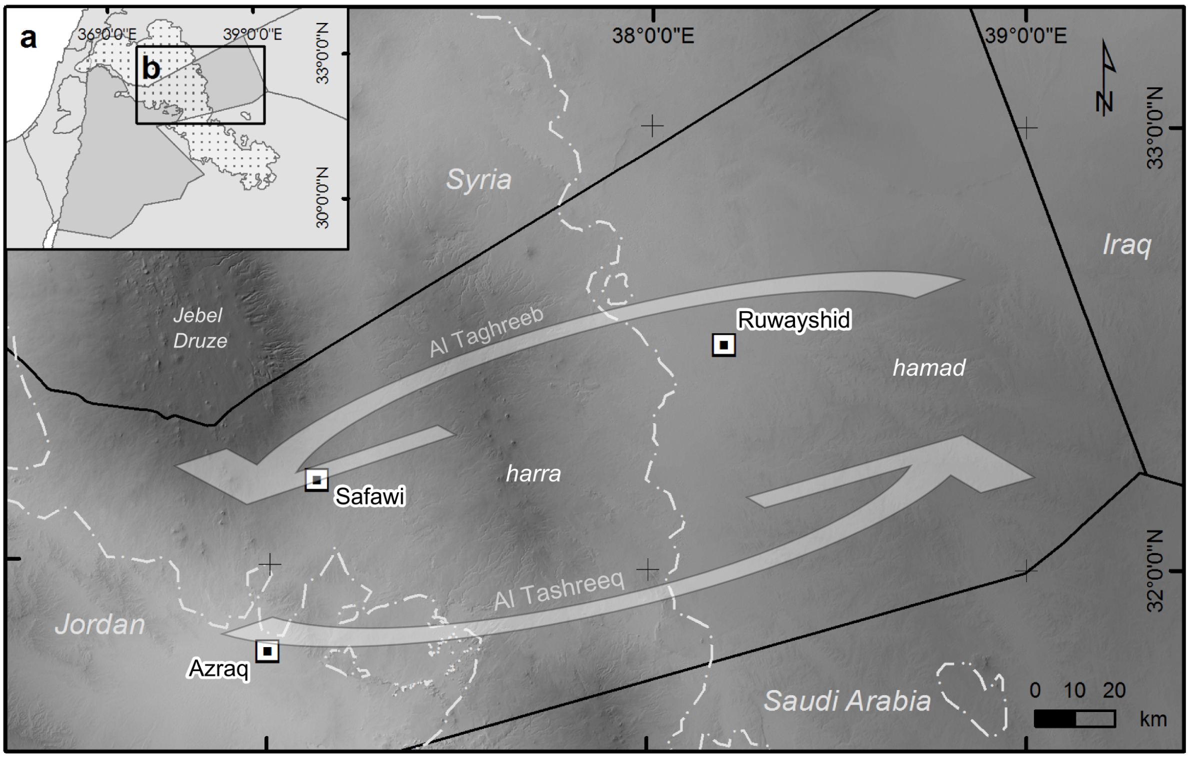

Figure 3.15.: Traditional annual migration cycle of the Ahl al-Jebel tribe (after Roe 2000) within northern Jordan.

The establishment of the state was accompanied by several infrastructural developments, including the digging of deep wells which provided reliable water supplies to nomadic livestock herders in many parts of the northern Badia (Roe, 2000). The additional construction and extension of road networks, the introduction of livestock feed subsidies and the replacement of camels by motorized transport meant that large herds could be supplied with water and fodder for long periods in previously remote areas, irrespective of natural grazing conditions and water supply (Roe, 2000). Moreover, a rapid population growth in Jordan during the 1960s and 1970s was associated with a market expansion for pastoral products. During the mid-1980s the consumer preferences changed, asking for cheaper white and imported meats, which reduced the demand in the domestic market (Oakeley, 1997). Since then, the export of pastoral goods increased considerably, especially to markets of the Gulf region, Iraq and Saudi Arabia (Roe, 2000).

Overall, the pastoral system has become monetized, market-oriented and the numbers of animals increased considerably (Al-Tabini et al., 2012; Roe, 2000). While the traditional migration pattern with its shifting pasture areas enabled the recovery of the flora, increased herd sizes and the year round grazing possibilities disturbed the natural balance (Roe, 2000).

As a result, the regional grasslands have been substantially degraded over the last decades (Juneidi and Abu Zanat, 1993).

In addition to these important changes in the traditional organization of livestock, also the settlement activities of the Bedouin tribes have changed. During the late 1970s and 1980s there was a widespread transformation to a predominantly sedentary way of life of the Ahl al-Jebel tribe who started to constructed houses and practice agriculture on the southern foothills of the Jebel Druze. At the beginning, the Bedouins continued their seasonal migration into the *harra* and the *hamad*, but with the increased utilization of subsidized fodder during the 1980s it was no longer necessary (Roe, 2000). By the end of the 20th century many of the formerly nomadic pastoralists were also employed in other sectors including military service (Findlay and Maani, 1998). Only about a quarter of the Badia population still relied on livestock herding as their primary means of subsistence (Roe, 2000).

Concerning transitions in agriculture, the northwestern part of northeastern Jordan has faced the most significant changes. Since the 1960s, there has been a dramatic eastward expansion of the cultivated area along the southern foothills of the Jebel Druze, triggered by population growth and migration and the establishment of new settlements or the expansion of existing ones (Millington et al., 1999). During this period there has been a change from agriculture practiced by mobile pastoralists to agriculture practiced by farmers who keep animals, coinciding with an increase in rainfed and irrigated cultivation. Cultivated crops mainly comprise rainfed barley, wheat, irrigated vegetables, forage crops, olives and fruit trees. The irrigation water for the fields originate from recently drilled wells or from piped 'domestic' water supplies (Millington et al., 1999). Overall, the economic change and development in the northern Badia has been very rapid and significant during the 2nd half of the 20th century (Roe, 2000).

3.1.8. Occupation history

In northeastern Jordan little is known about human activities in periods prior to the 10th millennium BCE. Epipaleolithic occupations in the *harra* are documented by small scatters of microliths, small camps and knapping sites dating to the Geometric Kebaran and Natufian periods (Betts, 1993, cf. Table 3.1, p. 43, for the chronology of the Southern Levant). While there is little evidence for the Pre-Pottery Neolithic A period (Betts et al., 2013), later prehistoric periods, dating from the 7th to the late 4th millennia BCE, offer a large number of archaeological sites and remains displaying extensive human activities (cf. Akkermans et al., 2014; Betts et al., 2013; Müller-Neuhof, 2014a; Kennedy, 2011; Rollefson et al., 2014a; Rowan et al., 2015b). Especially for the Late Neolithic period, a relatively large and rapid population increase is indicated (Rollefson et al., 2014a).

Besides archaeological survey and excavation works, intensive analyzes of satellite imagery and aerial photography, revealed hundred of thousands of stone structures all over 'Arabia' (stretching from Syria to Saudi Arabia; Kennedy, 2011), called 'The Works of the Old Men' (cf. Maitland, 1927; Rees, 1929). These structures are often only 50-100 cm in height and hardly visible on the ground (Kennedy, 2011). In northeastern Jordan alone, some tens of thousands structures have been discovered which are mainly restricted to the basaltic *harra*. Archaeological surveys and excavations have demonstrated that they are largely prehistoric in age, with some of them dating back to the 7th millennium BCE (Kennedy, 2011). Moreover, the *harra* is littered with thousands of prehistoric rock art images and inscriptions (e.g. Betts and Helms, 1986; Macdonald, 1982, 1983, Fig. 3.17d). Among the constructions of basalt stones visible from the air there are several major types:

- *Kites:* Kites are large funnel-shaped installations which consist of two or more stone walls ('tails') converging on an enclosure ('head') which usually has small circular 'hides' set around (cf. Akkermans et al., 2014; Kennedy, 2011, Fig. 3.16). There are various forms of kites which are distributed all over the Middle East and beyond (cf. Crassard et al., 2014). Commonly, they are interpreted as traps for wild animals such as gazelles, oryxes, and onagers (Kennedy, 2011). It is assumed, that the funnels guided the game into the kite's head or 'killing field' (e.g. Helms and Betts, 1987; Holzer et al., 2010; Kempe and Al-Malabeh, 2013; Kennedy, 2011; Nadel et al., 2010, see Braemer and Echallier 1995 for a different interpretation, Barge et al. 2015 for further discussions and Crassard et al. 2014 for an overview of this debate). The 'hunting' theory was recently strengthened by excavations of a circular feature incorporated into a kite-enclosure wall in the Jafr Basin of southern Jordan (Abu-Azizeh and Tarawneh, 2015). The structure proved to be a pit which was dug into the ground, reaching a depths of c. 1.7 m. This finding strongly supports the idea that the animals were forced to jump into these structures to be trapped inside. However, it is also possible that similar structures may have been shooting hides for hunters (Abu-Azizeh and Tarawneh, 2015).

  In the Jordanian *harra* only, there are more than 1000 recorded kites (Kennedy, 2011, maps showing the distribution of kites in this region are given e.g. by Kennedy 2012; Barge et al. 2015 and Kempe and Al-Malabeh 2013). Usually the kites are distributed along lines which extend over long distances, ranging from c. 15 to 60 km. To date, about twelve lines of kites could be identified in the Harrat Ash Shaam (Barge et al., 2015). Apart from very few exceptions, the kite openings in this region are oriented towards the east, the southeast and the south (Kempe and Al-Malabeh, 2013).

  To date, only a few kite structures have been dated (5th–3rd millennium BCE in southern Israel, Nadel et al. 2010; 4th–2nd millennium BCE in the Negev–southeast Sinai, Holzer et al. 2010). In the Jordanian *harra*, it is assumed that the construction of kites could have been started before the Pre-Pottery Neolithic based on the observation that the guiding wall of a kite was integrated in a Late Pre-Pottery Neolithic B (c. 7500–7000 cal BCE) architectural structure at Dhuweila (Helms and Betts, 1987; Betts, 1998). Further evidence for a Neolithic construction age of kites is given by Late Neolithic

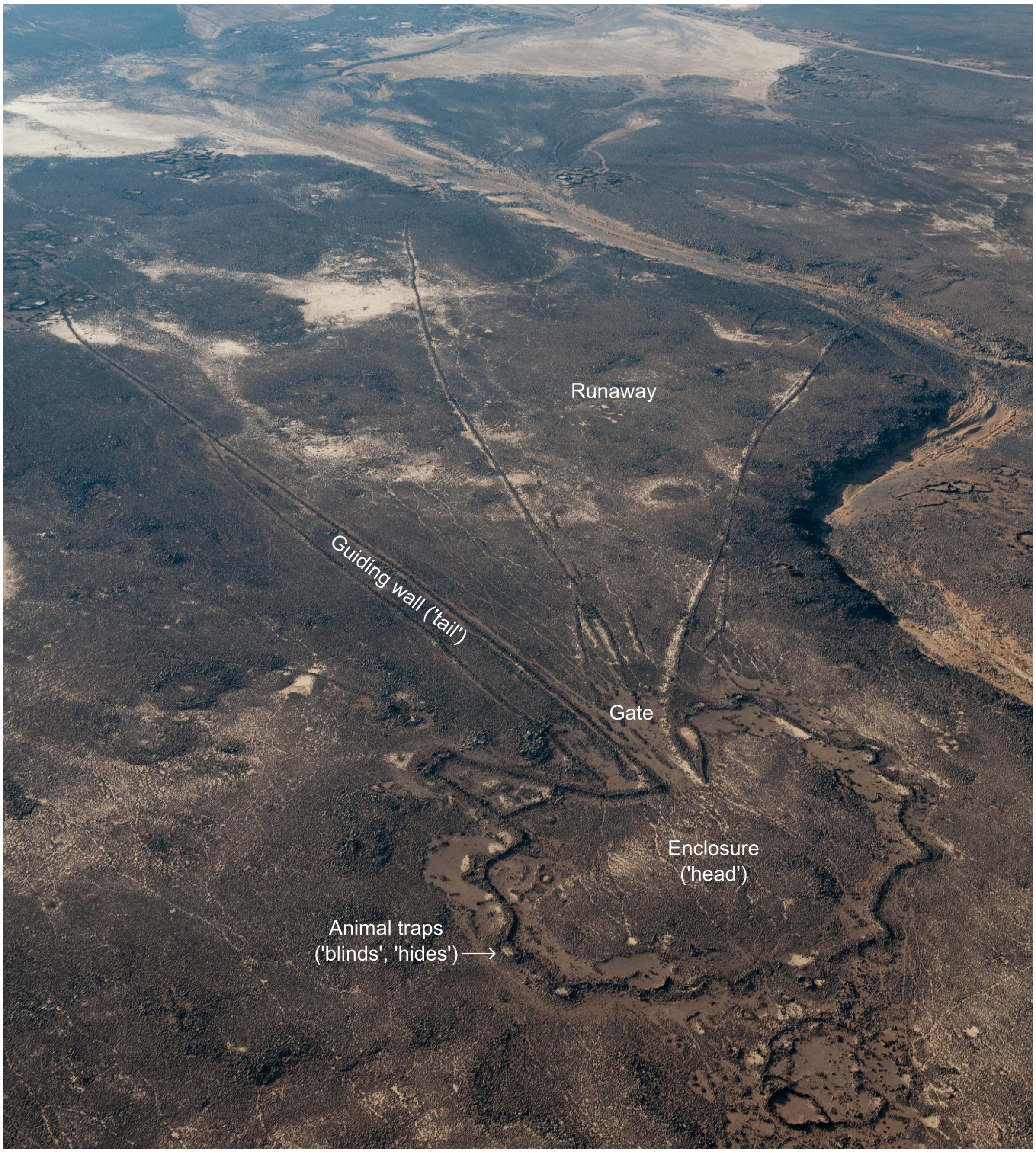

Figure 3.16.: Aerial photograph of a Jordanian kite (Safawi Kite 104, Head c. 200 m diameter; tails c. 600, 900 and 1300 m; APAAME_20090928_DLK-0058, cf. Kennedy 2011) and the main features of a kite after Kempe and Al-Malabeh (2013) and Kennedy (2011); © APAAME, by permission.

Figure 3.17.: (Aerial) photographs of archaeological features in northern Jordan. 17a: A complex meandering wall near the top of the photograph and two wheels close to the Wisad Pools site (APAAME_2009_1004_RHB-0108, cf. Rollefson et al. 2016); 17b: Amra pendant 1., the tail consists of a succession of small individual cairns to a length of c. 70 m. (APAAME_20090917_DLK-0052, cf. Kennedy 2011); 17c: Safawi wheel 6 — c. 35 m diameter, six spokes, five internal cairns (APAAME_20090928_DLK-95C, cf. Kennedy 2011); 17d: Safaitic inscriptions and rock art, Wadi Rajil, Jordan (APAAMEG_20100526_DLK-34, cf. Kennedy 2011); © APAAME, photographs modified, by permission.

enclosures which overlay kites in the western *harra*, suggesting that "[...] the kites in their original shapes must have been constructions of the earlier 7th millennium BCE or before" (Akkermans et al., 2014, p. 190). However, other scholars argue for later ages (cf. Braemer and Echallier, 1995). In view of their wide distribution, Rollefson et al. (2016) assume that kites were probably constructed over thousands of years. Despite the uncertainty about the kites chronology and their function(s), cultural issues such as social organization and economical aims are still hardly understood (Barge et al., 2015).

- *Meandering Walls:* Walls occur in various forms of complexity and some of them show signs of modifications (Kennedy, 2011). Next to kites and their guiding walls a second type of walls are 'meandering walls', described as "[...] low, zig-zagging barriers that criss-cross the ground for several kilometers [...]" (Rollefson et al., 2016, p. 941; Fig. 3.17a). Their function remains largely unknown. According to Kempe and Al-Malabeh (2010b) they seem to have guided migrating animals along specific paths or into bag-like constrictions. Due to the observation that some kites were built across the meandering walls or integrated them into their own structure, Kempe and Al-Malabeh (2010b) assume that meandering walls may have been their predecessors (cf. also Betts 1983).

  In the absence of available radiometric dates for these structures their ages remain largely unknown. For Wisad Pools, a meandering wall is reported that extends about seven kilometers in length (Rollefson et al., 2014c). Due to its close proximity to residential structures, Rollefson et al. (2016) presume that the wall is probably older than most of these structures. As three excavated buildings at Wisad Pools date to 6500–6000 cal BCE, the meandering wall possibly predates this period (Rollefson et al., 2016).

- *Cairns and pendants:* In the Jordanian *harra* there are thousands of cairns. In their modest form the bodies are simply covered by a few stones. More elaborated versions are chambered cairns made of dry-built stone slabs that have a circular form; also termed as 'tower' tombs. They usually have a corbelled roof and a doorway. A distinct version of these tower tombs are 'bulls-eye' chambered cairns which are characterized by an outer circle made of a stone ring wall (Kennedy, 2011).

  A specific mortuary structure are pendants. In the Harrat Ash Shaam, pendants are characterized by a burial cairn to which a chain of small stone-built chambers or simple piles of stones is added (Kennedy, 2011; Rollefson et al., 2016, Fig. 3.17b). While the burial cairns are usually about 3 m in diameter and can reach heights up to 3 m (Rollefson et al., 2016), the overall length of a pendant is rarely more than 20 to 30 m (Kennedy, 2011). Regarding their usage, pendants presumably functioned as memorial cenotaphs (cf. Rowan et al., 2011). Excavations of pendants at both Maitland's Mesa and Wisad Pools revealed that they are empty, showing no evidence of associated artifacts or bones (Rollefson et al., 2012; Rowan et al., 2015a). Because of their special position on hilltops or other locations from which they are easily visible, they may represent the honoring of a special individual. To date, Jordanian pendants have not been dated but it is conceivable that they were built over a long period of time in the late prehistory (Rollefson et al., 2016).

- *Wheels:* A distinctive version of roughly circular structures made of basalt stones are termed 'jellyfish' (Betts, 1982b,a), 'wheel houses' (Kempe and Al-Malabeh, 2013, 2010b) or 'wheels' (Kennedy, 2011; Akkermans et al., 2014; Rollefson et al., 2016). While many of these sites consist of a roughly circular structure, with numerous enclosures in the center, surrounded by small 'huts', others are segmented by radiating walls. Moreover, cairns occur frequently within the wheels or in their direct vicinity (cf. Akkermans et al., 2014; Betts, 1982b,a; Kennedy, 2011; Rollefson et al., 2016, Fig. 3.17a, c).

  Although, the utilization of the wheels is still unknown a hypothesis—given by Betts (1982a)—is that the interior divisions may have functioned as animals pens, whereas the 'huts' provided protection and shelter for herders and their family. Recently it has been suggested that the wheels had a funerary/religious purpose due to the frequent presence of cairns in their vicinity (Kennedy, 2011). Archaeological surveys of 16 prehistoric wheels (dated based on surface findings) in the Jebel Qurma region, however, revealed that although some associated cairns are presumably of prehistoric age, most of the cairns seem to be of Safaitic age, indicating that they were not directly related to the wheels (Akkermans et al., 2014). In view of the varying forms of wheels, Rollefson et al. (2016) note that it seems unlikely that they had only one function. Instead, they presume that different wheel subtypes were used for different purposes (Rollefson et al., 2016).

  To date, altogether more than 1000 wheels have been identified within the basalt region of the Harrat Ash Shaam (Kennedy, 2012). Thereby, many cases have been observed where a wheel overlies kite structures, implying the latter are older (Kennedy, 2012; Kempe and Al-Malabeh, 2010b). Surface findings and OSL dates of wheels in the *harra* of Jordan indicate that these structures originate from the Late Neolithic to the Chalcolithic/Early Bronze Age (cf. Akkermans and Huigens, in press; Athanassas et al., 2015).

- *'Camps':* Particular common architectural structures within the *harra* are simple stone circles (or enclosures) which are scattered throughout the region in a large variety of sizes and shapes (Betts, 1982b). Made of stockpiled basaltic stones, they usually occur in clusters of sub-circular structures (Betts et al., 2013). In the archaeological record, these sites are commonly linked to previous pastoral activities since the larger structures appear to be animal enclosures (also known as corrals or pens, Betts, 1982b) used by herders for corralling their flocks of sheep and goat during the night to prevent straying. The provision of shelter for the animals from wind is especially important in winter and early spring (Betts et al., 2013). Evidence for this interpretation is given by modern

Bedouins who apply the same technique, often re-using earlier structures (Betts, 1982b). In the past, these corrals were most likely also used to protect the herds against wild animals (Betts et al., 2013). Similar structures but smaller in size are commonly attached to the larger ones and are usually interpreted as simple windbreaks or huts used by the shepherds (Betts, 1982b; Rollefson, 2013). The abundant occurrence of artifacts in and around these enclosures in the Jebel Qurma region as well as the occasional occurrence of fireplaces suggest that these enclosures were also used for habitation and related domestic activities of mobile pastoral groups, rather than being simply corrals (Akkermans et al., 2014). Generally, enclosures are often associated with tent sites, marked by low straight stone lines that held down the tents against the wind (Betts, 1982b). An additional and important character of the enclosures indicating their use by herders is their location, which is often linked to periodic water sources, e.g. along wadis or the shorelines of mudpans (Akkermans et al., 2014; Müller-Neuhof, 2014b). The basic form of sub-circular stone enclosures has been in use in the Jordanian desert from earliest prehistoric times (Betts, 1982b). However, an exact age determination is often difficult since these structures were commonly rebuilt and reused in later periods (Betts, 1982b). This is also confirmed most recently by the findings of two archaeological transect surveys conducted within the *harra*, documenting that the majority of clustered enclosures investigated were already occupied by pastoral groups during the Late Neolithic or the Chalcolithic/Early Bronze Age and were commonly reoccupied in historic periods and modern times (Müller-Neuhof et al., 2013; Müller-Neuhof, 2014b). Since the basic architecture of the enclosures has not changed since prehistoric times and the structures are locally in use until today, it is difficult to categorize them (Betts, 1982b).

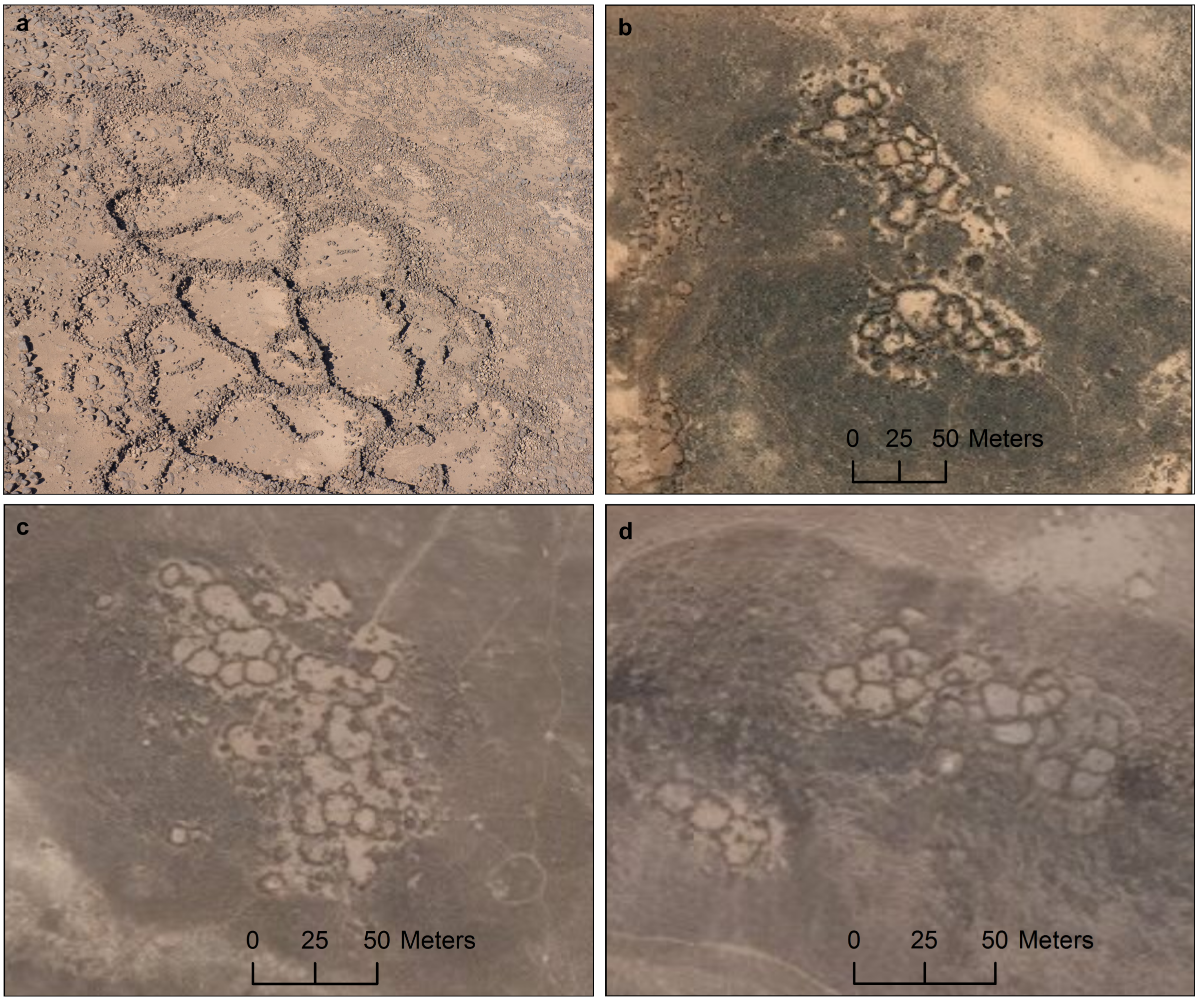

Figure 3.18.: 18a: Aerial photograph of clustered enclosures, ©*APAAME*, Photo: APAAME_20120522_DDB-0374, by permission; 18b, c, d: Satellite images of clustered enclosures. ©*Esri, Source: Esri, DigitalGlobe*

Hunting camps such as Dhuweila 1 and the use of 'kite' systems, give evidence for an expansion of hunting groups in the *harra* in the Late Pre-Pottery Neolithic B period towards the end of the 7th millennium BCE. The economic exploitation of the *harra* was still based on hunting and foraging in this period (Betts, 1993).

A typical Late Neolithic site is Jebel Naja, located on the western fringe of the *harra*, which includes several flint assemblages that are found in and around a group of animal pens and cleared terraces (Betts et al., 2013, Fig. 2.2). The occupation at the site dates to several periods, starting in the Middle Paleolithic, although the Late Neolithic occupation phase seems to be the most intensive one. The Neolithic assemblage is mainly composed of concave truncation burins, being representative of a 'burin Neolithic' site that are typical for the *harra*. A radiocarbon date from a hearth yielded an age of 6455–6080 cal BCE. The lack of Late Neolithic arrowheads indicates that hunting was not an important part of the site's economy. Instead, the occurrence of sheep and goat imply pastoral activities, although it is not known if the animals were already domesticated (Betts et al., 2013). Due to its size and architecture, the site may have hosted up to two families (Rollefson et al., 2014a). Overall, Jebel Naja is one of a great number of similar Late Neolithic sites located along the western edge of the *harra* (Betts et al., 2013) which are regarded as temporary camps or work sites (Rollefson et al., 2014a). One exception is the site at al-Ghirqa, characterized by a complex of corrals and dwellings; the latter being organized in at least two clusters (Rollefson et al., 2014a, cf. Betts and Helms 1987). Unlike Jebel Naja, the Late Neolithic site of Dhuweila was a hunting camp, indicated by faunal remains which mainly consist of gazelle. Moreover, the flint assemblage is largely composed of arrowheads, scrapers, knives and dihedral burins (Betts et al., 2013).

At the eastern edge of the *harra*, surveys and excavations in the Burqu' region recovered seven prehistoric sites, most of which date to the Late Neolithic period, while the earliest one dates to the late 8th millennium cal BCE (Betts et al., 2013, Fig. 2.2). Generally, the sites are characterized by Late Neolithic lithic scatters (including burin sites) which are commonly associated with circular structures, constructed out of drystone walls or upright slabs (Betts et al., 2013). Faunal remains from these sites contained high proportions of sheep and goat, indicating that pastoralism has already been an essential part of the economy by that period (Betts, 1993; Betts et al., 2013). Surveys in the *hamad* east of Burqu' showed that 'burin Neolithic' sites were common along the wadi systems, but there was little evidence for sites of earlier periods (Betts, 1993).

Based on their research results, Betts and her team assume that the Late Neolithic in northeastern Jordan was an intermediate stage representing a change from hunting to herding. The observation of an architectural shift from clustered room architecture to corrals with attached rooms around the Late Neolithic to Chalcolithic periods is interpreted as an indication that pastoralism became increasingly important, and probably reflects the gradual introduction of dairying (Betts et al., 2013). With respect to the question how specialized pastoral nomadism developed in this region, Betts and her colleagues suggest a transitional subsistence strategy where local hunter-gatherers adopted domestic caprines. They assume once pastoralism was introduced it gradually grew in importance over time (Betts et al., 2013; Garrard et al., 1999; Martin, 1999).

Based on their ongoing research at the Neolithic sites of Wisad Pools and the Wadi al-Qattafi mesas (Fig. 2.2), Rollefson et al. (2014a) argue for another scenario. Both sites are special in terms of their size and variety of archaeological finds, comprising hundreds of human-made stone structures that are often of unknown date or function (Rowan et al., 2015a).

The Wadi al-Qattafi mesas are located about 60 km east of Azraq at the southern fringe of the *harra*. The Wadi al-Qattafi is a major wadi that flows roughly from north to south. On both sides of the wadi, about 30 basalt-capped mesas are located with heights of about 40 to

60 m and sizes ranging from 60 x 75 m to about 1.20 x 0.40 km (Rowan et al., 2015a). Another string of about 20 mesas is situated along the eastern bank of Wadi Umm Nukhayla, a few kilometers to the south (Rollefson et al., 2014a; Rowan et al., 2015a). Archaeological surveys revealed that most mesas had at least one large basalt tower tomb on top. Next to a large number of circular or elliptical basalt structures, other common structural features are animal corrals which are usually found along the lower slopes of the mesas (Rowan et al., 2015a).

A particularly large number of structures were observed on Mesa-4, popularly known as 'Maitland's Mesa', where more than 250 structures (including small hut structures, corrals and a large tower tomb) on the mesas flat top were recovered. Nearly twice as many structures have been found on the slopes and base of the mesa (Wasse et al., 2012; Rollefson et al., 2014a; Rowan et al., 2015a). A corbelled dwelling (SS-11), c. 2 × 3 m in size, was excavated (Wasse et al., 2012). A piece of charcoal from a fireplace within the building yielded a radiocarbon date of 5475–5325 cal BCE (± 2σ; Rollefson et al. 2014a). In the close vicinity other small-corbelled structures were noticed, from which 10 houses were associated with corrals and another 9 without; the latter perhaps forming a 'village'. This finding also indicates two occupation phases, whereby the group of buildings without corrals possibly date back to an earlier period of the Late Neolithic (Rollefson et al., 2014a).

At the Mesa-8 and Mesa-5 there are several clusters with altogether over hundred potential dwellings, some of which are presumed to be of Late Neolithic age. Around Mesa-7 about 287 buildings of two different construction techniques were recovered, excluding corral structures (Rollefson et al., 2014a). Also at Mesa-1 and Mesa-10 a large number of structures were found, while the remaining mesas are characterized throughout by relatively low concentrations of structures (Rollefson et al., 2014a). Overall, it is yet unknown whether the occupation was contemporaneous at any of the structures, however, "the sheer numbers of buildings, and their density close to seasonal water sources, suggests a much larger population in the Badia, than, perhaps, previously imagined" (Rollefson et al., 2014a, p. 15).

The site of Wisad Pools is located about 100 km to the east of Azraq within a geomorphological complex, comprising a wadi and several natural depressions that store water during the rainy season (Rollefson et al., 2014a; Rowan et al., 2015b). To date, at least nine pools were identified within the wadi; some of them might be artificial built. Covering an area of 3 x 3.5 km, the site is large and comprises numerous structures of unknown age. The 'core' area, characterized by the highest density of architectural remains, covers about 1.5 km^2 and includes probably more than 300 architectural structures, excluding corrals. In addition, tower tombs and several high mounds were identified (Rollefson et al., 2014a). One high mound—a collapsed corbelled house (W-66) with a gypsum-plaster floor—was excavated in 2011. One radiocarbon date on charcoal from the plaster yielded an age of 6606–6455 cal BCE (± 2σ; Rollefson et al. 2014a). In 2013 and 2014 another structure (W-80), consisting of a circular tomb that was built on top of a Late Neolithic dwelling, was excavated (Rowan et al., 2015b). Three charcoal radiocarbon dates from this dwelling yielded ages of 6590-6580 cal BCE (± 2σ), 6000–5840 cal BCE (± 2σ)

and 5710–5610 cal BCE (± 2σ; Rollefson et al. 2014a). Both dwellings were utilized as wind shelters. The dwelling W-80 was also used for butchering activities, as well as for stone tool and bead production. Moreover, a large number of grinding slabs and pestles were found. Hunting activities are indicated by high numbers of arrowheads found within the fills (Rollefson et al., 2013, 2014a). Contrary to the original assumption that Wisad Pools was a large necropolis, the investigations showed that many of the funerary structures, such as the tomb at W-80, were built on former house structures—probably in order to heighten the burials for a better visibility (Rollefson et al., 2013).

Overall, based on the findings at Wisad Pools and the Wadi al-Qattafi mesas, Rollefson et al. (2014a) assume that the process of the emerging herder-hunter exploitation of the northern Badia during the Late Neolithic was more dynamic and marked by more interactions than expected by Betts et al. (2013). Their research has provided evidence that the onset of mobile pastoralism in the *harra* can be dated to the Pre-Pottery Neolithic C/Early Late Neolithic. This is done by showing that during the latter half of the 7th millennium and the early 6th millennium considerable numbers of pastoralists probably already occupied the regions at Wisad Pools and the Wadi al-Qattafi mesas. Living in villages on a seasonal basis, the settlers relied to a great extent on hunting and seem to have practiced opportunistic agriculture as well as herding caprines (Rollefson et al., 2014a). Noting that nomadic pastoralism may have contributed to a population growth of the former hunter-gatherer groups, Rollefson et al. (2014a) argue that it seems much more likely that the Late Neolithic population was heavily composed of members of a farming population, who moved seasonally from farming areas such as 'Ain Ghazal' into the Badia in order to protect the resources of the arable land by removing the animals until the harvest was completed (see also Köhler-Rollefson, 1988, 1992). Since it is difficult "[. . .] to declare that the development of pastoral nomadism was either one or the other", probably both models are correct (Rollefson et al., 2014a, p. 15). Once mobile pastoralism was established as a reliable economic subsistence strategy in the Badia, there may have been interaction between these two arrangements and a subsequent social merging into one population (Rollefson et al., 2014a). Moreover, a variety of different sites in the vicinity of the pools, dating from the early Epipalaeolithic to Safaitic periods (1st century BCE to 4th century CE), demonstrate that the region with its water resources played a major role for many millennia (Rowan et al., 2015b).

A large number of prehistoric sites, dating from the 7th to the late 4th millennia cal BCE, were recently revealed by extensive surveys in the Jebel Qurma region by Akkermans and colleagues (cf. Akkermans et al., 2014). The Jebel Qurma region is located on the western fringe of the *harra* about 30 km east of Azraq (Fig. 2.2), covering an area of about 300 km^2. Based on the investigation of numerous sites—ranging in size from a few dozen square meters to about eight hectares—and their surface findings (architecture, material culture etc.), Akkermans et al. (2014) were able to identify five major prehistoric occupation phases: (1) desert kites; (2) grouped enclosures and burin sites; (3) early 6th-millennium settlement; (4) Late Neolithic to

Chalcolithic 'wheels'; (5) Hazimah enclosures. Thereby, each phase has its own characteristics. Moreover, the late prehistoric habitation of the Jebel Qurma area seems to be divided in phases with very high settlement activity and phases with very low settlement activity (Akkermans et al., 2014).

The Chalcolithic/Early Bronze Age period has been investigated by Müller-Neuhof and colleagues in extensive surveys in northeastern Jordan between 2010 and 2016, revealing abundant traces of socio-economic activities, such as the exploitation of large flint mines in the *hamad* (Müller-Neuhof, 2014b, 2013b, 2006, Fig. 2.2). Three mining districts were identified in the Wadi ar-Ruwayshid region, located on the western escarpment of the ar-Risha plateau in the *hamad*, east of the *harra*. Altogether, 207 flint mining sites with cortical scraper blank production were discovered, including about 19 exploratory sites and several workshops (Müller-Neuhof, 2013b). Cortical scrapers, also known e.g. as 'fan scrapers', 'tabular scrapers' or 'Jafr tools' were important lithic tools during the Late Chalcolithic/Early Bronze Age in many regions of Southwest Asia (Müller-Neuhof, 2013b). Presumably, they were mainly used by caprine herders for slaughtering animals and processing their products (Barket and Bell, 2011; Henry, 1995). On the basis of their appearance, the mines in the Wadi ar-Ruwayshid region can be differentiated into outcrop mines, possible pit mines, and large trench mines. Covering about 38 ha, the production rate of cortical flakes in this mining region was roughly estimated at a minimum of 1,900,000 blanks (Müller-Neuhof, 2013b). Accordingly, cortical scraper blanks were produced in an 'industrial' scale, making the region to one of the most important flint mining regions in Southwest Asia (Müller-Neuhof, 2013b). It is assumed that the transport of such large amounts of blanks from the mines to the areas where they were consumed was only feasible after the donkey has been domesticated, which roughly dates to the 1st half of the 4th millennium BCE (Müller-Neuhof, 2013b, see also Quintero et al. 2002). The blank production was probably conducted by mobile pastoralists, who visited this area with their flocks on a regular basis as part of their migration cycle. However, the high organizational level of the flint mining and cortical scraper blank production could be also an indication for groups who were specialized in mining (Müller-Neuhof, 2013b). Overall, the cortical tool blank production was most likely part of a supra-regional exchange system (Müller-Neuhof, 2014b).

In addition to the well-known Early Bronze Age settlement of Jawa (Betts et al., 1991; Helms, 1981; Müller-Neuhof et al., 2015, see chapter 3.2), another two Chalcolithic/Early Bronze Age settlements in the *harra*, Tulul al-Ghusayn and Khirbet Abu al-Husayn, have been discovered (Fig. 2.2). They were probably inhabited on a perennial basis (Müller-Neuhof, 2014b). Khirbet Abu al-Husayn is located on a small volcano on the eastern fringe of the *harra* in the close vicinity of the big mudpan Qa Abu al-Husayn. With the presence of wide double-faced walls, possible gates, and evidence for two tower structures, the site has a defensive character. Dwelling structures are missing but the site seems to be sub-divided into several walled terraces (Müller-Neuhof, 2014b). Except for some well-like structures which probably served as contemporary water holes, the question on how the site's water supply has been secured remains largely unclear (Müller-Neuhof et al., 2013). Tulul al-Ghusayn is also situated on a volcano, characterized by a large crater, located about 40 km north of Khirbet Abu al-Husayn. The site comprises three separate habitation areas including about 180 double apsidal small dwelling structures; approximately half of these structures were examined showing that they are usually 5.5 x 2.5-3 m in size (Müller-Neuhof et al., 2013). The main habitation area, located on the southeastern edge of the crater, recovered the remnants of an enclosing wall which presumably served as a fortification. Moreover, a large cairn, to which a chain of smaller cairns is added, was discovered. At the foot of the southern slope of the volcano a potential 'sanctuary'—characterized by standing stones—was found (Müller-Neuhof et al., 2013). In addition, terrace wall structures on the crater slopes and the volcano's outer slopes have been identified which are interpreted as terraced gardens. Since up-slope areas and water canals are missing they indicate rainfed agriculture (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013). The few surface findings, mainly lithic artifacts, at both Tulul al-Ghusayn and Khirbet Abu al-Husayn indicate a Chalcolithic/Early Bronze Age date (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013).

Moreover, abundant indications of ancient pastoralism in the *harra* have been found by two transect surveys of Müller-Neuhof along a system of wadis and mudpans from the southeast to the northwest, and from the east to the west (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013). During the surveys, surface finds from about 200 sites—the majority of them characterized by clustered enclosures—were investigated. The finds indicate occupation phases during the Late Neolithic, the Chalcolithic/Early Bronze Age, the Roman/Byzantine period, the Umayyad, the Abbasid, the Mamluk, the Ayyubid, the later Islamic/Ottoman periods and modern times. While surface finds from the majority of these pastoral campsites suggest an initial occupation in the Chalcolithic/Early Bronze Age many of them were re-used in later periods, testifying the presence of herders at the same locations throughout time (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013). Pastoral activities during the Chalcolithic/Early Bronze Age, especially those producing secondary products (see also Sherratt, 1983), were probably related to a medium-range exchange or trade network, connecting pastoral groups of the *harra* with societies in the more fertile areas who were presumably dependent on the import of animal products (Müller-Neuhof, 2014b).

For post-Early Bronze Age periods there is little evidence for human activities until the Safaitic period (Rollefson et al., 2014a, cf. Huigens 2015; Müller-Neuhof 2014b; Müller-Neuhof et al. 2013). For the Safaitic period, dating from the 1st century BCE to the 4th century CE (Betts et al., 2013), an extensive collection of Safaitic rock inscriptions provides evidence for abundant activities by mobile pastoralists (Macdonald, 1993, 1992, 1983, 1982). The vast majority of these inscriptions have been found in the *harra* of southern Syria and northeastern Jordan and the *harra* and *hamad* of northern Saudi Arabia. From a total of 18,000 inscriptions (identified by 1993) more than 12,000 were found in northeastern Jordan (Macdonald, 1993). In addition to the description of pastoral practices and seasonal migration routes (Macdonald, 1993), they also document the rise of camel pastoralism by the 1st century BCE which might also have increased the trading possibilities on a supra-regional scale (Betts et al., 2013) and the number of sheep and goats in the *harra* due to the use of camels as water carriers (Lancaster and Lancaster, 1991).

According to the survey results of the Jebel Qurma Archaeological Landscape Project in the Jebel Qurma region, the occupation history during the Late Antiquity is divided in phases with very high human activity and phases with very low human activity (Akkermans and Huigens, in press, Fig. 2.2). After a phase of local habitation roughly dating from the 2nd century BCE to the 8th century CE (as indicated from campsites, tombs and rock art), there was a period of local abandonment until the late 13th to 14th century Mamluk epoch (as indicated from campsites and Arabic inscriptions). The short-lived Mamluk period was followed by another local abandonment between the 15th to the late 19th or even the early 20th century. Since then human activity in the Jebel Qurma region significantly increased before it declined again at the beginning of the 21st century (Akkermans and Huigens, in press).

Table 3.1.: Chronology of the Southern Levant and neighboring regions (modified after Betts et al. 2013, p.10; Rosen 2007, p. 35).

Period	**Age**
Late Epipaleolithic	
Early Natufian	12,550–11,050 cal BCE
Late/ Final Natufian	11,050–9,650 cal BCE
Neolithic	
Pre-Pottery Neolithic A	9800–8400 cal BCE
Early Pre-Pottery Neolithic B	8400–8100 cal BCE
Mid Pre-Pottery Neolithic B	8100–7500 cal BCE
Late Pre-Pottery Neolithic B	7500–7000 cal BCE
Terminl PPNB/ Pre-Pottery Neolithic C/ Early Late Neolithic	7000–6500 cal BCE
Pottery Neolithic/ Late Neolithic	6500 cal BCE–4500 BCE
Chalcolithic	4500–3800 BCE
Early Bronze Age	
Early Bronze Age I	3800–3000 BCE
Early Bronze Age II	3000–2650 BCE
Early Bronze Age III	2650–2200 BCE
Early Bronze Age IV	2200–2000 BCE
Middle Bronze Age	2000–1550 BCE
Late Bronze Age	1500–1200 BCE
Iron Age	1200-586 BCE
Babylonian and Persian Periods	586–332 BCE
Hellenistic Period	332–37 BCE
Roman Period	37 BCE–324 CE
Byzantine Period	324–639 CE
Early Arab Period	638–1099 CE

3.2. Local scale: Jawa

3.2.1. Geographical setting

The ancient city of Jawa (32.336 N, 37.002 E, 1002 m asl) is located in the basaltic *harra* of northeastern Jordan on the left bank of Wadi Rajil, about 7 km south of the present-day border with Syria (Fig. 2.2, cf. chapter 3.1 for a detailed description of the environmental setting). At the location of Jawa the upstream catchment of Wadi Rajil comprises an area of about 270 km^2, making it to one of the major ephemeral streams of the region (Whitehead et al., 2008). With its headwaters in the sub-humid regions of the Jebel Druze in Syria, the wadi usually carries more water than the small tributaries of Jawa's surroundings and the variability of annual discharge is reduced (Helms, 1981). Since the Syrian government built a dam across the river in 1968 the wadi's natural downstream runoff behavior is disturbed (Lancaster and Lancaster, 1999).

3.2.2. Settlement phases and their chronology

The fortified ancient settlement of Jawa measures approximately ten hectares and is regarded as one of the major towns in the Middle East during the 4th millennium BCE (Helms, 1981). The well-preserved site was discovered by the French pilot Poidebard in 1931 and partly excavated by Helms between 1972 and 1976 (Helms, 1981, 1989; Betts et al., 1991). Based on ceramic evidence two main occupation periods were defined dating to (a) the Early Bronze Age (EBA) I (c. 3500–3000 BCE) and (b) the transition of the Early Bronze Age IV to the Middle Bronze Age I (around 2000 BCE; Helms, 1989, 1981). First radiocarbon dates from Jawa, obtained by analyzing samples from the excavations in the 1970s, support this chronology by indicating that the earliest occupation phase at Jawa started between 3500 and 3400 cal BCE (Levantine EBA IB; Müller-Neuhof et al., 2015). Contrary to Helms (1991b) presumption of a very limited time span of only 3 to 50 years for the first occupation phase, the new dating results by Müller-Neuhof et al. (2015) indicate a much longer time span. However, it remains unknown when this phase exactly ended and whether or not the transition from Levantine Early Bronze Age IB to Early Bronze Age II at around 3000 BCE was reached (Müller-Neuhof et al., 2015).

Architecturally, the Early Bronze Age I settlement phase is characterized by the construction of a large fortification wall with several gates, numerous dwelling structures and a complex water diversion and storage system. The Early Bronze Age IV/Middle Bronze Age I settlement phase only comprises a large multi-chambered building which was built in the center of the site (Helms, 1981, 1989, Figs. 3.19, 3.20). Based on simple calculations taking the inhabited area of the town in relation to the estimated population density, ancient Jawa reached its largest extent during the earlier occupation phase and may have been inhabited by up to 3400 to 5000 people (Helms, 1981).

Figure 3.19.: Aerial photograph of Jawa and site plan after Helms (1981); ©*APAAME*, Photo: APAAME_20130409_RHB-0019, by permission.

3.2.3. Subsistence strategy

The inhabitants of Early Bronze Age Jawa relied on agropastoralism for subsistence with some hunting (Köhler, 1981). Animal remains at the site are dominated by domestic sheep (*Ovis aries* L.) and goats (*Capra hircus* L.) (86.7 %), followed by domestic cattle (*Bos taurus* L.) (8.5 %) and gazelles (*Gazella spp.* L.) (2.3 %) (Köhler, 1981). According to rough estimates of stock sizes, Jawa's inhabitants kept about 10,000 sheep and goats and 800 cattle for meat and milk production (Helms, 1981). In addition to small areas of agricultural fields (cf. section 3.2.4, Fig. 3.20) evidence for farming is also shown in a large number of grinding stones and sickle blades found at the excavation site (Helms, 1981). Macrobotanical analyses revealed the presence of several crop taxa such as six-row hulled barley (*Hordeum vulgare* L. emend. LAM), einkorn (*Triticum monococcum* L.), bread wheat (*Triticum aestivum* L. sensu lato), emmer (*Triticum dicoccum* Schrank), chickpea (*Cicer arietinum* L.), pea (*Pisum sativum* L.) and lentil (*Lens culinare* Medicus) (Willcox, 1981).

3.2.4. Water storage and diversion systems

Due to the arid environmental conditions (cf. chapter 3.1.4.3), Jawa's inhabitants had to apply various water management strategies to secure their food and water supply. This is apparent from the existence of a highly elaborated water distribution and storage system, which appears to be one of the earliest hydraulic systems of its kind (Helms, 1981; Roberts, 1977; Viollet, 2007; Whitehead et al., 2008). This system is described in detail by Helms (1981) and includes a range of water management structures for controlling the diversion and storage of water. Overall, there are three separate water supply systems, each comprising a deflection dam, local micro-catchments from which surface runoff is collected, water reservoirs and smaller areas of arable land (Helms, 1981, Fig. 3.20).

The first system, situated in the west of Jawa, consists of a canal which deflects water from Wadi Rajil (deflection area DaI) to small areas of agricultural land, an underground cistern (P1) and the water reservoirs P2, P3, P4 and P5. Besides, the system is additionally fed by surface runoff from adjacent micro-catchments (Helms, 1981).

The second system, located east of Jawa, deflects water from the deflection area DaII where water from Wadi Rajil was transported along a canal and distributed to the pools P6 and P7. Another canal and a deflection wall, located along the slopes in the northeast and the western edge of Wadi Rajil, collected runoff from a micro-catchment in order to fill the reservoir P7 and to irrigate a small area of agricultural land (Helms, 1981).

The third system, situated in the southwest of system II, collects water from Wadi Rajil by a canal and leads it to three storage pools (P8–P10). Similar to the systems I and II, also system III utilizes runoff from a micro-catchment and is associated with a small area of fields (Helms, 1981).

Due to a lack of radiometric dates a chronology of the construction phases of these water management systems is missing. However, on the basis of flint and pottery finds associated with some of the structures as well as the general design and the development of the systems, Helms (1981) proposes that all three systems date to the Early Bronze Age settlement phase of Jawa. He also concludes that, at one time, all three systems were in simultaneous use. According to radiocarbon dates of two samples from the ancient dam that is associated with the reservoir P4, the construction of this dam can be roughly dated to the period between 3500 and 3400 cal BCE (Müller-Neuhof et al., 2015), confirming the assumption of Helms (1981) in dating the water storage system, at least in parts, into the Early Bronze Age I.

The total water storage capacity of all three systems is approximately 52,000 m^3 (Helms, 1981). Following Helms (1981), each pool is categorized as either for human consumption or for watering animals, although the classification criteria he used are unclear (Whitehead et al., 2008). The availability of water within these water storage systems depended on sufficient runoff of the Wadi Rajil and its tributaries in order to re-fill the reservoirs each rainfall season. In order to evaluate the water resources at Jawa, Whitehead et al. (2008) applied an annual water balance model for Wadi Rajil based on historical precipitation estimates from a Global Circulation Model, showing that this system could probably meet the water demand of a population of 6000 and their livestock during predicted wetter times of the Early Bronze Age—in case all the ponds were in use and the stored water was not used for crop irrigation. However, Whitehead et al. (2008) also point out that during dryer periods the water management system was unable to supply such a high number of inhabitants.

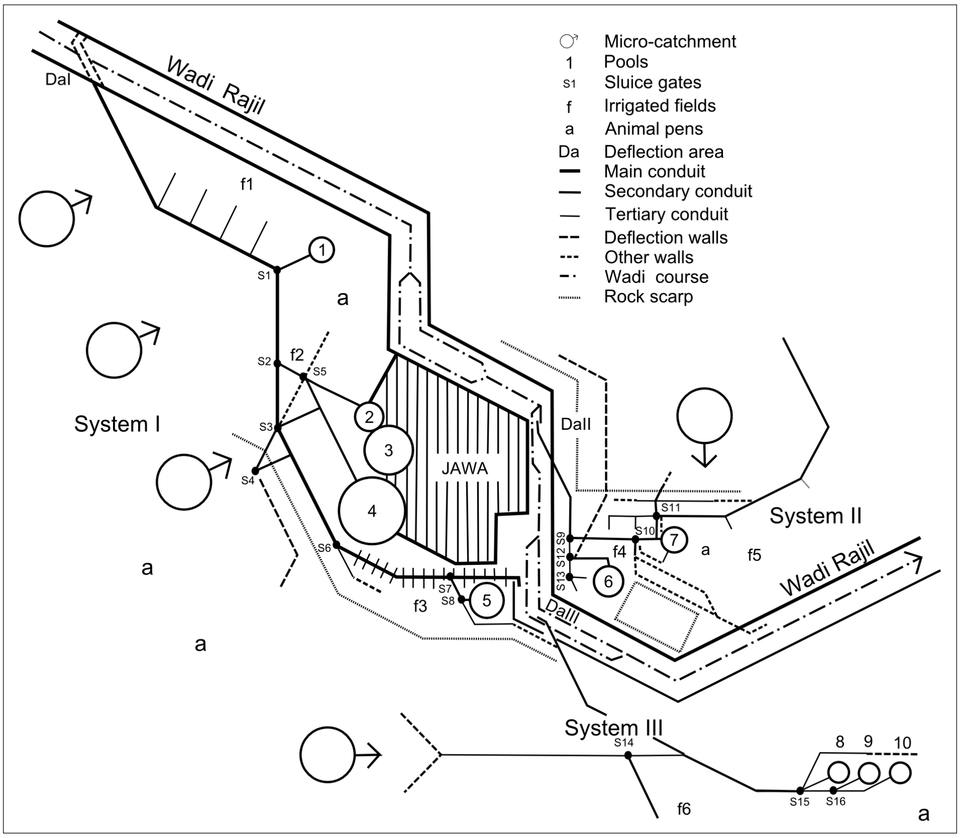

Figure 3.20.: Schema of the Jawa water management systems; modified after Helms (1981).

3.2.5. Agricultural systems

Apart from the small areas identified by Helms (1981, cf. Fig. 3.20), evidence of irrigated arable land in the vicinity of Jawa has been scant (Mithen et al., 2008). Recent geoarchaeological surveys have revealed the well-preserved remains of several abandoned agricultural terrace systems in the vicinity of Jawa (Müller-Neuhof, 2014b,a, 2012), which were only partly recognized during earlier surveys or were interpreted as animal pens (cf. Helms, 1981). According to lithic evidence, the initial construction of these systems most presumably dates to the Late Chalcolithic/Early Bronze Age (Müller-Neuhof, 2014b). Since detailed descriptions of these systems are widely missing and radiometric datings are as yet unavailable, they are examined in more detail within this thesis (chapters 5 and 6).

CHAPTER 4

Methods and materials

This chapter collects—in an extended and modified form—the methods employed in the publications Meister et al. (2017, chapter 5), Meister et al. (in press-a, chapter 6) and Meister et al. (in press-b, chapter 7). In contrast to commonly known structures of method sections, the methods in this chapter are presented according to the two main themes of the thesis, i.e. desert agriculture at Jawa (chapter 4.2) and mobile pastoralism in northeastern Jordan (chapter 4.3).

4.1. General approach

The general methodical approach of this thesis is integrated into the interdisciplinary landscape archaeological Topoi research project A-1-5 *Badia, Jordan* and based on the close collaboration between the German Archaeological Institute and the Institute of Geographical Sciences at the Freie Universität Berlin. With the focus on human-environment interactions and the research questions outlined above, the methodical strategy of this thesis follows two approaches (Fig. 4.1):

(1) In order to investigate and reconstruct agricultural activities in the close vicinity of the Early Bronze Age settlement of Jawa, four identified terrace systems were documented through detailed mapping to gain a better understanding of their function. Catchment delineations were generated in a GIS environment by using elevation data from a Global Digital Elevation Model. A multi-proxy approach was applied for studying sediment records of different terraces. By investigating bulk chemistry, texture and microfossils (phytoliths, diatoms, dung spherulites) it was aimed to characterize their environmental and depositional conditions. Furthermore, it was clarified whether the sedimentary record and the paleoenvironmental proxies analyzed

are suitable for identifying former land use, especially in this nowadays desert environment where organic remains are often rare. In order to establish a chronology of the terrace systems optically stimulated luminescence (OSL) dating was applied on sediments from two selected terraces (Meister et al., 2017, chapter 5).

In order to assess the scale of the 'on-site' crop production at Jawa the crop simulation model CropSyst (Stöckle and Nelson, 1994; Stöckle et al., 2003) was used. To determine the impact of the applied water management techniques on harvest yields, different runoff scenarios depending on rainfall intensity and the specific catchment area of each terrace system were applied. To estimate the number of people that could have been supplied by the local food production at Jawa, simple calculations based on metabolic calorie requirements and agricultural and pastoral production rates were conducted (Meister et al., in press-a, chapter 6).

(2) To examine pastoral mobility in northeastern Jordan, clustered enclosures were systematically recorded in the *harra* based on satellite imagery. In order to investigate the absolute and relative locations of the recorded enclosure sites, their first- and second-order geospatial characteristics were examined using distance and density based approaches of point pattern analyses by including geomorphometric and geomorphological site characteristics (Meister et al., in press-b, chapter 7).

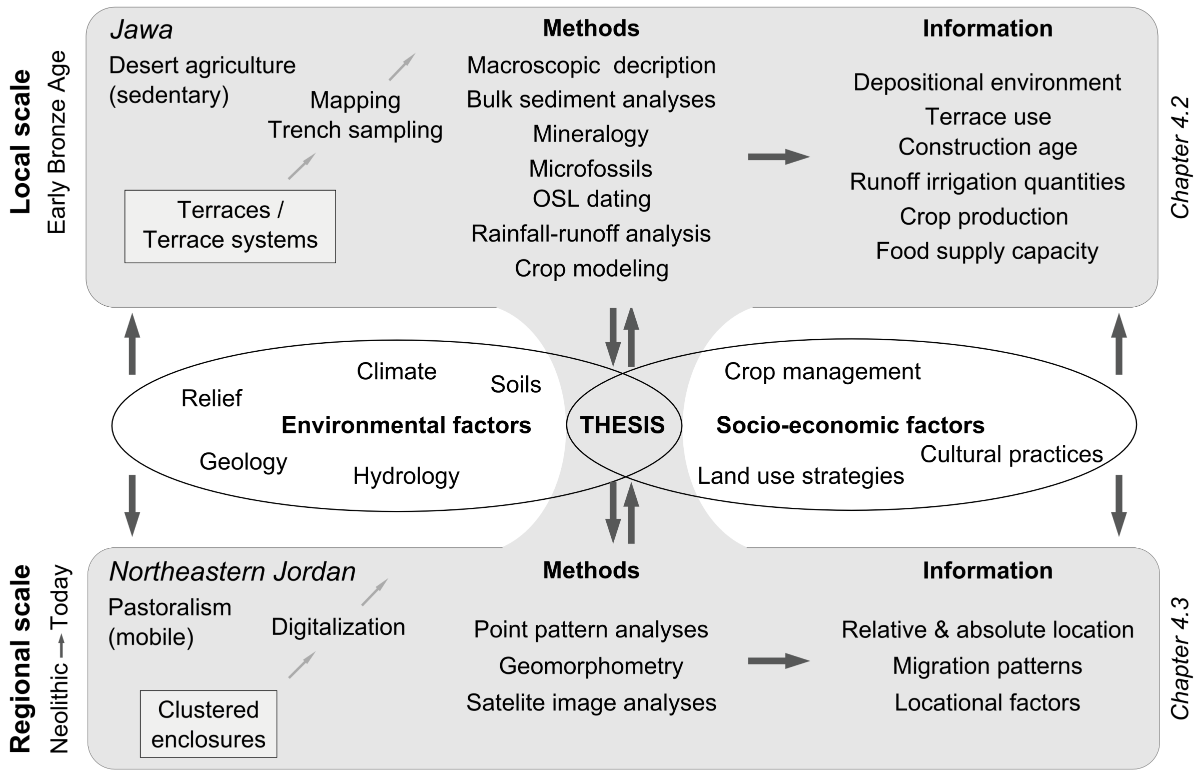

Figure 4.1.: Schematic methodological approach of this study.

4.2. Investigation of agricultural systems at Early Bronze Age Jawa

In the direct vicinity of Jawa, four agricultural terrace systems were identified and investigated. They can be differentiated into two major types: (a) those located on slopes, plateaus and small valleys close to Jawa, irrigated mainly by rainwater runoff (TG-1, TG-2, TG-3), and (b) those located on wadi terraces of Wadi Rajil—approximately two kilometers downstream of Jawa—irrigated by floodwater harvesting (WTG-1) (see Beckers et al., 2013a, for a general introduction to runoff and floodwater harvesting; see Fig. 4.2 for their locations).

4.2.1. Data collection and sampling strategy

Detailed archaeological, geomorphological and hydrological mapping of the terraced field systems was based on a WorldView-2 satellite image (ground resolution: 0.5 m x 0.5 m) and ground surveys during two field campaigns in 2011 and 2013. The catchment delineations were generated by applying the GRASS r.watershed module, using elevation data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (resolution: 30 m x 30 m). For all terrace systems, the ratio R was determined by dividing the catchment area of each terrace system by its total cultivation area (Evenari et al., 1961). Thirteen sediment profiles with depths of up to 1 m were investigated (see Fig. 4.2 and Table 4.1 for their locations). Due to the generally observed low heights of terrace walls and, thus, small depths of tread fills (cf. section 5.4.1), only the surface layer (tread) is usually cultivated (Frederick and Krahtopoulou, 2000, cf. Fig. 4.3a). Therefore, most of the profiles were analyzed only to a depth of about 30 cm. The sampling strategy included the recording and sampling of multiple profiles within a terrace system. Control profiles outside the areas formerly used for agriculture were recorded and sampled. One control profile (C1) is located on a slope west of the terrace systems TG-1 and TG-2; a second control profile (C2) is situated on a valley floor close to terrace system TG-3 (Fig. 4.2). In total, 45 samples were collected for further analysis. For subsequent comparison and due to the fact that a clear stratigraphy was not evident in all profiles, samples were systematically taken from analog depth levels (c. 3, 11, 22 cm depth).

4.2.2. Optically stimulated luminescence (OSL) dating

Since the sediments did not contain organic macro-remains, radiocarbon dating was not possible. Therefore, OSL dating on sand-sized grains from two agricultural terrace fills was applied in order to date the terraces investigated. The deposition and burial ages of terrace fill sediments provide indirect information about the construction time of the associated terrace wall (riser), assuming that the terrace fill stratigraphy generally corresponds to terrace filling periods after its initial construction (Beckers and Schütt, 2013). Two sediment profiles (T1, T5) from two different terrace systems (TG-1, TG-2), both presumably dating to the Late Chalcolithic/Early

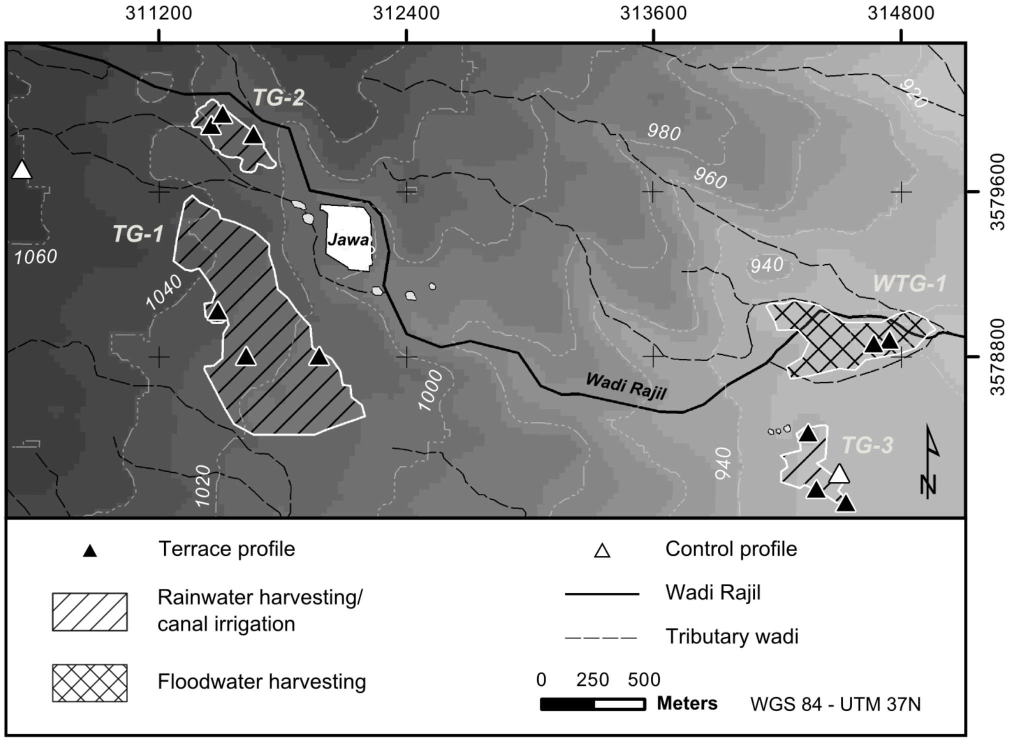

Figure 4.2.: Detailed map of the topography in the surroundings of Jawa, showing the major drainage and terrace systems (TG 1-3, WTG-1) and profile locations (Database: Aster DEM).

Table 4.1.: List of sampling profiles and their location.

Profile name	Location	Altitude (m asl)	Coord. East	UTM 37 N North
T1	TG-2	1052	311454	3579922
T2	TG-2	1045	311510	3579976
T3	TG-2	1045	311658	3579877
T4	TG-1	1040	311623	3578804
T5	TG-1	1043	311485	3579022
T6	TG-1	1032	311976	3578804
T7	TG-3	949	314348	3578433
T8	TG-3	943	314387	3578160
T9	TG-3	944	314530	3578093
W1	WTG-1	934	314741	3578882
W2	WTG-1	940	314666	3578864
C1	CP	1074	310535	3579710
C2	CP	941	314498	3578235

Bronze Age (Müller-Neuhof, 2014b), were sampled. Both OSL samples were taken with metal tubes at a depth of approximately 30 cm (see Table 4.2 for sample laboratory numbers and data; Fig. 4.2 and Table 4.1 for profile locations; and Fig. 4.3b, c for sample locations). Additional material was sampled for gamma spectrometry. In the laboratory, activity concentrations of 40 K and several nuclides from the uranium and thorium decay chains were measured using high-resolution gamma-ray spectrometry.

Results were combined with information on burial history, water, and organic content history to assess the average moisture and soft component related attenuation of the beta and gamma radiation in the sediment since burial (Madsen et al., 2005). The water content was estimated at 6–9 %. The effective sediment dose rate was calculated considering the beta attenuation of the relevant grain size fraction (Mejdahl, 1979), and the contribution from the cosmic dose rate was calculated according to Prescott and Hutton (1994). Since the cosmic dose rate is dependent on the thickness of the overburden an assumption had to be made with regard to the development of this overburden since burial; in this setting it is presumably fair to assume immediate burial of the samples to the present depth below the surface and thus a constant cosmic dose rate since burial. There were no signs of disequilibrium in the uranium decay chain. Resulting dose rate values were 2.13 ± 0.07 Gy*ka^{-1} (NCL-7114013) and 1.87 ± 0.06 Gy*ka^{-1} (NCL-7114014). The quartz fraction of 90–180 μm was density-separated and purified through sieving and chemical treatment (HCl, H_2O_2, and HF, and HCl rinse). Following a number of tests, suitable measurement parameters were selected for use in the Single Aliquot Regenerative (SAR) dose procedure (Murray and Wintle, 2003). The most light-sensitive OSL signal of quartz grains was selected using the early background approach (Cunningham and Wallinga, 2010). To obtain a good estimate of the burial dose, measurements were repeated on at least 30 aliquots per sample, with each aliquot containing approximately 100 grains (2 mm-diameter sample). To test the SAR procedure and the selected measurement parameters, a laboratory-given dose was retrieved with the adopted procedure; the measured dose agreed favorably with the given dose (dose recovery ratio 1.00 ± 0.01, n = 6). Paleodoses measured on the single aliquots showed a symmetric distribution with moderate over-dispersion values (24–33 %). This extra scatter (unexplained by experimental uncertainties) in the paleodose distributions might be related to either insufficient signal resetting at the time of burial or post-depositional mixing (e.g., through tillage) of the soil matrix, or both. In order to obtain a conservative paleodose estimate for the original terrace forming, the Central Age Model (Galbraith et al., 1999, CAM) was applied to the paleodose distribution. For both samples, the burial age was determined by dividing the paleodose by the dose rate (Table 4.2).

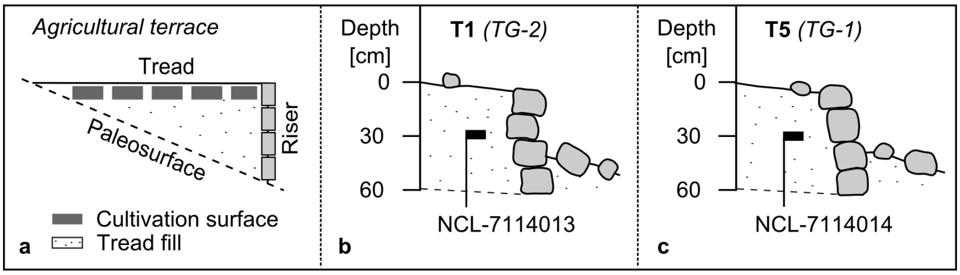

Figure 4.3.: a: Sketch of an agricultural terrace with terrace components mentioned in the text, modified after Frederick and Krahtopoulou (2000); b, c: Terrace sketch of the section and OSL sample location at profiles T1 and T5 (see Fig. 4.2 and Table 4.1 for profile locations).

Table 4.2.: List of OSL samples and their location.

Location / sample ID	**Depth (m)**	**Coord. UTM 37 N East**	**North**	**Palaeodose (Gy)**	**Dose rate (Gy*ka^{-1})**
TG-2, T1 / NCL-7114013	0.28	311454	3579922	11.3 ± 0.5	2.13 ± 0.07
TG-1, T5 / NCL-7114014	0.30	311485	3579022	9.8 ± 0.5	1.87 ± 0.06

4.2.3. Bulk sediment analyses

Bulk sediment- and biogenic microfossil analyses (section 4.2.4) were performed at the Physical Geography laboratory, Department of Earth Sciences, Freie Universität Berlin.

4.2.3.1. Electrical conductivity- and pH determination

For evaluating the acidity and alkalinity of sediments, pH values were measured whilst the sediment salinity was assessed by measuring the electrical conductivity (Blume et al., 2011). The pH value is the negative logarithm of the hydrogen ion concentration in a solution and affects the chemical, physical and biological properties of soils and sediments (Blume et al., 2011). The electrical conductivity is a measure of the concentration of ionisable dissolved substances and therefore indicates the salinity of a sediment (Blume et al., 2011).

The pH and electrical conductivity (EC) values were measured using a handheld pH/EC reader (Hanna content instruments) in a suspension of 5 g of dried sediment and 12.5 ml of KCL and distilled water after a reaction time of 30 min. During the measurements each sample was measured twice and subsequently averaged. In case of identified deviations, measurements were repeated and outliers erased.

4.2.3.2. Carbon determination

The total (TC), inorganic (TIC) and organic (TOC) carbon contents of sediments and soils provide information about diagenetic processes in sediments and help to characterize them (Charles and Simmons, 1986).

Total carbon content (TC mass-%) was analyzed on homogenized samples using a Leco TruSpec CHN analyzer, detecting CO_2 flow by highly selective infrared (IR) and thermal conductivity. Total inorganic carbon (TIC mass-%) was determined by the evolution of CO_2 during acid (H_3PO_4) treatment and the subsequent quantification of the evolved CO_2 in 20 ml 0.05 N NaOH solution by conductivity (Woesthoff Carmhograph C-16). Total organic carbon content (TOC mass-%) was calculated by subtracting TIC from TC. All measurements were performed following laboratory operational manuals and applying different calibration measurements of reference materials with varying TIC and TC contents. The deviations from these calibration materials averaged 0.45 mass-% (n = 10) for the TIC measurements and 0.05 mass-% (n = 19) for the TC analyses. The detection limit of carbon for the Woesthoff method is approximately 0.02 mass-% (Schwanghart et al., 2009), while it is about 0.01 mass-% for the Leco TruSpec CHN analyzer (Anonymous, 2011).

4.2.3.3. Grain size analysis

Grain size distributions provide important hints on sedimentation and transport processes of sediments (Tucker, 1996). In order to make statements about these processes within the different terraces and terrace systems and compare them afterwards, grain size analyses were executed using the laser diffraction technique. Laser diffractometry has become a widely used method to analyze grain size distributions from a wide range of sediments (e.g. Buurman et al., 2004; Klug et al., 2009; Machalett et al., 2008; Vandenberghe and Nugteren, 2001). The method is based on the principle that grains of a given size diffract light through a given angle (Di Stefano et al., 2010), assuming that the following behavior: the bigger the grains are the smaller the angle of diffraction becomes (Beuselinck et al., 1998; Di Stefano et al., 2010). The grain size is measured by detecting the light intensity from a beam of monochromatic light after diffraction by passing the sample in suspension. The subsequent calculation of grain size distribution from the light intensity is commonly based on the Fraunhofer and Mie diffraction theories (Beuselinck et al., 1998; Di Stefano et al., 2010).

In this study, grain size distributions were measured using a Beckman-Coulter LS 13320 PIDS laser diffraction particle size analyzer for grain sizes <2 mm, after sample partition by dry sieving. Sample preparation for grain size analysis included the removal of carbonates with HCl and dispersion with $Na_4P_2O_7$. Following the study results of Beuselinck et al. (1998) and Machalett et al. (2008), indicating that the removal of organic matter can be neglected, and due to the low organic carbon contents of the analyzed samples (mean = 0.45 mass-%, $\sigma = 0.39$, n = 45) organic material was not removed from sediment samples prior to the measurements.

Data quality was evaluated according to the obscuration rate and PIDS (Polarization Intensity Differential Scattering) value of each measurement. The grain size boundary of the clay fraction was set at <5.5 μm (Vandenberghe and Nugteren, 2001).

4.2.3.4. Magnetic susceptibility

The magnetic susceptibility (MS) gives information about the 'magnetisability' of a material (Dearing, 1994) and their measurement is widely used to detect magnetic minerals, e.g. in sediments and soils (e.g. Mullins, 1977; Dearing et al., 1996; Markovic et al., 2009).

Volume-specific magnetic susceptibility was measured with low frequency on approximately 10 cm^3 of sample material, using the Bartington Instruments MS2B system. The Bartington sensor detects the magnetization of the sediments by creating a weak magnetic field from an alternating current (AC) (Dearing, 1994). Subsequently, the volume susceptibility κ is calculated according to the equation:

$$\kappa = \frac{M}{H}$$

where M is defined as the material magnetization and H as the magnetic field (Ahrens, 1995). The ratio is dimensionless and was measured in Standard International (SI) units. A calibration check was provided by using a calibration sample, consisting of a mixture of Magnetite (Fe_3O_4) and Aluminum.

4.2.3.5. Mineral determination

The knowledge about the mineral composition of sediments can provide important hints about their origin and formation (Schütt, 2004).

In this study, it was specified for powder samples by X-ray diffraction (Rigaku MiniFlex 600) using a copper Kα tube from 3 to 80° 2θ with steps of 0.02 2θ. Each step was measured for 2.4 s. The method is based on the principle that a monochromatic X-ray which incidents on the lattice-plane is always diffracted with a maximum gain when the Bragg-Equation is fulfilled:

$$n\Lambda = 2d * sin\theta$$

n = diffraction order
Λ = wavelength of X-ray radiation
d = lattice spacing
θ = diffraction angle.

If the wavelength and the diffraction angle are known, the mineral can be determined by calculating the lattice spacing, which is determined as follows and specific for each mineral:

$$d = \frac{\Lambda}{2 * sin\theta}.$$

The amounts of mineral components were semiquantitatively derived from diffraction intensity using Philips X'Pert HighScore software (v. 1.0b) according to Schütt (2004), with the accuracy of measurements and detection limits specific to minerals (Schütt et al., 2010). Data preprocessing included (a) correction of outliers, (b) elimination of Kα2-emissions, (c) quartz calibration, (d) identification of reflex peaks and (e) subtraction of background noise (Thelemann, 2016).

4.2.4. Biogenic microfossils: phytolith, diatom and dung spherulite analyses

Opal phytoliths, microscopic bodies composed of pure amorphous silica (Piperno, 1988, 2006), are often used in paleoecological and archaeological studies to investigate paleoenvironmental change (e.g. Fredlund and Tieszen, 1997; Neumann et al., 2009) or past agricultural activity (e.g. Pearsall and Trimble, 1984; Weisskopf et al., 2014). The combined use at archaeological sites of phytoliths and dung spherulites, calcitic crystalline features formed in the intestines of many animals (Brochier et al., 1992; Canti, 1997, 1998, 1999) is a common approach to studying herding activities and husbandry practices (e.g. Delhon et al., 2008; Portillo et al., 2009), while diatoms, a type of algae composed of amorphous, hydrated silica (Werner, 1977; Smol and Stoermer, 2010), can be analyzed to identify ancient water canals (e.g. Grana et al., 2014) or irrigation agriculture (e.g. Trombold and Israde-Alcantara, 2005).

Phytolith extraction followed the procedures outlined by Albert et al. (1999). Approximately 1 g of air-dried sediment was treated with 3 N HCl, 3 N HNO_3, and H_2O_2 to remove carbonates, phosphates, and organic material. The mineral components of the samples were separated according to their densities using 2.4 g*ml^{-1} sodium polytungstate solution [$Na_6(H_2W_{12}O_{40})H_2O$]. Slides were prepared by weighing out about 1 mg of sediment onto a microscope slide, mounting with Entellan New (Merck). The counting was performed using a Leica DM 2000 microscope at 400x magnification; two hundred phytoliths with recognizable morphologies were identified and counted in each sample wherever possible. Phytoliths that were unidentifiable because of dissolution were counted and recorded as weathered morphotypes. The estimated phytolith numbers per gram of sediment are related to the initial sample weight and allow quantitative comparisons between the samples and profiles. Morphological identification of phytoliths was based on standard literature (Twiss et al., 1969; Brown, 1984; Piperno, 1988; Mulholland and Rapp Jr., 1992; Rosen, 1992; Twiss, 1992), as well as on modern plant reference collections from the Mediterranean area (Albert, 2000; Albert and Weiner, 2001; Tsartsidou et al., 2007; Albert et al., 2011; Portillo et al., 2014). The International Code for Phytolith Nomenclature was followed where possible (Madella et al., 2005).

Besides phytoliths, diatoms were identified at 400x magnification to genera level and counted on the same slides. The soil samples for the spherulite analyses were prepared following the method by Canti (1999). Approximately 1 mg of dried sediment was placed on a slide and examined at 400x magnification with a polarization microscope. Similar to the phytolith and diatom analyses, the number of spherulites was counted on each slide and related to the initial sediment weight in order to calculate the amount of spherulites per gram of sediment.

4.2.5. Crop modeling

CropSyst (Cropping Systems Simulation Model) is a complex functional crop growth simulation model which serves as an analytical tool to compute crop productivity in regard to crop management and the environmental conditions (Stöckle and Nelson, 1994; Stöckle et al., 2003). On the basis of fixed parameters (e.g. soil composition, plant phenology) and dependent stress parameters (e.g. soil water budget, nitrogen budget, thermal time, decomposition, erosion) the model simulates crop growth, crop development stages and the resulting crop yield in daily time steps and for multiple crops and years. Management options are diverse and include e.g. crop selection, irrigation, fertilization, tillage operations and residue management. CropSyst is open source and written in C++. A detailed User's Manual is published by Stöckle and Nelson (1996); Stöckle et al. (1994); Stöckle and Nelson (2000). The model requires daily weather values of solar radiation, maximum and minimum temperatures and precipitation. Other input data for the model include soil properties, crop characteristics and management practices. The input parameters are given in four data files: Weather, Soil, Crop and Management, each containing numerous sub-parameters (Table 4.4). These parameters interact in various ways during the simulation, e.g. the nitrogen and water budgets influence the nitrogen transport as a function of the soil characteristics.

The model has been applied to several crops (e.g. corn, wheat, barley and soybean) and regions (e.g. US, Italy, Syria, Spain and Australia), generally with satisfactory results (e.g. Benli et al., 2007; Donatelli et al., 1997).

4.2.5.1. Study Approach

One of the common crop modeling applications is the estimation of potential productivity under different environmental conditions or irrigation strategies. To assess the impact of seasonal rainfall and runoff variability on crop production and its variability, the yield potential of rainfed and runoff irrigated crops at Jawa was simulated for 1983–2014. We chose to run the crop simulation model (CropSyst, v4-19-06) under modern environmental conditions since modern climate data is more reliable than simulated paleodata from Global Climate Models (GCMs; Hemming et al., 2010). Moreover, small differences in climate variability, as expected for deserts, are often insufficiently depicted by GCMs (Gonzalez-Rouco et al., 2011). In order to assess the efficiency of the agricultural terrace systems and their irrigation measures it is assumed that the given crop productivity of the terrace systems is exclusively on a rainfed basis, and thus without runoff/floodwater irrigation, reflecting the system's minimum productivity. Accordingly, it is assumed that each runoff event that was harvested by irrigation measures and/or the choice of the terrace system's location increased crop yields. Since there are no gauging data of the wadis in the Jawa basin a runoff time series for the individual catchments was generated, based on rainfall and soil data in order to study the frequency and volumes of the runoff events. The resulting data served as input parameters in the cropping system model (cf. section 4.2.5.2). Consequently, the efficiency of the systems was evaluated by comparison of crop yields simulated under rainfed conditions and different runoff irrigation levels as resulting from the occurrence of effective rainfall. In order to assess the impact of rainfall and runoff variability, the relation between yield and total water amount was analyzed by calculating the Pearson product-moment correlation coefficient using the *cor.test* function of the *stats*–package (R Development Core Team, 2013) in *R*. With respect to the crop selection for the simulations, winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.) and lentils (*Lens culinaris* Medikus) were chosen, since they were commonly cultivated in the Middle East during the Early Bronze Age (Zohary et al., 2012; Zohary and Hopf, 1973) and are documented for Early Bronze Age Jawa (Willcox, 1981), although the exact races of Early Bronze Age cultivars are not known. During simulations common agricultural practices of the modern Bedouins were followed, assuming that they correspond to traditional practices. For sake of simplicity of the model, information on tillage operations or on crop rotations were neglected. Hence, the model presented here probably does not represent the full complexity of Early Bronze Age crop cultivation. Nevertheless, it is believed that it is a valuable tool for understanding the role of runoff irrigation and describing the relation between water and crop yields.

4.2.5.2. Weather data and analysis

For simulation runs CropSyst requires comprehensive meteorological input data including precipitation, maximum and minimum temperatures and wind speed on a daily basis, while other parameters (e.g. solar irradiance) can be generated based on local information such as coordinates and altitude by the implemented climatic data generator ClimGen (Stöckle et al., 1999).

Only few climate stations cover the Jordanian desert steppe and adjacent areas. The meteorological station of Safawi is located in the vicinity of Jawa (Fig. 3.7), but its records are fragmentary and daily data are inaccessible. The station provides long-term averages for the period from 1961–1991 (FAO, 2001, Fig. 3.8). Monthly averages of wind speed, maximum and minimum temperatures are available for the period 1973–1992 (FAO, 2007). In the absence of available daily time series, we interpolated daily values by applying a quintic polynomial fitting-line on the monthly parameters of the aforementioned dataset (n = 12–16 for each month, $r^2 = 0.99$), being aware that this smooths the natural noise of the parameters. Since data on relative humidity and dew point are not available, these parameters were not considered.

To obtain daily precipitation data for Jawa we applied daily satellite precipitation estimates received from the daily gridded RFE (NOAA-CPC Rainfall Estimator) ARC 2 (African Rainfall Climatology Version 2.0), which were generated by merging gauge measurements and satellite infrared measurements using the RFE2 algorithm (Xie and Arkin, 1996). The dataset covers Jordan with a spatial resolution of 0.1° x 0.1°. It has the highest spatial resolution of comparable datasets (Love et al., 2004; Novella and Thiaw, 2012) and is frequently used in data-sparse regions, e.g. for hydrological modeling (Beckers et al., 2013b; Stisen and Sandholt, 2010). In addition, RFE data perform particularly well in homogenous, flat areas such as the Jawa region (Novella and Thiaw, 2010). We analyzed the available period from January 1983 to December 2014 for the cell of Jawa (37.0 E, 32.2 N). To validate the satellite precipitation estimates we compared them with the GPCC (Global Precipitation Climatology Centre) FDP v.6 dataset (Schneider et al., 2011) for gridded monthly time series by using the Pearson product-moment correlation coefficient. The GPCC dataset has a spatial resolution of 0.5° x 0.5° and is based on spatially interpolated meteorological station data (Rudolf et al., 2010). Due to the different temporal resolutions of both datasets, the higher-resolution ARC 2 daily time series was aggregated on a monthly basis before performing the calculations. Given the differences in spatial resolution, the ARC 2 data was spatially extended to the GPCC grid extent and subsequently averaged. All rainfall datasets were downloaded via the IRI/LDEO Climate Data Library (http://iridl.ldeo.columbia.edu/).

Regarding rainfall analysis, the approach of Beckers et al. (2013b) was followed. The rainy season, i.e. the hydrological year and the agricultural growing season, was defined as lasting from October to May (Trigo et al., 1999). In the following the rainy season is referred to as 'season'. In order to classify the seasons regarding their magnitude in dryness or wetness the standardized precipitation index (SPI) was applied (McKee et al., 1995). Calculations were performed with the SPEI package v.1.6. in R (Vicente-Serrano et al., 2010) and categorized in accordance with McKee et al. (1995). Daily rainfall intensities were classified according to Gallego et al. (2005). To examine the relation to seasonal rainfall amounts the mean daily intensities of each season were calculated considering only days with precipitation values > 0.1 mm (Beckers et al., 2013b).

To generate runoff volumes for the different catchments the SCS runoff curve number method (CN) was applied. The CN is an empirical parameter for estimating direct runoff or infiltration rates from rainfall excess, following the assumption that surface runoff or overland flow always appears when rainfall rates exceed infiltration rates (Mishra and Singh, 2013). Based on the hydrologic conditions, land cover and soil type, the CN method is commonly used in hydrological modeling, especially for small to medium-sized catchments in arid and semi-arid environments (e.g. Beckers et al., 2013b; Berking et al., 2010; El-Hames, 2012; Foody et al., 2004; Hammouri and El-Naqa, 2007; Krause, 2013).

Assuming similar hydrological and soil characteristics within the small-scale catchments of the terrace systems, the area's hydrological soil group, D, and curve number, 88, were picked from published tables (SCS, 1985). The resulting values of 34.5 mm for potential maximum retention (S) and 6.9 for initial abstraction (Ia) using an initial abstraction ratio of $Ia/S = 0.20$ (Table 4.3) is in accordance with values of other studies conducted in comparable environments

Table 4.3.: Hydrological properties of the Jawa region.

Terrain unit	Dominant Texture	Hydrolog. condition	Hydrolog. soil group	CN*	S0.20 [mm]**	Ia0.20 [mm]***
Terraces and slopes	Clay	Poor	D	88	34.5	6.9

* Curve Number for arid and semi-arid rangelands (SCS, 1985),
** Potential maximum retention, S0.20=25.4*(1000/CN-10), S0.05 = 1.33*S0.20,
*** Initial abstraction ratio, Ia = 0.2*S

(e.g. Beckers et al., 2013b; Berking et al., 2010). The relationship Ia = 0.2 x S was empirically derived from the study of many small watersheds. A more recent analysis by Hawkins et al. (2002), however, found that this ratio is usually too high. Based on this study, the use of Ia/S ratios of 0.05 seems more appropriate, as supported by many other studies (e.g. Baltas et al., 2007; Lim et al., 2006). Therefore, an initial abstraction ratio of Ia/S = 0.05 was applied, following the runoff equation (P-0.05*S0.05)2/P+0.95*S0.05 for calculating runoff (with P = precipitation in mm). Runoff was estimated for each rainfall event with a value P>S0.05, driven by the ARC 2 daily rainfall estimates for the entire analysis period (1983–2014). The resulting amount of runoff per square meter was multiplied by the respective terrace system catchment and subsequently divided by its agricultural area, assuming that the generated runoff within the catchment was equally distributed within the fields. With respect to the terrace system TG-2 and the potential diversion of floodwater from Wadi Rajil, it seems reasonable to assume that the regional runoff amount estimated for a catchment area of 160 ha (C2.2, R = 20) is generated within the large catchment, although the runoff behavior probably changes within the upstream area and nowadays a dam disturbs the natural discharge. The specific objective in this case, however, is to estimate the impact of such a diversion in the past and, thus, the effect of an increase in water availability on harvest yields.

4.2.5.3. Soil, crop and management data

Data on soil types and their physical and chemical properties were obtained from a field campaign in 2013 (Meister et al., 2017). The sediments from profile T5 (32°19’56” N, 36°59’50” E, located in terrace system TG-1) were chosen as representative for the soils occurring in the terrace systems. The sediments of profile T5 consist of yellowish silty clay (average textual composition: 43 % clay; 43 % silt, 14 % sand) with an average pH of 7.9 (Table 4.4; see Meister et al. 2017 for detailed data and method descriptions). Soil organic matter and electrical conductivity average 0.8 % and 0.73 mS*m^{-1}. Soil hydraulic properties were estimated on texture after Saxton and Rawls (2006, Table 4.4). Because initial soil water contents were not determined, a reasonable value was chosen to match to the expected yields under rainfed conditions. The chosen value of 0.25 m^3/m^3 also matches with the measured values from an experiment conducted at Ramtha Station, northern Jordan (Al-Issa and Samarah, 2007). The crop growth parameters were set by using the default settings (Stöckle and Nelson, 1994). The beginning and end of the simulation period in October and September were chosen as per ethnographic observation of agricultural cycles in the area (Helms, 1981). The sowing date was set shortly after the first greater seasonal rainfall event (>5mm), whereby the crop harvest date was determined by CropSyst based on a specified number of days after maturity (Stöckle and Nelson, 1994). As known from recent rainfed agricultural practices in the region, neither fertilization nor supplemental irrigation are applied and were therefore not simulated (Al-Bakri et al., 2011). Subsequently, the different levels of runoff irrigation depending on catchment size were considered in the model runs.

4.2.5.4. Model validation

Model calibration was not conducted due to missing field observations and regional data on annual grain yields both in general and for the modeled period. However, the model was validated by comparing simulated crop yields with available data for the region or from areas with similar environmental conditions. In particular we used estimated crop production values of wheat cultivated in Jordan by rainfall regimes (Appendix A.1) and production rates for wheat and barley in the Negev desert as expected by Bedouin farmers (Appendix A.2), given by Russel (1988). Validation for lentil production used the average crop yield data from 1994 to 2013 for Jordan provided by the Jordanian Department of Statistics (DOS, http://web.dos.gov.jo/).

4.2.6. Food supply capacity estimation

The food supply capacity by crop production from the terrace systems was estimated based on the ratio of the mean and maximum crop yields for all three crops and each irrigation level (terrace system) as well as the annual calorie consumption per person. The latter is calculated from the ratio of the current daily calorie consumption rate per person in Jordan (2270 kcal*day^{-1}; Roser, 2015) and the average caloric value of each crop, using the modern values of 3.5 kcal*kg^{-1} for barley and lentils and 2.7 kcal*kg^{-1} for bread wheat (USDA, 2015). In addition, the supply capacity of Jawa's sheep, goat and cattle herds was calculated based on estimated flock sizes (Helms, 1981, cf. section 3.2.3) and annual caloric herd productivity values, including milk and meat production (Russel, 1988, Appendix A.3).

Table 4.4.: Used input data and settings for the CropSyst modeling approach. Non-listed parameters were used in the default setting.

Data-file / parameters	**Activity**	**Value / method description**
Weather		
Precipitation	Estimated (ARC 2, Jawa)	Section 4.2.5.2
Irrigation	Calculated (SCS runoff curve number method)	Section 4.2.5.2; Appendix A.5
Max. and min temp.	Interpolated from monthly means of Safawi weather station	Section 4.2.5.2
Solar irradiance	Calculated by CropSyst (Location file)	
Maximum solar irradiance	Calculated by CropSyst (Location file)	
Daylight (h)	Calculated by CropSyst (Location file)	
Relative humidity	Not used	Missing data
Dew Point	Not used	Missing data
Wind speed	Interpolated from monthly means of Safawi weather station	Section 4.2.5.2
Soil		
Albedo	Given by CropSyst	Dry: 0.16; wet: 0.09
Clay	Observed	43 %; Section 4.2.5.3
Silt	Observed	43 %; Section 4.2.5.3
Sand	Observed	14 %; Section 4.2.5.3
pH	Observed	7.9; Section 4.2.5.3
Hydrologic group	Estimated from soil texture	D; Section 4.2.5.2
Hydrologic condition	Estimated from soil texture	Poor; Section 4.2.5.2
Permanent wilting point	Estimated from soil texture	0.260 m^3/m^3; Section 4.2.5.3
Field capacity	Estimated from soil texture	0.41; Section 4.2.5.3
Bulk density	Estimated from soil texture	1.21; Section 4.2.5.3
Sat. hydr. cond.	Estimated from soil texture	0.141 $m*day^{-1}$; Section 4.2.5.3
Saturation	Estimated from soil texture	0.54 m^3/m^3; Section 4.2.5.3
Management		
Sowing date	Extracted from rainfall data	1-2 days after the first greater rainfall event (>5mm) of every year
Land treatment	Assumed	Straight row
Fertilization	Not set	No fertilization
Initialization		
Water content	Estimated	0.25 m^3/m^3; Section 4.2.5.3
NO_3/NH_4	Not set	Missing data
Salinity	Observed	0.73 $mS*m^{-1}$; Section 4.2.5.3
Organic matter	Observed	0.83 %; Section 4.2.5.3
Submodels		
Precipitation	Precipitation event duration	240
Freezing	No snow pack	On
Chemistry	Nitrogen / salinity	On
Evapotranspiration	Penman-Monteith	On
Soil	Infiltration (FD)	On
	Runoff model (FD)	On
	Subdivide soil layers	On
	Erosion	On
Organic matter	Single organic matter pool	On

4.3. Analysis of pastoral mobility in northeastern Jordan

Following the common interpretation that clustered enclosures were primary used by mobile pastoralists on a short-term or seasonal basis, either for domestic or herd-management purposes (e.g. Akkermans et al., 2014; Betts et al., 2013; Müller-Neuhof et al., 2013; Rollefson, 2013; Tarawneh and Abudanah, 2013), makes them particularly interesting for the investigation of a pastoral landscape that has been used by herders during the last eight to nine millennia. Their distributional pattern at a local and regional scale provides information on how mobile groups interacted with (a) the landscape and (b) each other. However, to interpret this distributional pattern further information on favored pasturelands, migration pattern, and social interactions need to be considered. Therefore, all clustered enclosure sites were systematically recorded based on satellite imagery. The mapping focused on the basaltic *harra* since enclosures only rarely occur in the limestone desert of the *hamad* (Betts et al., 2013). In order to investigate the absolute and relative spatial locations of the recorded enclosure sites their first- and second-order characteristics are examined using distance and density based approaches of point pattern analyses by including geomorphometric and geomorphological site characteristics. The results of this spatial analysis are combined with hydrological, meterological and archaeological data and a review on traditional herding practices in northeastern Jordan (Fig. 4.4).

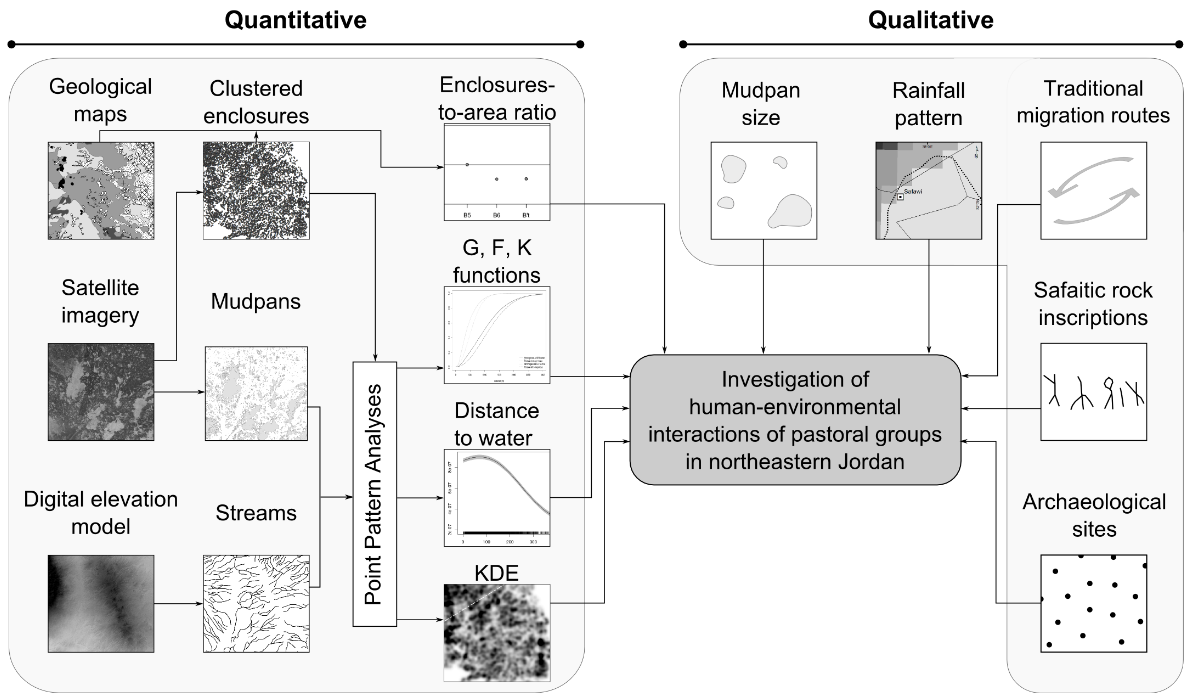

Figure 4.4.: Qualitative and quantitative data basis and methods applied in the investigation of human-environmental interactions of pastoral groups in northeastern Jordan.

4.3.1. Clustered enclosures mapping

Satellite data were used in order to map the clustered enclosures in the study area, covering in total c. 10,000 km^2. The sites were systematically recorded from satellite images applying the World Imagery web service of *Esri* using *ArcMAP* (v. 10.0). This service provides about one-meter high-resolution satellite imagery for Jordan. Site mapping was conducted on a dataset updated on 17th March 2016 for a fixed scale of 1:8000. To avoid the mapping of other enclosure-like structures, such as dwellings (cf. Rollefson et al., 2014a), small (hunting) camps (cf. Betts, 1998) or single/double enclosures associated with desert kites (cf. Helms and Betts, 1987; Kempe and Al-Malabeh, 2013), only sites with more than two enclosure-like clustered structures and a minimum site size of 20 meters in diameter were recorded. Potential 'wheels' were recorded when they were characterized by clustered enclosures, fulfilling the criteria described above.

Mapping was confined to the area of the basaltic *harra* due the restricted detectability of clustered enclosures in the *hamad*. The research area is delimited to the east by the transition to the limestone plateau of the *hamad* and to the south by a cover of aeolian sediments. The northern boundary is set artificially, including parts of southern Syria. The western boundary is determined by the change towards limestone bedrock in the south and modern agriculture and settlement activities in the north.

4.3.2. Data processing, remote sensing and geomorphometric approaches

In order to investigate possible relationships between locations of clustered enclosures and their environmental conditions, geological maps (scale of 1:250,000; sheets: El Azraq, Mahattat el Jufur; source: Bender et al., 1968) were digitized (Fig. 7.3). Additionally, geological features on a smaller scale were identified by applying band ratios after Inzana et al. (2003), using three scenes of Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), recorded in June/July 2015 (available from http://glovis.usgs.gov/). To identify areas of fine-grained deposits the Landsat band ratio SWIR1/NIR*red/NIR was used to discriminate mafic from non-mafic rocks (Inzana et al., 2003, Table 4.5). The band rationed image corresponds well with geologic maps of the area showing different basalt flows, fluvial deposits and limestones. To extract the mudpan and wadi deposits (subsequently recapped as 'mudpan class') from other geological units the transformed multispectral image was classified by applying a supervised random forest classification after Breiman (2001). The required training and test datasets were digitized using ten polygons for the total of nine identified classes corresponding to the geological basic information. Each polygon was filled with 20 randomly distributed points, ten as training data and ten as test data. A total number of 200 trees were selected using expert knowledge based on variogram analysis. The calculations were conducted in R using the package *randomForest* (Liaw, 2015; Liaw and Wiener, 2002). With an overall accuracy of 96.5 %, the Random Forest classifier performed well. With a user's accuracy of the mudpan

Table 4.5.: Band designations for the Landsat TM and OLI/TIRS satellites. Since the band designations differ between Inzana et al. (2003; Landsat 4/5) and the present study, the Landsat 8 bands with the most similar wavelength characteristics were selected.

Landsat 4/5 TM		**Landsat 8 OLI/TIRS**	
Band	**Wavelength (μm)**	**Band**	**Wavelength (μm)**
3	0.63 - 0.69	4 (red)	0.64 - 0.67
4	0.76 - 0.90	5 (NIR)	0.85 - 0.88
5	1.55 - 1.75	6 (SWIR 1)	1.57 - 1.65

class of 91.9 %, representing the fraction of correctly classified pixels with regard to all pixels of that ground truth class, the classification result is reasonably reliable.

The GRASS r.watershed module (Metz et al., 2011) was applied using elevation data from the Shuttle Radar Topography Mission (SRTM) 1 (resolution: 30 m * 30 m, available at http://earthexplorer.usgs.gov/) to delineate catchments and channel networks. In order to determine the distance from pastoral sites to the closest potential periodic water source the spatial information on the occurrence of 'mudpans', as deduced from satellite images, and to 'river channels', as derived from the morphometric analysis of the digital elevation model, were merged. After reclassification, a raster of the cumulative distance from mudpan/river pixels was created using the *gridDistance* function of the *raster*–package (Hijmans, 2015). The 'clustered enclosures to water source' distance was extracted by using the *extract* function of the same package.

4.3.3. Spatial point pattern analyses

In order to determine the processes that affected the spatial distribution of clustered enclosures within the study area spatial point pattern analyses were carried out. A spatial point pattern consists of locations of a set of point objects, representing the simplest possible spatial data (O'Sullivan and Unwin, 2010; Nakoinz and Knitter, 2016). Point pattern analyses focus on the spatial distribution of known events and aim to identify the factors controlling the processes that generated them (e.g. Bivand et al., 2013). Emphasis was put on the analysis of (1) the distribution of clustered enclosures in space, i.e. their absolute location, and (2) potential interactions between clustered enclosures, i.e. their relative location (see O'Sullivan and Unwin, 2010).

Based on the analysis of the clustered enclosures, i.e. their spatial distribution, first- and second-order effects were traced (O'Sullivan and Unwin, 2010). First-order effects describe the locations of points and the influence of different parameters (covariates) on point locations. This is assessed by investigating the intensity of events within the region, i.e. their density distribution. In contrast, second-order effects are present when the occurrence of points is influenced by the occurrence of other points; this effect is analyzed using distance-based approaches (O'Sullivan and Unwin, 2010).

In cases where the distribution of known events is independent from site-related factors and regional characteristics, e.g. the distances to river channels and mudpans or bedrock characteristics, complete spatial randomness (CSR) prevails. The mathematical representation of CSR is the homogeneous Poisson process that assumes a constant intensity function. In contrast, an inhomogeneous Poisson distribution assumes that the intensity varies from place to place (Bivand et al., 2008; for detailed descriptions on method and theory see Baddeley et al., 2015; Diggle, 2013).

4.3.3.1. Density based analyses of clustered enclosures

Kernel density estimation: In order to detect first-order effects and obtain information about the spatial density of the clustered enclosures their intensity functions were assessed using kernel density estimations (KDE). This enabled a differentiation between high and low-density areas to be made. The resulting intensity surface depends strongly on kernel type and its bandwidth (for a more detailed description see Bivand et al., 2008; Nakoinz and Knitter, 2016). In this study, an isotropic Gaussian probability density kernel was applied (Baddeley et al., 2015). The bandwidth of the kernel determines the level of smoothing; small values produce very tapered surfaces, while large values produce very smooth functions (Bivand et al., 2008). To determine the appropriate empirical kernel bandwidth the likelihood cross-validation approach was used, which assumes an inhomogeneous Poisson distribution (Baddeley et al., 2015). Depending on the data the optimal bandwidth can also be selected by experiments and based on expert knowledge (Bivand et al., 2008; Nakoinz and Knitter, 2016). In line with this and to obtain information on the general data trend a large bandwidth was additionally selected. The calculations were conducted applying the software *R* using the *density* function of the *spatstat*-package (Baddeley et al., 2016; Baddeley and Turner, 2005; details on the method: Baddeley et al., 2015).

The density of clustered enclosures as a function of a covariate: In order to identify whether the density of clustered enclosures is influenced by the water availability, i.e. whether first-order effects prevail, their spatial relation to the 'distance to river channels and mudpans' was analyzed. However, since natural springs and lava tubes are largely unknown and near surface groundwater aquifers are absent these factors were not integrated into the analyses. The calculations were conducted in *R* using the spatstat function *rhohat* with a bandwidth of 100 m (see Baddeley et al., 2015). The resulting covariate function was used to predict a density raster that mirrors dependence on the covariate. This raster was subtracted from the empirical density of the clustered enclosures in order to identify areas where the dependence of the covariate is strong or weak.

4.3.3.2. Distance based analyses of clustered enclosures

In order to identify an interaction between the recorded sites three types of analyses, namely the G, F and K functions, were conducted. These functions demonstrate whether the interactions lead to an aggregated or regular pattern of clustered enclosures (Diggle, 2013). The resulting empirical distributions of G, F and K functions are compared to two theoretical models that assume independence: (1) a homogeneous Poisson distribution, and (2) an inhomogeneous Poisson distribution, considering the influence of a covariate, e.g. water availability.

The G function is the cumulative frequency distribution of the nearest-neighbor distances (O'Sullivan and Unwin, 2010). The F function is the cumulative frequency distribution function of the nearest-neighbor distance between locations where points occur and locations where no points occur. The non-point locations are selected at random and their nearest-neighbor distance to a known point is determined (O'Sullivan and Unwin, 2010). Since the F function is a measure of the space left between points it is also called the empty-space function (see Baddeley et al., 2015).

A shortcoming of the G and F functions, especially in clustered point patterns, is that they only use nearest-neighbor distances (Bivand et al., 2008; Nakoinz and Knitter, 2016). Therefore, the K function was additionally applied, also known as Ripley's K (Ripley, 2004). The K function measures the fraction of all points found within a given distance by drawing circles with increasing radii around points (Bivand et al., 2013).

The calculations of the G, F, and K functions were conducted applying the software package *R* using the appropriate functions provided by the *spatstat*–package (Baddeley and Turner, 2005). More detailed method descriptions of the applied functions are given e.g. by Baddeley et al. (2015); Bivand et al. (2013); Diggle (2013); O'Sullivan and Unwin (2010).

4.3.4. Frequency distribution of clustered enclosures within different geological units

In order to investigate the frequency distribution of clustered enclosures within different geological units, the area of each geological unit and the number of clustered enclosures per geological unit was calculated for the Jordanian part of the study area in *R* using the *gArea* and *poly.counts* functions provided by the *rgeos* and *GisTools*—packages (Bivand and Rundel, 2016; Brunsdon and Chen, 2016). The geological units were differentiated according to petrographic (e.g. limestone, basalt) and stratigraphic characteristics (e.g. different basalt flows) based on the geological maps (Bender et al., 1968).

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CHAPTER 5

Desert agricultural systems at EBA Jawa (Jordan): Integrating archaeological and paleoenvironmental records

Abstract

Located in the arid basalt desert of northeastern Jordan, the settlement of Jawa is by far the largest and best-preserved archaeological site in the region. The Early Bronze Age (EBA) settlement phase of Jawa (3500–3000 BCE) is characterized by a highly sophisticated water storage system made of a series of pools, dams, and canals. In addition, recent archaeological and geoarchaeological surveys have uncovered agricultural terrace systems in the nearby vicinity.

In this study, four of these runoff terrace systems were investigated by detailed mapping. Additionally, thirteen sediment profiles from inside and outside the terrace systems were recorded and sampled. The examined samples were analyzed for bulk chemistry, texture, phytoliths, diatoms, and dung spherulites to supply information on the environmental and depositional conditions. The terrace systems were dated using optically stimulated luminescence (OSL).

Ancient terrace agriculture was practiced on slopes, small plateaus, and valleys close to Jawa through the use of surface canals, which collected and diverted floodwater from nearby wadis or runoff from adjacent slopes. The terraced fields were usually arranged in cascades and comprised a system of risers, canals, and spillways. The terrace fills investigated yield OSL ages of around 3300 BCE, indicating that the terraces were constructed in the Early Bronze Age. The terrace fill sequences are composed of mixed unstratified fine sediments of local origin, reflecting low-energy fluvial deposition regimes. The phytolith record is dominated by Pooid grasses that include the most common Near Eastern cereals, such as wheat and barley. Increased phytolith concentrations in terrace fill sediments, as compared to samples from non-terrace deposits nearby, suggest increased plant growth and water availability within

the terraces. Whether the terrace systems were used for growing food crops only or whether they were additionally used for grazing cannot be ascertained. Overall, quantitative phytolith analyses in arid environments are well suited to investigate temporal and spatial distributions of plant microfossil concentrations and their relation to human activity or paleoenvironmental conditions.

Keywords

Ancient agricultural terraces; Early Bronze Age; Terrace fill sediments; Multi-proxy approach; Phytoliths; OSL dating

5.1. Introduction

The fortified settlement of Jawa, approximately ten hectares in size, is located in the basalt desert steppe of northeastern Jordan and is by far the largest and one of the best-preserved Early Bronze Age sites in the region. It may have functioned as an important trading center between the southern Levant and Mesopotamia (Müller-Neuhof, 2014b). Jawa has been partly excavated between 1972 and 1976 by S. Helms (Helms, 1981; Betts et al., 1991). The pottery remains indicate two occupation periods: the earlier and largest occupation phase, in which Jawa may have up to 5000 inhabitants, dates to the end of the Late Chalcolithic and beginning of the Early Bronze Age (Levantine Early Bronze Age IA, c. 3500–3000 BCE, as verified by radiocarbon dating, see Müller-Neuhof et al., 2015). A later and much smaller reoccupation of the site dates to the transition from the Early Bronze Age IV to the Middle Bronze Age I (around 2000 BCE).

The Jawa region is located in transition zone between the semi-arid southern Levant and the arid Syrian Desert, where these climatic conditions roughly prevailed since the Mid-Holocene aridisation (Robinson et al., 2006; Rambeau, 2010; Finné et al., 2011; Roberts et al., 2011). While the Dead Sea area has been extensively studied (Bar-Matthews et al., 1997, 1998, 1999; Frumkin et al., 1999a; Migowski et al., 2006; Neumann et al., 2007; Bar-Matthews and Ayalon, 2011, e.g.), there is a lack of high-resolution proxy records in northeastern Jordan (see Rambeau, 2010; Finné et al., 2011). Therefore, detailed reconstructions of paleoenvironmental conditions during the Late Pleistocene and Holocene for Jawa are missing. According to isotopic compositions of speleothems from the Soreq Cave in Israel (Bar-Matthews et al., 1997, 1998), annual rainfall rates during the second half of the fourth millennium BCE are estimated to have been temporarily ∼100 mm higher than today (Issar and Zohar, 2004). However, this does not necessarily mean that the Jawa region shared the same temporal and intense precipitation conditions (Rambeau, 2010).

The seemingly unfavorable environmental conditions in the region necessitated water management strategies to supply Jawa's inhabitants with local food and water (Roberts, 1977; Helms, 1981). The site's highly sophisticated water storage system appears to be one of the earliest hydraulic system of its kind in the world (Roberts, 1977; Helms, 1981; Viollet, 2007; Whitehead et al., 2008). Combining a series of pools, dams, and canals to utilize surface and wadi runoff, it could probably meet the water demand of a population of 6000 and their livestock, at least during predicted wetter times of the Early Bronze Age (Whitehead et al., 2008). For subsistence, the inhabitants of the Early Bronze Age settlement relied on agropastoralism with some hunting; animal remains at the site are dominated by sheep and goat (86.7 %), followed by cattle (8.5 %) and gazelles (2.3 %) (Köhler, 1981). Evidence of farming is shown in the large number of grinding stones and sickle blades (Helms, 1981) as well as plant remains, including several cereal seed taxa such as six-row hulled barley (*Hordeum vulgare*), einkorn (*Triticum monococcum*), bread wheat (*Triticum aestivum sensu lato*), and emmer (*Triticum dicoccum*) (Willcox, 1981). Apart from a few small areas, however, evidence of arable land in the vicinity of Jawa has been scant until this study (Mithen et al., 2008). Recent archaeological and geoarchaeological surveys have revealed the well-preserved remains of several abandoned complex runoff terrace systems in the vicinity of Jawa (Müller-Neuhof, 2014b,a, 2012). Runoff terraces are one of the various types of agricultural terraces (reviewed in e.g. Frederick and Krahtopoulou, 2000; Spencer and Hale, 1961; Treacy and Denevan, 1994) typical for the southern Levant (e.g. Evenari, 1982; Beckers and Schütt, 2013). They are usually built across channel beds and floodplains of ephemeral rivers (*wadis*) or on hillslopes. The terraces consist of stone walls (commonly called *risers*) which retain and collect water and sediments of episodic flash floods and runoff events, gradually silting up the fields in a self-filling process. When the terrace surfaces are sufficiently leveled and large enough, they are cultivated (commonly known as *tread*). The sediment body referred to as terrace- or tread fill (Fig. 5a). Once the terrace is filled, the farmer can easily enlarge its sediment storage capacity by adding a new row of stones on top of the riser (Beckers and Schütt, 2013).

Located on small plateaus or on the valley floor of Wadi Rajil and its tributaries, the runoff terrace systems at Jawa were only partly recognized during earlier surveys or were interpreted as animal pens (Helms, 1981). According to lithic evidence, the initial construction of these systems most presumably dates to the Late Chalcolithic/Early Bronze Age. If so, they would be the oldest example of its kind known to date (Müller-Neuhof, 2014a). However a detailed description of these systems is missing and the dating is still being debated. In this study we document these terrace systems through detailed mapping in order to gain a better understanding of their function. We also take a multi-proxy approach for studying sediment records of different terraces. By investigating bulk chemistry, texture, phytoliths, diatoms, and dung spherulites we aim at characterizing their environmental and depositional conditions. Furthermore, we clarify whether the sedimentary record and the paleoenvironmental proxies analyzed are suitable for identifying former land use (crops or pasture), especially in this nowadays desert environment where organic remains are often rare. In order to establish a chronology of the terrace systems we applied optically stimulated luminescence (OSL) dating on sediments from two selected terraces.

5.2. Regional setting

The ancient settlement of Jawa (32.336 N, 37.002 E, 1002 m asl) is located on Wadi Rajil in the basalt desert steppe (Arabic *al-harra*) in northeastern Jordan, close to the Syrian border (Whitehead et al., 2008, see Fig. 5.1a, b). Geologically, the region is part of the north Arabian volcanic province of Harrat Ash Shaam, which extends from southern Syria to Saudi Arabia and is composed of Quaternary and Neogene basalt lava flows extruded from widespread volcanic centers (Bender, 1968; Taqieddin et al., 1995; Allison et al., 2000). There are numerous small volcanoes and fissures in the Jordan territory (Bender, 1968), and the relief gradually declines from north to south, with elevations ranging between c. 1200 and 400 m asl (Allison et al., 2000). The topography is dominated by a gently undulating plain riddled by low hills. Slopes are generally slightly inclined and concavo-convex in shape. Between the basalt hills, depressions filled with fine-grained sediment deposits are common, locally called *Qa'a* (Al-Homoud et al., 1996). Apart from these topographic lows, the entire surface area is covered with extensive stone pavements formed by basalt boulders of varying size and shape from the weathering of the volcanic rocks (Allison et al., 2000).

As for climate, this region is located in the transition zone between the Mediterranean climate and the fully arid zone that predominates in northeastern Jordan (Al-Homoud et al., 1996). Following the Köppen-Geiger classification, the area around Jawa is classified as a hot desert climate (BWh) (Kottek et al., 2006), characterized by marked seasonal variations: hot, dry summers and cool, moist winters (Allison et al., 2000). The average summer temperature reaches 28 °C, while the mean winter temperature is 10 °C. Under present-day conditions, the mean annual rainfall is less than 100 mm and occurs mainly between November and March (see the climate diagram for the nearby Safawi station, shown in Fig. 5.1a, c). The mean annual temperature is about 19 °C and potential evaporation rates are high, ranging from 1500 mm*a^1 to 2000 mm*a^1 (Allison et al., 2000). Strong winds occur frequently, in the summer coming mostly from the northwest and in the winter prevailing from the northeast, caused by cyclonic disturbances from the Mediterranean Sea (Al-Homoud et al., 1996).

In the absence of natural springs, the only natural water sources are ephemeral river systems (Arabic al-wadi) and groundwater aquifers (Helms, 1981). The uppermost of three groundwater aquifer complexes is situated below the entire basalt plateau (Dottridge and Abu Jaber, 1999). The depth of the water Table varies from 250 to 100 m (Al-Homoud et al., 1996), depending on the topography, which made it inaccessible to prehistoric communities (Whitehead et al., 2008). The drainage system is dense and drains into the Azraq basin in the southwest (Al-Homoud et al., 1996). Wadi Rajil, one of the major rivers in the region, has its headwaters in the sub-humid Druze Mountains in Syria and enters the Azraq basin from the northeast. At the Jawa location, its catchment area totals about 270 km^2 (Whitehead et al., 2008).

The current natural vegetation cover of northeastern Jordan is classified as part of the Saharo-Arabian plant region (Al-Eisawì, 1996), whose characteristic taxa are *Fabaceae*, *Tamaricaceae*, *Chenopodiaceae*, *Caryophyllaceae*, *Zygophyllaceae* and *Brassicaceae* (Frey and Lösch, 2010). Vegetation around Jawa is very sparse, consisting of grasses, herbs, and shrubs, and is dominated by chenopod plants such as *Salsola vermiculata* and *Halogeton alopecuroides* (Al-Eisawì, 1996). The basalt boulders spread across the surface are often covered by lichens (Al-Eisawì, 1996), indicating the availability of ground surface moisture (Al-Homoud et al., 1996). The modern soil is poorly developed and characteristic of raw desert soils (Al-Eisawì, 1996). Because of the high aridity and subsequent poor quality of the soil, irrigation is necessary for farming. Today, rainfed agriculture is practiced only in the Druze Mountains to the north (Helms, 1981), in the Qa'a ash Shubayka and Qa'a al Buqayawiyya area to the south where the environmental settings support the growth of cereal crops (Tansey, 1999). The present-day form of land use is dominated by mobile pastoralism based on camel, sheep and goat herding (Lancaster and Lancaster, 1991; Al-Tabini et al., 2012; Müller-Neuhof, 2014a).

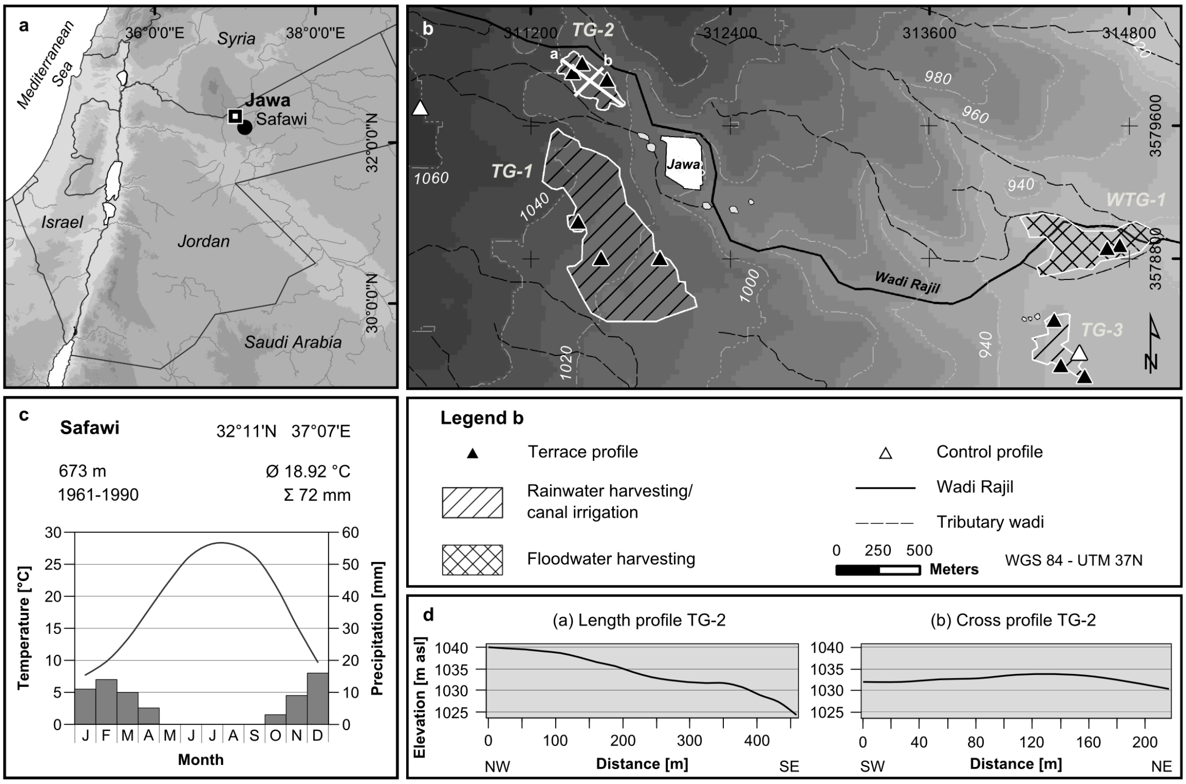

Figure 5.1.: 1a: Location of Jawa and the modern town Safawi in Jordan (Database: SRTm 250); 1b: Detailed map of the topography, showing the major drainage and terrace systems (TG 1-3, WTG-1) and profile locations in the vicinity of Jawa (Database: Aster DEM); 1c: Climate diagram of Safawi (Data source: FAOClim-Net); 1d: Length- (a) and cross (b) profiles of terrace system TG-2 in Fig. 5.1b (Database: ASTER DEM).

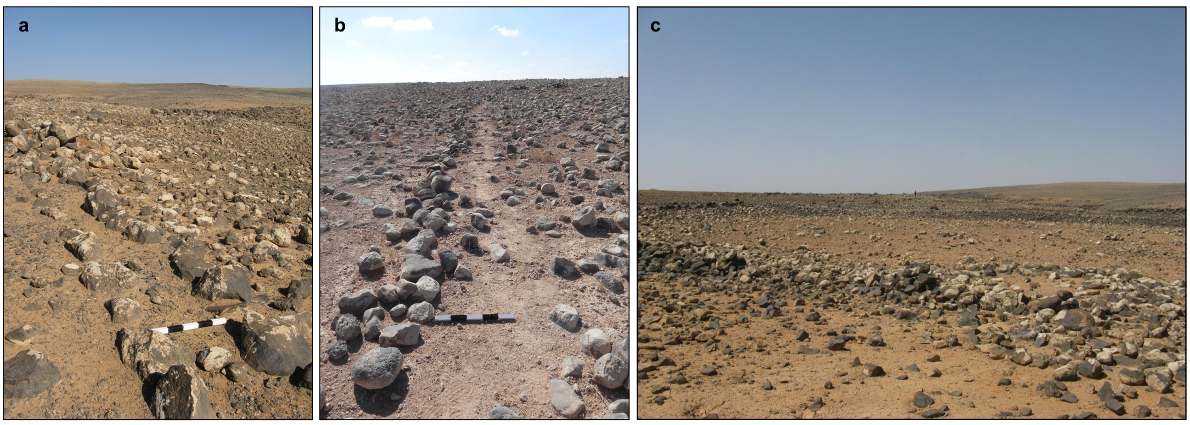

Figure 5.2.: Photographs of structures of the agricultural terrace systems in the vicinity of Jawa. 2a: stone-lined canal of terrace system TG-2 (© J. Meister); 2b: cleared surface canal of terrace system TG-1 (© DAI-Orientabteilung, B. Müller-Neuhof); 2c: walled field of terrace system TG-2, note two colleagues in the background as scale (© J. Meister).

5.3. Material and methods

5.3.1. Data collection and sampling strategy

Four agricultural terrace systems were identified and investigated. These can be differentiated into two major types: a) those located on slopes, plateaus, and small valleys close to Jawa, irrigated mainly by rainwater runoff (TG-1, TG-2, TG-3), and b) those located on wadi terraces of Wadi Rajil, approximately 2 km downstream of Jawa, irrigated by floodwater harvesting (WTG-1) (see Beckers et al., 2013a, for a general introduction to runoff and floodwater harvesting; see Fig. 5.1b for their locations). Detailed archaeological, geomorphological, and hydrological mapping of the terraced field systems was based on a WorldView-2 satellite image (ground resolution: 0.5 m x 0.5 m) and ground surveys during two field campaigns in 2011 and 2013 (Figs. 5.2, 5.3, 5.4). The catchment delineations were generated by applying the GRASS r.watershed module, using elevation data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (resolution: 30 m x 30 m). For all terrace systems, the ratio R was determined by dividing the catchment area of each terrace system by its total cultivation area (Evenari et al., 1961). Thirteen sediment profiles with depths of up to 1 m were investigated (see Figs. 5.1b and 5.4a-d for their locations). Due to the generally observed low heights of terrace walls and, thus, small depths of tread fills (s. section 5.4.1), only the surface layer (tread) is usually cultivated (Frederick and Krahtopoulou, 2000, Fig. 5.5a). Therefore, most of the profiles were analyzed only to a depth of about 30 cm. The sampling strategy included the recording and sampling of multiple profiles within a terrace system. Control profiles outside the areas formerly used for agriculture were recorded and sampled. One control profile (C1) is located on a slope west of the terrace systems TG-1 and TG-2; a second control profile (C2) is situated on a valley floor close to terrace system TG-3 (see Fig. 5.1b). A total of 45 samples were collected for further analysis. For subsequent comparison, and because a clear stratigraphy was not evident in all profiles, samples were systematically taken from analog depth levels (c. 3, 11, 22 cm depth).

5.3.2. Optically stimulated luminescence (OSL) dating

Since the sediments did not include organic macro-remains, radiocarbon dating was not possible. We therefore applied OSL dating to sand-sized grains from two agricultural terrace fills in order to date the terraces investigated. The deposition and burial ages of terrace fill sediments can provide indirect information about the time of construction of the associated terrace wall (riser), assuming that the terrace fill stratigraphy generally corresponds to terrace filling periods after its initial construction (Beckers and Schütt, 2013). Two sediment profiles (T1, T5) from two different terrace systems (TG-1, TG-2), both presumably dating to the Late Chalcolithic/Early Bronze Age (Müller-Neuhof, 2014b), were sampled. Both OSL samples were taken with metal tubes at a depth of approximately 30 cm (see Table 5.1 for sample laboratory numbers and data;

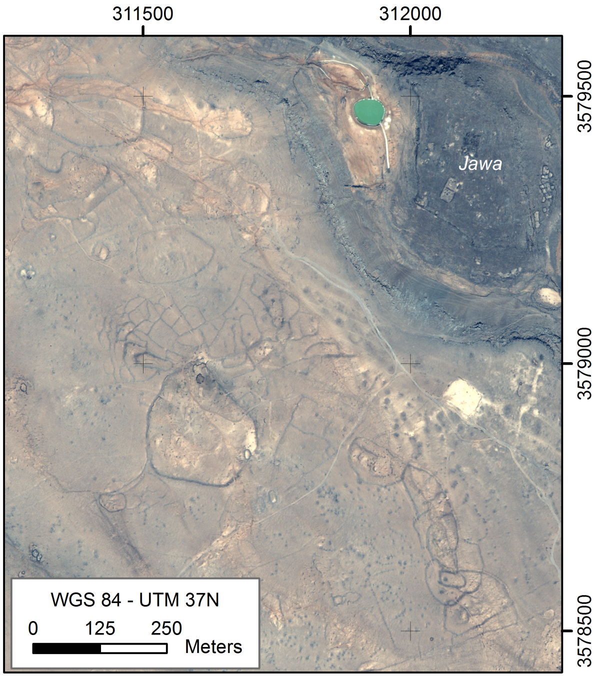

Figure 5.3.: Satellite image of terrace system TG-1 (WorldView-2, recorded on the 17 March 2011).

Figs. 5.1b and 5.4a, b for profile locations; and Fig. 5.5b, c for sample locations). Additional material was sampled for gamma spectrometry. In the laboratory, activity concentrations of 40 K and several nuclides from the uranium and thorium decay chains were measured using high-resolution gamma-ray spectrometry.

Results were combined with information on burial history,water, and organic content history to assess the average moisture and soft component related attenuation of the beta and gamma radiation in the sediment since burial (Madsen et al., 2005). The water content was estimated at 6–9 %. The effective sediment dose rate was calculated considering the beta attenuation of the relevant grain size fraction (Mejdahl, 1979), and the contribution from the cosmic dose rate was calculated according to Prescott and Hutton (1994). Since the cosmic dose rate is dependent on the thickness of the overburden we had to make an assumption with regard to the development of this overburden since burial; in this setting we presume it is fair to assume immediate burial of the samples to the present depth below the surface and thus a constant cosmic dose rate since burial. There were no signs of disequilibrium in the uranium decay chain. Resulting dose rate values were 2.13 ± 0.07 Gy*ka^{-1} (NCL-7114013) and 1.87 ± 0.06 Gy*ka^{-1} (NCL- 7114014). The quartz fraction of 90–180 μm was density-separated and purified through sieving and chemical treatment (HCl, H_2O_2, and HF, and an HCl rinse). Following a number of tests, suitable measurement parameters were selected for use in the Single Aliquot Regenerative (SAR) dose procedure (Murray and Wintle, 2003). The most light-sensitive OSL signal of quartz grains was selected using the early background approach (Cunningham and Wallinga, 2010). To

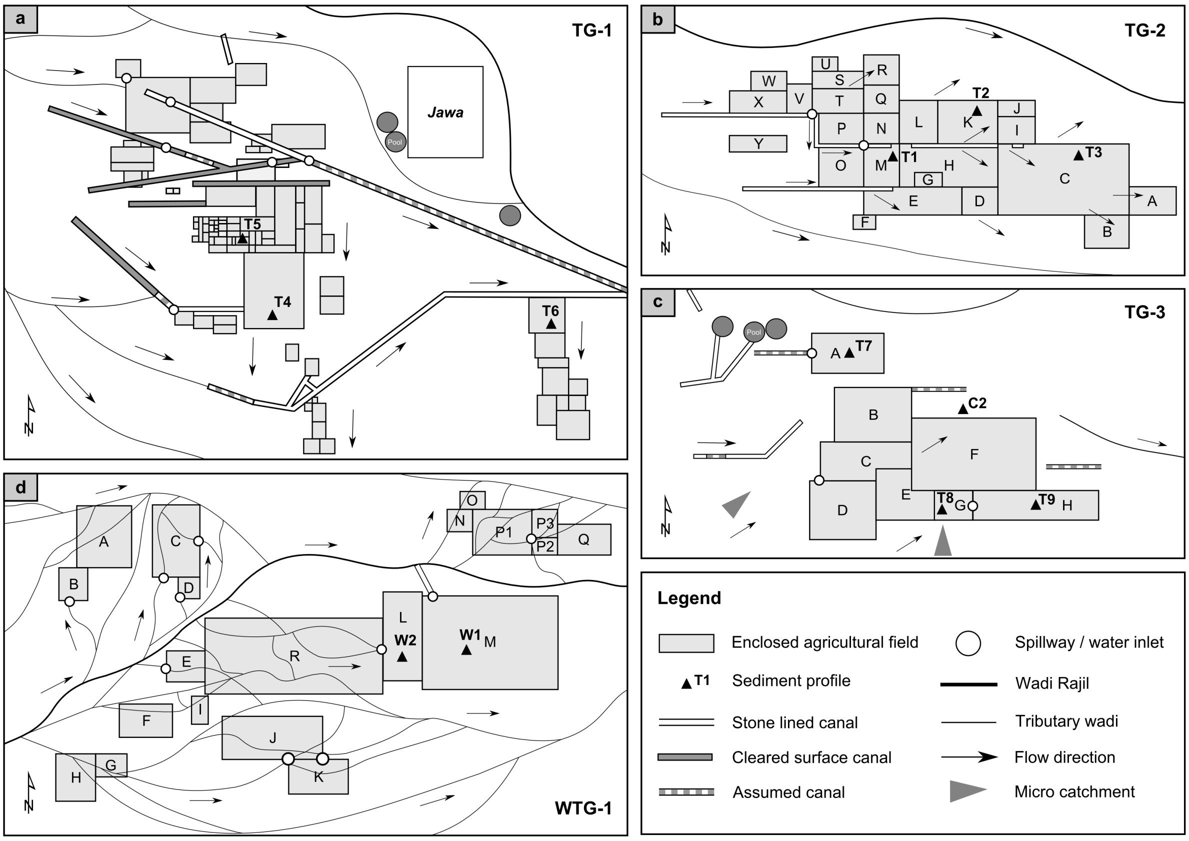

Figure 5.4.: 4a-d: Detailed maps of the recorded terrace systems with the sampling profiles (for their location and scale see Fig. 5.1b). Note that profile C1 is not displayed according to its remote location.

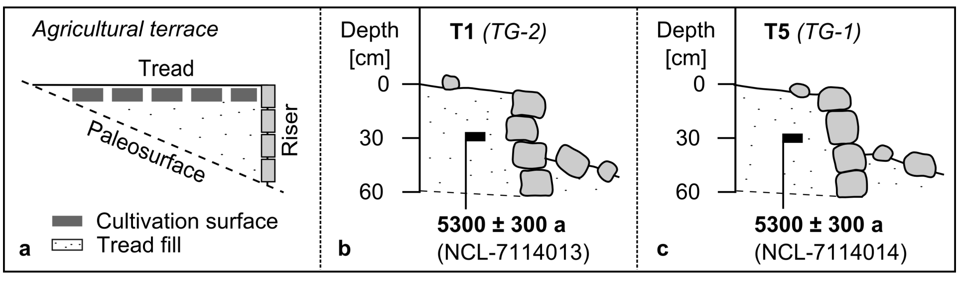

Figure 5.5.: 5a: Sketch of an agricultural terrace with terrace components mentioned in the text modified after Frederick and Krahtopoulou (2000); 5b, c: Terrace sketch of the section and OSL sample location at profiles T1 & T5 (see Fig. 5.1b and 5.4a,b for profile locations) with OSL results (1σ errors).

obtain a good estimate of the burial dose, measurements were repeated on at least 30 aliquots per sample, with each aliquot containing approximately 100 grains (2 mm-diameter sample). To test the SAR procedure and the selected measurement parameters, a laboratory-given dose was retrieved with the adopted procedure; the measured dose agreed favorably with the given dose (dose recovery ratio 1.00 ± 0.01, n = 6). Paleodoses measured on the single aliquots showed a symmetric distribution with moderate over-dispersion values (24–33 %). This extra scatter (unexplained by experimental uncertainties) in the paleodose distributions might be related to either insufficient signal resetting at the time of burial or post-depositional mixing (e.g., through tillage) of the soil matrix, or both. In order to obtain a conservative paleodose estimate for the original terrace forming, the Central Age Model (Galbraith et al., 1999, CAM) was applied to the paleodose distribution. For both samples, the burial age was determined by dividing the paleodose by the dose rate (Table 5.1).

5.3.3. Bulk sediment analyses

In order to characterize and quantify the contrasts between sediment strata and profiles, we subjected bulk sediment samples to standard sedimentological analysis. Analyses were performed at the Physical Geography laboratory, Department of Earth Sciences, Freie Universität Berlin. Dry sediment colors were distinguished using a Munsell soil color chart. The pH and electrical conductivity (EC) values were measured using a handheld pH/EC reader (Hanna content instruments) in a suspension of 5 g of dried sediment and 12.5 ml of KCL and distilled water after a reaction time of 30 min. Total carbon content (TC mass-%) was analyzed on homogenized samples using a Leco TruSpec CHN analyzer, detecting CO_2 flow by highly selective infrared (IR) and thermal conductivity. Total inorganic carbon (TIC mass-%) was determined by the evolution of CO_2 during acid (H_3PO_4) treatment and the subsequent quantification of the evolved CO_2 in 20 ml 0.05 N NaOH solution by conductivity (Woesthoff Carmhograph C-16). Total organic carbon content (TOC mass-%) was calculated by subtracting TIC from TC. Calcite ($CaCO_3$) was used as the calibration standard for TC and TIC analyses. Grain size distributions were measured using laser diffractometry (Beckman Coulter LS 13320 PIDS) for grain sizes <2 mm, after sample partition by dry sieving. Sample preparation for grain size analysis included the removal of carbonates with HCl and dispersion with sodium pyrophosphate ($Na_4P_2O_7$). Data quality was evaluated according to the obscuration rate and PIDS (Polarization Intensity Differential Scattering) value of each measurement. The grain size boundary of the clay fraction was set at <5.5 μm (Vandenberghe and Nugteren, 2001). Volume-specific magnetic susceptibility was measured with low frequency on approximately 10 cm^3 of sample material, using the Bartington Instruments MS2B system. The mineralogical composition was specified for powder samples by X-ray diffraction (Rigaku MiniFlex 600) using a copper Kα tube from 3 to 80° 2θ with steps of 0.02 2θ, with each step measured for 2.4 s. Amounts of mineral components were semiquantitatively derived from diffraction intensity

Table 5.1.: List of OSL samples, with location, summary of the OSL results and final calender ages with 1σ errors.

Location / sample ID	**Depth (m)**	**Coord. East**	**UTM 37 N North**	**Palaeodose (Gy)**	**Dose rate (Gy*ka-1)**	**Age (ka)**	**Systematic**	**Random**	**Validity**
TG-2, T1 / NCL-7114013	0.28	311454	3579922	11.3 ± 0.5	2.13 ± 0.07	5.3 ± 0.3	0.19	0.21	Likely OK
TG-1, T5 / NCL-7114014	0.30	311485	3579022	9.8 ± 0.5	1.87 ± 0.06	5.3 ± 0.3	0.18	0.27	Likely OK

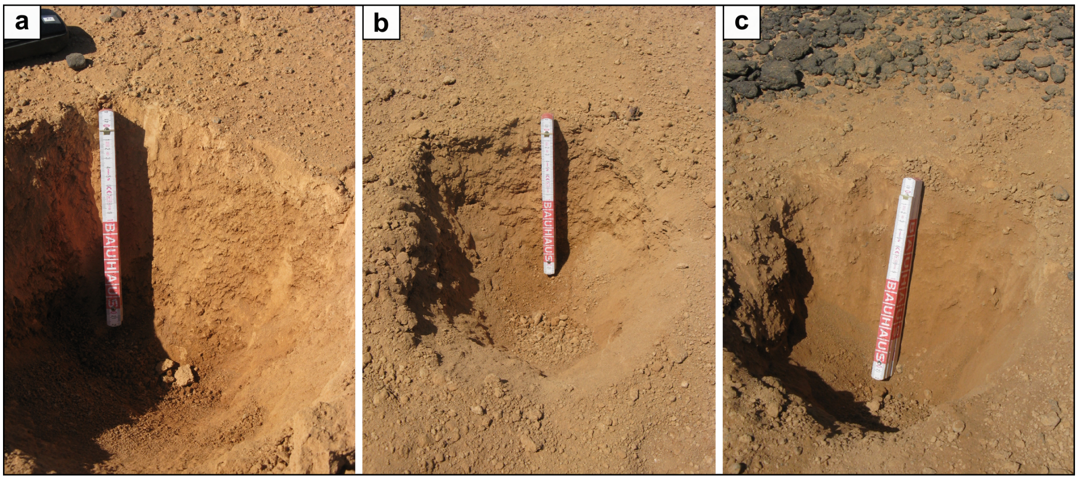

Figure 5.6.: Photographs showing profiles of three test pits during sampling. 6a: Profile T3, terrace system TG-2; 6b: Profile T6, terrace system TG-1; 6c: Profile T9, terrace system TG-3. The length of the scale bar is 22 cm.

using Philips X'Pert HighScore software (v. 1.0b), with the accuracy of measurements and detection limits specific to minerals (Schütt et al., 2010).

5.3.4. Biogenic microfossils: phytolith, diatom and dung spherulite analyses

Opal phytoliths, microscopic bodies composed of pure amorphous silica (Piperno, 1988, 2006), are often used in paleoecological and archaeological studies to investigate paleoenvironmental change (e.g. Fredlund and Tieszen, 1997; Neumann et al., 2009) or past agricultural activity (e.g. Pearsall and Trimble, 1984; Weisskopf et al., 2014). The combined use at archaeological sites of phytoliths and dung spherulites, calcitic crystalline features formed in the intestines of many animals (Brochier et al., 1992; Canti, 1997, 1998, 1999) is a common approach to studying herding activities and husbandry practices (e.g. Delhon et al., 2008; Portillo et al., 2009), while diatoms, a type of algae composed of amorphous, hydrated silica (Werner, 1977; Smol and Stoermer, 2010), can be analyzed to identify ancient water canals (e.g. Grana et al., 2014) or irrigation agriculture (e.g. Trombold and Israde-Alcantara, 2005).

Phytolith extraction followed the procedures outlined by Albert et al. (1999). Approximately 1 g of air-dried sediment was treated with 3 N HCl, 3 N HNO_3, and H_2O_2 to remove carbonates, phosphates, and organic material. The mineral components of the samples were separated according to their densities using 2.4 g*ml^{-1} sodium polytungstate solution [$Na_6(H_2W_{12}O_{40})H_2O$]. Slides were prepared by weighing out about 1 mg of sediment onto a microscope slide, mounting with Entellan New (Merck). The counting was performed using a Leica DM 2000 microscope at 400x magnification; two hundred phytoliths with recognizable morphologies were identified and counted in each sample wherever possible. Phytoliths that were unidentifiable because of dissolution were counted and recorded as weathered morphotypes. The estimated phytolith numbers per gram of sediment are related to the initial sample weight and allow quantitative comparisons between the samples and profiles. Morphological identification of phytoliths was based on standard literature (Twiss et al., 1969; Brown, 1984; Piperno, 1988; Mulholland and Rapp Jr., 1992; Rosen, 1992; Twiss, 1992), as well as on modern plant reference collections from the Mediterranean area (Albert, 2000; Albert and Weiner, 2001; Tsartsidou et al., 2007; Albert et al., 2011; Portillo et al., 2014). The International Code for Phytolith Nomenclature was followed where possible (Madella et al., 2005).

Besides phytoliths, diatoms were identified at 400x magnification to genera level and counted on the same slides. The soil samples for the spherulite analyses were prepared following the method by Canti (1999). Approximately 1 mg of dried sediment was placed on a slide and examined at 400x magnification with a polarization microscope. Similar to the phytolith and diatom analyses, the number of spherulites was counted on each slide and related to the initial sediment weight in order to calculate the amount of spherulites per gram of sediment.

5.4. Results

5.4.1. Terrace systems

The terrace systems studied are composed of several field units, surrounded and divided by almost deflated dry walls, which are easily detecTable on-site and on satellite imagery (Figs. 5.2c, 5.3 and 5.4). Nowadays, the walls are a few decimeters in height and were originally stacked in several layers of basalt stones (Müller-Neuhof, 2014b,a). On slope positions, these dry walls naturally caused siltation and the consequent development of terraces by retaining and collecting water and sediments from episodic flash floods and runoff events. Along the slopes the single terraced fields were arranged cascade-like, allowing the water—often controlled by spillways and water inlets—to flow from the upper terraces downhill to the lower terraces. Between field clusters, the water runoff was controlled and diverted by “stone-lined canals” constructed from one or two neap stone walls, or by “cleared-surface canals” constructed by clearing the ground surface of basalt boulders (Müller-Neuhof, 2014b,a, Fig. 5.2a, b).

5.4.1.1. Terrace system TG-1

The largest terrace system surveyed is TG-1, which is located to the west of Jawa on a slope immediately adjacent to the settlement site (Fig. 5.1b). The slope inclines between 0° and 6°. The complete terrace system TG-1 consists of 96 ancient fields covering a total area of 24 ha (Fig. 5.4a; Table 5.2). The fields are arranged in a cascade formation and grouped into around five different subsystems depending on their location and water source. Field sizes vary highly, ranging from 0.003 to 3.5 ha. Canals diverted water from natural streams to the fields. Additionally, the field’s upslope areas served as micro-catchment areas from which surface runoff was collected and channeled to the fields by surface conduits (Fig. 5.2b). The whole

Table 5.2.: Terrace systems geometric data.

Terrace system	**Nr. of fields**	**Min. field size [ha]**	**Max. field size [ha]**	**Slope range [°]**	**Total cultivation area**	**Catchment area**	**Ratio R**
TG-1	96	0.003	3.5	0–6	24.0 ha	240 ha	10:01
TG-2	25	0.04	2.0	0–8	8.0 ha	8 ha (60 ha)* (270 km^2)**	01:01 (7.5:1)* (3375:1)**
TG-3	8	0.27	1.23	0–3	6.2 ha	40 ha	6.5:1
WTG-1	19	0.02	3.8	0–4	11.7 ha	270 km^2	2308:1

* In case the detected canal, diverting water from the small tributary wadi, reached the fields of TG-2.
** In case the detected canal, diverting water from the Wadi Rajil, reached the fields of TG-2.

catchment area of this system spans about 240 ha and is artificially subdivided by the conduits into a number of smaller catchments. The ratio R of the total catchment area to the total area of cultivation is 10:1.

Surface finds appear to date the system to the Late Chalcolithic/Early Bronze Age (Müller-Neuhof, 2014a).

5.4.1.2. Terrace system TG-2

The terrace system TG-2 is situated on a small plateau northwest of Jawa that is bordered by Wadi Rajil and a small tributary of the wadi (Fig. 5.1b, d). The 25 terraced fields are of various sizes, ranging from 0.04 to 2.0 ha, and cover an overall area of 8 ha (Figs. 5.2c and 5.4b; Table 5.2). Two stone-lined canals and two spillways were identified for collecting and distributing the water within the cascade-like arranged terrace system (Fig. 5.2a). It is most likely that these canal structures are remnants of originally longer conduits that diverted floodwater either from the small tributary wadi in the west or from the upper course of Wadi Rajil in the northwest, to supplement the direct water supply from rainwater runoff. The existence of such a diversion system is indicated by a solidly built stone canal of about 1.5 km, also described by Helms (1981), that diverts floodwater from Wadi Rajil toward Jawa. This canal ends abruptly, however, 400 m before reaching system TG-2, apparently eroded by an incoming wadi. The catchment of the small tributary of Wadi Rajil providing runoff to TG-2 totals 60 ha (R = 7.5:1), while the catchment of Wadi Rajil comprises 270 km^2.

Surface finds appear to date the system to the Late Chalcolithic/Early Bronze Age (Müller-Neuhof, 2014a).

5.4.1.3. Terrace system TG-3

Terrace system TG-3 is located within a small valley about 2 km west of Jawa (Fig. 5.1b), consisting of eight fields of varying sizes (0.27–1.23 ha). The formerly cultivated area covered a total 6.2 ha. Unlike the two previous systems TG-1 and TG-2, the fields of TG-3 are mainly fed by surface runoff from adjacent upslope areas which cover about 40 ha (Fig. 5.4c), corresponding to a ratio R of 6.5:1 (Table 5.2). The remnants of a runoff-collecting canal in the west probably indicate an additional source of runoff water for the fields. Some smaller structures located east of fields B and F might have been conduits with a similar function. A special feature of this system is its proximity to three pools north of the field units, which are part of the Jawa water storage system as described by Helms (1981). According to information from a local Bedouin the team met in 2013, however, these three pools were constructed in the 1920s in order to supply water to livestock.

Surface finds date the terrace system roughly to the Late Chalcolithic/Early Bronze Age.

5.4.1.4. Wadi terrace system WTG-1

North of terrace system TG-3, the wadi terrace system WTG-1 lies on natural terraces of Wadi Rajil where its valley widens providing flat areas of arable land (Fig. 5.1b). WTG-1 consists of 19 fields that cover an area of about 12 ha in total. Located directly in Wadi Rajil, the enclosed fields were irrigated by a densely branched channel network (Fig. 5.4d; Table 5.2), so that the floodwater cascaded gently down from terrace to terrace. Most of these terraces are in good condition, with only a few partly eroded, presumably from extreme flood events.

Surface finds indicate that the system was most likely constructed at the beginning of the twentieth century. There is no archaeological evidence for earlier periods.

5.4.2. OSL dating

Two OSL samples taken from the tread fills of T1 and T5 at around 30 cm beneath the surface give an age of 5.3 ± 0.3 ka for both samples (Table 5.1; Fig. 5.5b, c). The errors shown indicate the 1-sigma (68 %) uncertainty, including all systematic and random uncertainties in both burial dose and dose rate estimation.

5.4.3. Macroscopic, chemical and mineralogical sediment characteristics

All 13 sediment profiles examined are generally similar in macroscopic character, showing slight to moderate compaction, granular structure, loamy to clayey texture, and yellowish/brownish color (Fig. 5.6). The topmost layer (~0–5 cm depth) of each profile is usually less compacted, lighter in color, coarser in texture, and influenced by bioturbation. Apart from this differentiation, the sediment profiles are not visibly layered. Secondary carbonate precipitations were observed in all profiles recorded, either in the form of calcrete with thin superficial gravel coatings, or interstitial in powdery form. Organic layers, plant macro-remains, or rooting have not been observed.

Sediment textures are primary dominated by clay, with content ranging from 29.6 to 70.2 vol.-% (mean = 51.4 vol.-%, $\sigma = 8.6$, n = 45), showing a general trend to increase from top to bottom within a profile (Table 5.3). Silt content is also high, with an average of 39.0 vol.-% ($\sigma = 5.6$, n = 45) for all samples, but does not show any significant depth trends. Sand content is generally low, ranging from 2.8 to 23.5 vol.-% (mean = 10.5 vol.-%, $\sigma = 4.8$, n = 45), and is usually highest in the uppermost layers. The mean grain sizes within a terrace cascade system often decrease slightly in the downstream direction, but there were no significant differences of mean grain size compositions for the terrace-, wadi terrace-, and control profiles examined. The sediment pH levels within a profile are usually similar and show low variability (Table 5.3). All samples analyzed were moderate to strong alkaline in reaction, ranging from 7.2 to 9.1 (mean = 8.0, $\sigma = 0.3$, n = 45). The concentration of easily soluble content in the sediments is generally low (mean EC = 0.37 mS*cm^{-1}, $\sigma = 0.32$, n = 35) and does not show any significant depth trends. Significantly higher EC values than these were observed in control profile C2 (mean = 2.18 mS*cm^{-1}, n = 6, $\alpha<0.05$) and in the lower profile sequences of T3 and T9, reaching an average of 8.0 mS*cm^{-1} (n = 4, $\alpha<0.05$).

Organic carbon content in the sediments (TOC) is generally low, averaging 0.46 mass-% ($\sigma = 0.33$, n = 45), and shows a decrease with depth in all profiles studied (Table 5.3). Inorganic carbon content (TIC) shows a mean value of 2.66 mass-% ($\sigma = 0.72$, n = 45) and regularly increases from bottom to top within a profile. A maximum value of 4.27 mass-% TIC is reached in the uppermost layer of terrace profile T1, while the lowest TIC content was detected within the wadi terrace profile sequences W1 and W2 (mean = 1.2 mass-%, n = 5).

Magnetic susceptibilities are generally low, with highest values observed in the top sections of the sediment profiles and regularly decreasing values with increasing depth (Table 5.3). Magnetic susceptibilities of terrace samples from TG-1 to TG-3 and control samples average 171 SI ($\sigma = 41$, n = 40), while the values of the sediments originating from the wadi profile samples W1 and W2 are noticeably higher, reaching a mean of 411 SI (n = 5, $\alpha<0.05$).

The mineralogical compositions of the sediments show trends similar to the bulk chemical composition in all terrace and control profiles (Table 5.3): the samples consist mainly of quartz and calcite, with feldspar (plagioclase) occurring as a minor component. In the sediments from the wadi terrace profiles W1 and W2, quartz dominates the mineralogical composition, while calcite and feldspar occur only as minor components. In general, the calcite content increases toward the surface within a profile. Traces of clay minerals are present in all samples and consist mainly of kaolinite. Only four samples from the lower profile sequences of T3 and T9 contain traces of the evaporitic mineral sylvite; other indications for evaporite deposits were absent. Note that these samples are characterized by extremely high electrical conductivity values. Pedogenic oxides such as hematite or goethite could not be detected in the sediments.

Table 5.3.: Texture, bulk chemistry and mineral composition of all sediment samples (Profile/ID = profile/ sample ID; depth [cm]; clay [vol.-%]; silt [vol.-%]; sand [vol.-%]; pH = pH level; EC = electrical conductivity [$mS*cm^{-1}$]; TOC = total organic carbon [mass-%]; TIC = total inorganic carbon [mass-%]; MS = magnetic susceptibility [SI]; Q = quartz; F = feldspars; C = calcite; K = kaolinite; s = sylvite; +++ major components; ++ minor components; + traces; max. counts per sample are highlighted in grey).

Location	**Profile/ ID**	**Depth**	**Clay**	**Silt**	**Sand**	**pH**	**EC**	**TOC**	**TIC**	**MS**	**Q**	**F**	**C**	**K**	**S**
	T1 – I	3	29.6	46.8	23.5	7.7	0.12	0.4	4.3	180	+++	++	+++	+	
	T1 – II	11	58.3	32.4	9.2	8.1	0.14	0.3	3.4	139	+++	++	+++	+	
TG-2	T1 – III	22	53.9	31.3	14.8	7.8	0.37	0.3	3.4	139	+++	++	+++	+	
	T1 – IV	37	47.7	42.2	10.1	8.1	0.12	0.2	3.0	125	+++	++	+++	+	
	T1 – V	50	57.1	31.0	11.9	7.8	0.19	0.2	2.9	127	+++	++	+++	+	
	T2 – I	3	46.0	38.5	15.5	7.9	0.21	0.5	2.8	190	+++	++	+++	+	
TG-2	T2 – II	11	55.9	34.8	9.3	8.1	0.23	0.4	2.6	156	+++	++	+++	+	
	T2 – III	22	53.4	36.1	10.5	8.0	0.37	0.5	2.4	153	+++	++	+++	+	
	T3 – I	3	56.2	40.0	6.4	8.0	0.56	0.4	3.2	122	+++	++	+++	+	
TG-2	T3 – II	12	64.0	36.6	2.9	8.1	8.59	0.4	2.5	111	+++	++	+++	+	+
	T3 – III	22	63.9	33.8	4.4	8.1	7.44	0.3	2.4	93	+++	++	+++	+	+
	T4 – I	3	46.3	39.7	16.1	8.1	0.20	1.3	3.2	177	+++	++	+++	+	
TG-1	T4 – II	11	70.2	28.1	3.9	8.3	0.28	0.8	3.4	130	+++	++	+++	+	
	T4 – III	22	61.3	31.6	9.1	7.9	0.32	1.3	2.9	128	+++	++	+++	+	
	T5 – I	11	45.1	40.1	14.8	8.3	1.19	0.3	3.8	230	+++	++	+++	+	
	T5 – II	22	42.4	44.6	13.0	7.9	0.31	0.7	3.1	199	+++	++	+++	+	
TG-1	T5 – III	32	39.2	42.8	18.0	7.8	0.36	0.2	3.1	176	+++	++	+++	+	
	T5 – IV	42	44.3	43.3	12.4	7.2	0.73	0.2	2.6	157	+++	++	+++	+	
	T5 – V	52	45.5	42.7	11.8	8.1	1.05	1.0	2.1	133	+++	++	+++	+	
	T6 – I	3	37.3	44.6	18.1	8.0	0.16	0.7	4.0	148	+++	++	+++	+	
TG-1	T6 – II	11	54.7	30.4	14.9	8.1	0.13	0.4	3.5	194	+++	++	+++	+	
	T6 – III	22	55.2	31.7	13.1	8.1	0.31	0.3	3.0	145	+++	++	+++	+	
	T7 – I	3	44.9	41.2	13.9	8.2	0.12	0.7	2.6	323	+++	++	+++	+	
	T7 – II	11	62.7	29.9	7.4	8.9	0.65	0.3	2.2	241	+++	++	+++	+	

TG-3															
	T7 – III	22	58.0	33.1	8.9	9.1	1.37	0.3	2.0	199	+++	++	+++	+	
	T8 – I	3	52.5	38.2	11.6	8.1	0.27	0.6	3.1	190	+++	++	+++	+	
TG-3	T8 – II	11	60.5	39.9	2.8	8.3	0.30	0.1	2.5	162	+++	++	+++	+	
	T8 – III	22	55.5	43.6	3.8	7.7	0.29	0.3	2.5	169	+++	++	+++	+	
	T9 – I	3	52.8	41.0	8.5	8.1	0.90	0.3	2.7	205	+++	++	+++	+	
TG-3	T9 – II	11	57.2	41.6	4.5	8.0	6.15	0.2	2.7	163	+++	++	+++	+	+
	T9 – III	22	48.3	51.8	3.2	7.8	9.81	0.3	2.4	161	+++	++	+++	+	+
WTG-1	W1 – I	3	50.8	41.8	9.8	7.9	0.18	0.8	1.2	386	+++	++	++	+	
	W1 – II	11	61.9	33.1	6.8	8.0	0.13	0.7	0.9	389	+++	++	++	+	
	W2 – I	3	42.2	47.0	10.8	7.8	0.17	0.7	1.4	470	+++	++	++	+	
WTG-1	W2 – II	11	43.4	41.9	14.6	7.7	0.21	0.5	1.2	417	+++	++	++	+	
	W2 – III	22	53.6	39.6	6.8	8.0	0.47	0.4	1.3	393	+++	++	++	+	
	C1 – I	3	30.0	48.6	21.4	7.9	0.24	0.8	3.3	220	+++	++	+++	+	
CP	C1 – II	11	50.7	38.6	10.7	8.2	0.25	1.4	2.2	180	+++	++	+++	+	
	C1 – III	22	50.4	37.5	12.0	8.1	0.10	0.0	2.9	166	+++	++	+++	+	
	C2 – I	11	44.6	45.6	9.8	7.9	0.32	0.2	2.5	205	+++	++	+++	+	
	C2 – II	22	48.7	45.2	6.0	8.2	1.90	0.1	2.4	163	+++	++	+++	+	
CP	C2 – III	42	51.9	38.3	9.8	8.1	2.15	0.0	2.8	185	+++	++	+++	+	
	C2 – IV	62	51.1	41.5	7.4	8.2	2.43	0.6	2.4	178	+++	++	+++	+	
	C2 – V	82	62.8	32.0	5.2	8.2	3.34	0.2	2.4	179	+++	++	+++	+	
	C2 – VI	102	49.6	38.6	11.7	7.9	2.95	0.1	2.4	190	+++	++	+++	+	

5.4.4. Phytolith concentrations and morphologies

As might be expected with off-site samples, only six out of 45 samples achieved the wanted count of 200 phytoliths per sample. Eleven samples yielded at least 100 counts.

The amount of phytoliths in the samples varies (Table 5.4; Figs. 5.7a–c and 5.8). In general, phytolith concentrations decrease from top to bottom within a sediment profile. Highest concentrations were reached in the topmost samples of profiles T3, T6, T9, W1, and W2, ranging from 243,000 to 467,000 phytoliths per 1 g of sediment (Fig. 5.8). Highest average concentrations occurred in samples from the wadi terrace profiles (W1, W2), followed by the terrace profiles (T1-T9). The lowest levels of phytolith abundances were found in the two control profiles C1 and C2, where almost all samples contained fewer phytoliths than the samples originating from the terraces and wadi terraces. Considering only the mid-level samples ($\sim$11 cm depth), concentrations of all terrace and wadi terrace profiles reach an average of 123,000 phytoliths per 1 g of sediment (σ = 53,000, n = 11), which is about three times higher than the average amounts of both control samples (mean = 8000, σ = 1400, n = 2).

The morphological analyses show that almost all samples with a minimum of 100 counted phytoliths are similar in their morphotype assemblages (Fig. 5.9a). About 19 % (σ = 7, n = 12) of the phytoliths were not morphologically identifiable, while grass phytoliths, occurring at a rate of about 75 % (σ = 6, n = 12) were the most common group identified. According to their morphologies, grasses belong mostly to the C3 Pooid subfamily. Fig. 5.9b shows the grass phytolith morphological distribution of selected samples according to the part of the plant where they formed. Rondel short cells, commonly produced in leaves, stems, and inflorescences, were dominant in all samples, with an average of 59 % (σ = 6, n = 12), and indicate the presence of Pooids. Other common morphotypes are bulliforms and different types of parallelepiped and elongate phytolith forms, typically produced by grasses (Table 5.5). The absence of multicellular phytoliths in the samples did not allow for identifying the type of grasses. With an average value of 5 % (σ = 1.4, n = 12), the amounts of dicotyledonous phytoliths are generally low (Fig. 5.9a). For instance, parallelepipedal rugose phytoliths, one of the most common wood/bark morphotype, accounts for only 0.3 % at average. Other diagnostic dicotyledonous morphotypes such as globulars, polyhedrals or jigsaw-shaped phytoliths were not observed.

5.4.5. Spherulite and diatom concentrations

Fecal spherulites were found in some sediment samples, although not in large numbers (Table 5.4; Figs. 5.7f and 5.10). In general, they occurred only in the near-surface samples. The uppermost sample of the control profile C1 shows the largest amount of dung spherulites, with 150,000 spherulites per gram of sediment. Within deeper profile levels, spherulites were almost absent. Note that spherulite content does not correlate very well with phytolith content (ρ = 0.5).

Diatoms were found in significant quantities within some samples, usually originating from the topmost profile level (Table 5.4; Figs. 5.7d,e and 5.10). The topmost sample of control

Table 5.4.: Main phytolith, diatom and spherulite results obtained from all samples (1 $g*s^{-1}$ = per 1 gram of sediment).

Profile/ sample ID	**Depth [cm]**	**Phytoliths [1 $g*s^{-1}$]**	**Spherulites [1 $g*s^{-1}$]**	**Diatoms [1 $g*s^{-1}$]**
T1 – I	3	150,000	70,000	167,000
T1 – II	11	142,000	0	0
T1 – III	22	103,000	0	3000
T1 – IV	37	58,000	0	0
T1 – V	50	56,000	0	0
T2 – I	3	179,000	67,000	129,000
T2 – II	11	150,000	0	5000
T2 – III	22	72,000	0	1000
T3 – I	3	243,000	75,000	873,000
T3 – II	12	89,000	0	0
T3 – III	22	59,000	0	4000
T4 – I	3	138,000	50,000	137,000
T4 – II	11	90,000	20,000	5000
T4 – III	22	64,000	11,000	1000
T5 – I	11	177,000	14,000	29,000
T5 – II	22	118,000	0	0
T5 – III	32	63,000	0	3000
T5 – IV	42	23,000	0	0
T5 – V	52	14,000	0	0
T6 – I	3	415,000	80,000	272,000
T6 – II	11	138,000	11,000	13,000
T6 – III	22	134,000	0	3000
T7 – I	3	149,000	87,000	76,000
T7 – II	11	76,000	0	1000
T7 – III	22	56,000	0	0
T8 – I	3	167,000	50,000	49,000
T8 – II	11	88,000	0	2000
T8 – III	22	50,000	0	1000
T9 – I	3	467,000	50,000	415,000
T9 – II	11	94,000	10,000	0
T9 – III	22	46,000	0	1000
W1 – I	3	398,000	29,000	151,000
W1 – II	11	263,000	0	35,000
W2 – I	3	259,000	66,000	86,000
W2 – II	11	101,000	0	0
W2 – III	22	58,000	0	1000
C1 – I	3	101,000	150,000	1,381,000
C1 – II	11	37,000	8000	9000
C1 – III	22	21,000	0	1000
C2 – I	11	39,000	17,000	0
C2 – II	22	18,000	9000	0
C2 – III	42	15,000	0	0
C2 – IV	62	7000	0	0
C2 – V	82	9000	0	0
C2 – VI	102	12,000	0	0

Table 5.5.: Most frequent phytolith morphotypes obtained from Jawa samples, correspondence to the ICPN morphotypes (Madella et al., 2005) and plants or plant parts to which they are attributed based on modern reference studies from the Mediterranean area (Albert, 2000; Albert and Weiner, 2001; Portillo et al., 2014; Portillo and Albert, 2011; Tsartsidou et al., 2007).

Phytolith morphotype	**ICPN equivalents**	**Attribution**
Bulliform (fan and pillow shape)	Cuneiform bulliform cell and Parallepipedal bulliform cell	Grass leaves
Long cell echinate	Elongate echinate long cell	Grass inflorescences
Long cell dendritic	Dendritic	Grass inflorescences
Long cell polylobate	Cylindrical polylobate	Grass leaves
Short cell Pooideae	Rondel short cell/ Trapeziform short cell	C3 Grasses
Parallelepiped elongate	Elongate	Monocots
Parallelepiped thin psilate	Tabular/Trapeziform	Grass leaves
Epidermal appendage prickle	Prickle	Grass leaves

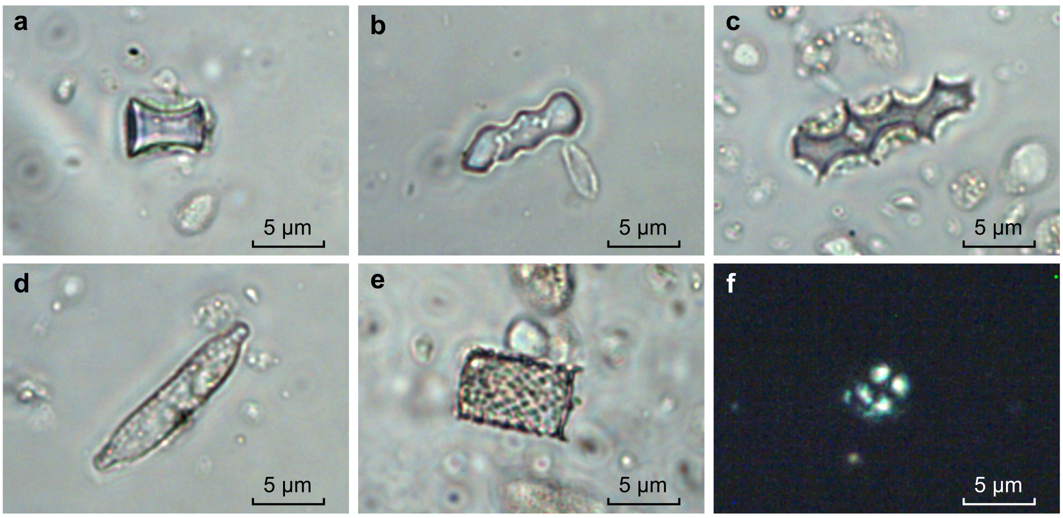

Figure 5.7.: Photomicrographs of phytoliths, diatoms and dung spherulites identified in the Jawa samples. The photographs have been taken at 400x magnification. 7a: short cell rondel; 7b: long cell polylobate; 7c: dendritic long cell; 7d: Hantzschia diatom; 7e: Aulacoseira diatom; 7f: dung spherulite.

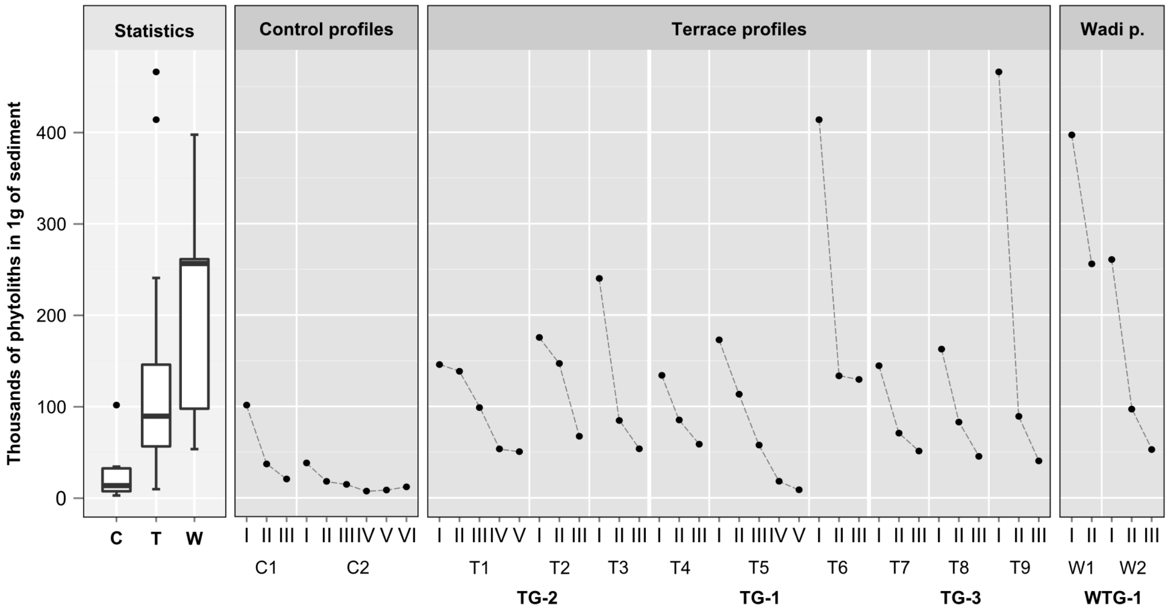

Figure 5.8.: Box-and-whisker diagrams and plot of phytolith concentrations of all studied sediment samples. Box-and-whisker plots (left hand side) of data from the control- (left), terrace- (center) and wadi terrace (right) samples. Outliers are plotted as individual points. Points at the right hand side show the phytolith concentrations of control-, terrace- and wadi terrace samples from each level in the sediment profiles.

profile C1 yielded the largest number of diatoms, with about 1.3 million diatom frustules per gram of sediment. Overall, diatom content correlates well with spherulite content ($\rho = 0.8$) and, similarly to the spherulites, diatoms are almost absent in deeper profile levels. The correlation with phytolith content is very weak ($\rho = 0.35$). The two genera with the highest abundances are Aulacoseira and Hantzschia, with the latter having far higher concentrations, at an average of 75 % ($\sigma = 10$, n = 6; n of d>100). Two undetermined genera were also present, but in considerably reduced amounts (<10 %).

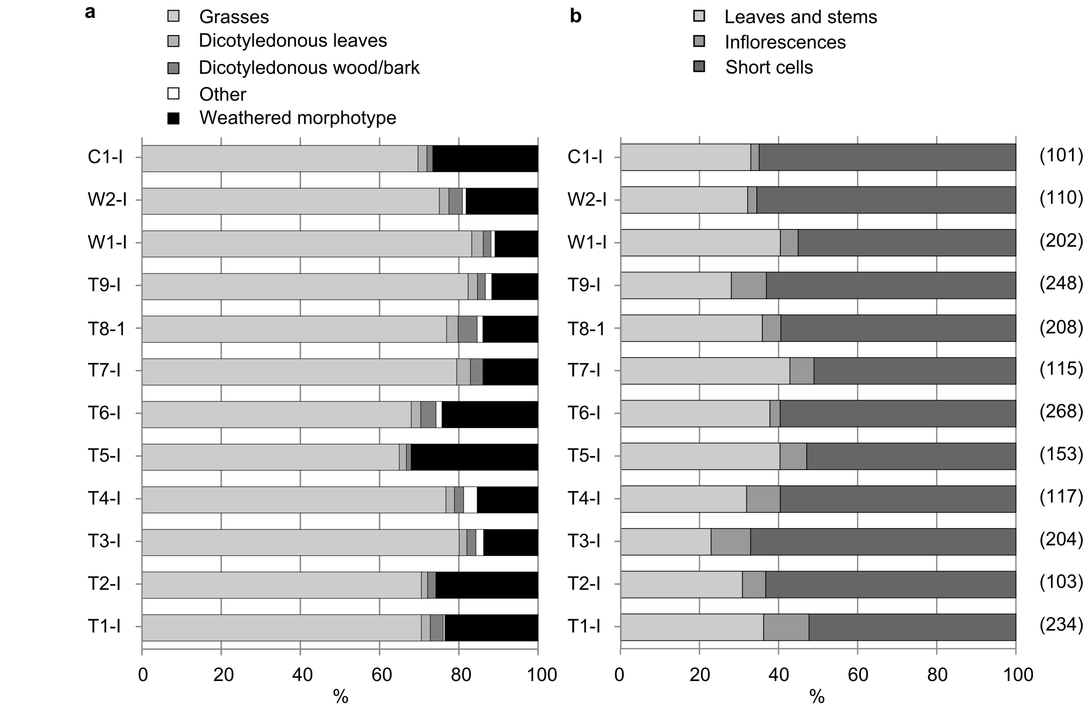

Figure 5.9.: 9a: Relative abundances of phytoliths obtained from selected Jawa samples; 9b: Anatomical origin of grass phytoliths in selected Jawa samples. Number of counted phytoliths per sample is given in brackets.

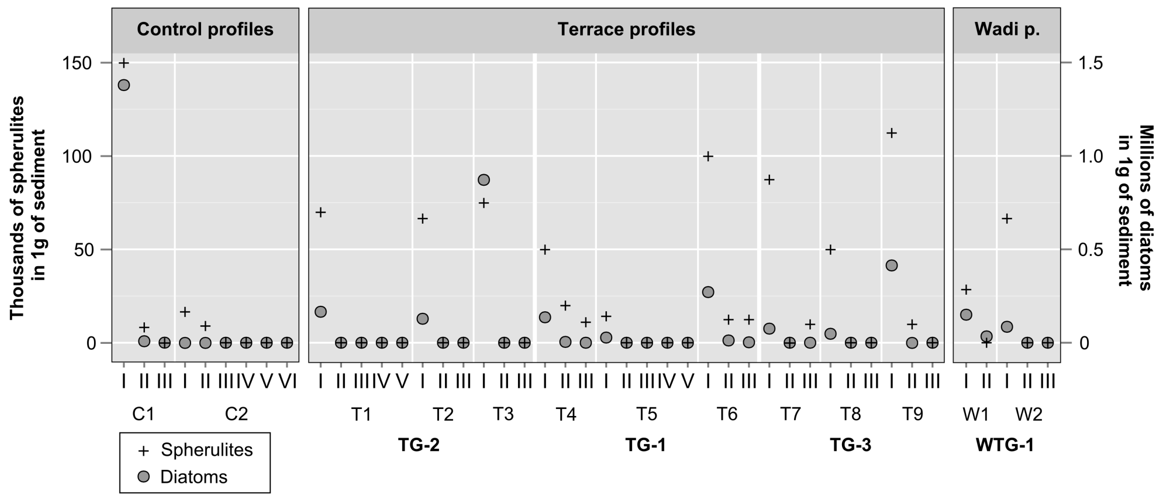

Figure 5.10.: Plot of spherulite and diatom concentrations of all control-, terrace- and wadi terrace samples from each level in the sediment profiles. Points show the spherulite concentrations, while crosses show the diatom concentrations.

5.5. Discussion

5.5.1. The terrace systems and their chronology

All the terrace systems presented here were established to utilize either runoff or floodwater harvesting to provide water for irrigation (Beckers and Schütt, 2013). In the case of terrace systems TG-1, TG-2, and TG-3, located on slopes or within small valleys, additional irrigation water was provided by surface canals collecting surface and wadi runoff from the tributary slopes and wadis. The poor preservation of certain canals precludes a conclusive answer as to whether they supplied the associated terrace systems or not. The canal assumed to have collected water from Wadi Rajil could have been used to divert water to the fields of TG-2 with little effort. Groundwater was irrelevant for all systems; it lies too deep and was unobtainable until recently (Dottridge and Abu Jaber, 1999). The terrace constructions fostered water infiltration and storage in the terrace sediments (Beckers and Schütt, 2013). Besides irrigation, the terrace systems also provided erosion control: the canals collected surface runoff from the upslope areas, and the overall runoff was then subdivided into multiple chutes that presumably prevented the occurrence of large flash floods (Evenari et al., 1961) that would have destroyed built structures. Surface runoff was generally exploited only from small watersheds of several hectares, a technique that required a good understanding of the local hydrology, geomorphology, and pedology (Evenari et al., 1961).

Regarding the chronology, most of the measures and techniques presented here have been reported for subsequent periods for many archaeological sites in arid areas in the Middle East, especially for the southern Levant and the Negev (Evenari et al., 1961; Evenari, 1982; Avni et al., 2006; Hunt et al., 2007; Beckers and Schütt, 2013) such terrace systems have so far not been documented for the period of the Early Bronze Age. Following the assumption of Critchley et al. (1994) that terraces commonly start to accumulate sediments shortly after the construction of their risers, the OSL ages obtained for terrace systems TG-1 and TG-2 indicate that the terrace fills studied accumulated at around 5.3 ± 0.3 ka. The effective age of the riser construction must therefore be younger. Since the tread fill stratigraphies studied are generally thin, and fast rates of accumulation can be expected for active terraces, the age of terrace construction can be assumed as Early Bronze Age I. These conclusions are in general agreement with the archaeological evidence for both terrace systems investigated, dating the systems to the main occupation phase of Jawa in the second half of the fourth millennium BCE (Müller-Neuhof, 2014a). Moreover, the consistent OSL ages of both tread fills in combination with similar construction designs of the terraces indicate the simultaneous construction and agricultural usage of both terraces and terrace systems (TG-1, TG-2), making it difficult to differentiate between different chronological stages of development. The same seems valid for terrace system TG-3, according to the archaeological evidence, although absolute datings are not available yet. Indications of the reconstruction and reuse of these terrace systems in later periods are missing. There is, however, some evidence of subsequent occupation and use of the Jawa region by Bedouins for camping or pastoralism in the Roman-Byzantine and Islamic Period (Müller-Neuhof, 2014a).

In contrast to the terrace systems TG-1, TG-2, and TG-3, the wadi terrace system WTG-1 was based on floodwater irrigation, exploiting runoff from a large catchment area of several thousands of hectares. According to archaeological survey results, it was constructed at the beginning of the twentieth century and did not exist during the Early Bronze Age settlement phase of Jawa. This matches the archaeological survey results for another two wadi terrace systems of Wadi Rajil that are located downstream and also date to the beginning of the twentieth century.

5.5.2. Sedimentology

Stratigraphy. The lack of stratification in terrace sediments is a common feature of tread fills, resulting from the mixing of sediments during tillage, which destroys any form of sedimentary structures and stratification (Frederick and Krahtopoulou, 2000). In the absence of micromorphological analysis, however, the existence of microlayers, which are indicative for multiple runoff and deposition events (Stoops et al., 2010), cannot be excluded. Buried soils which are common in terraces with multiple fill- and terrace construction events (Sandor, 1992) have not been observed indicating only one construction- and utilization phase of these terraces. The undisturbed reference sediments from profiles C1 and C2 are not stratified either, illustrating the poor soil development within the region. The similarities of the textures and bulk chemical characteristics of the terrace sediments from the profiles T1–T9, compared to those of the reference profiles C1 and C2, corresponding to natural slope and valley deposits (see Section 5.4.3), affirm the assumption that the terrace sediments were deposited by hillwash or as alluvial fills and originated from the surrounding hills (Frederick and Krahtopoulou, 2000). Whether the terraces were additionally filled manually cannot be proven (Frederick and Krahtopoulou, 2000). The rates of sediment deposition after the abandonment of the studied terrace systems seem to be generally low or even absent, as documented by the presence of terrace walls, canals, and numerous archaeological finds directly on the ground surface. The development of deep stratigraphies was probably prevented by low rates of fluvial erosion and intensive deflation processes (Whitehead et al., 2008).

Grain size composition. The detected grain size compositions of the terrace infills correspond to those of regional soils (Khresat and Qudah, 2006). High clay and silt content is generally related to physical weathering processes and aeolian deposition. The increase of clay with depth is attributed to illuviation processes, while accumulations of coarse-grained particles at the surface indicate the deflation of fine-grained material (Goudie, 2008). The lack of clear variation in grain size distribution within the profiles indicates stable deposition and erosion conditions (Beckers and Schütt, 2013). The general downslope decrease in grain size within a terrace cascade is attributed to the transport of fines in suspension along the drainage system, while coarser fractions were already deposited in the upper parts of the cascade. Similar observations were made in current functioning tank cascade systems in Sri Lanka (Daleus et al., 1988).

Mineral composition. The mineral composition of the sediments is a mixture of different components derived by basalt weathering, aeolian deposition, and secondary precipitation. Whereas feldspars are derived locally by the weathering of basaltic rocks (Howari et al., 2010), the quartz is very likely derived by aeolian deposition (Allison et al., 2000; Howari et al., 2010). The origin of calcite in the sediments can be explained by wind deposition as well as by authigenic precipitation (Allison et al., 2000; Khresat and Qudah, 2006; Howari et al., 2010). Secondary calcite accumulations in soils and sediments, in the form of powder, concretions, or calcrete, are common features in arid and semi-arid regions (Sehgal and Stoops, 1972; Young, 1976), often precipitated from ascendant soil water through capillary action (Ettensohn et al., 1988), as observed in all studied profiles and reflected in the TIC content increasing from bottom to top. Besides secondary formation, increased inorganic carbon content at the surface can be also related to calcite additions by aeolian activity (Khresat et al., 1998). The slightly alkaline pH values of all samples studied demonstrate the presence of calcium carbonate (Khresat and Qudah, 2006). The high quartz content in the terrace sediments originating from the floodwater harvesting system in the valley infill of Wadi Rajil (W1, W2) can presumably be attributed to an increased detrital input of quartz from the 270 km^2 large drainage basin, where the basalt flows overlie Cenozoic sandstone conglomerates (Bender, 1968; Al-Homoud et al., 1995).

Salinization. The degree of soil salinization is generally low within the studied sediments, indicating the still-functioning drainage and thus the high functionality of the terrace systems surveyed (Luedeling et al., 2005). Only in profiles T3 and T9, where at least the latter is located on the downslope end of the associated terrace system, was the evaporitic mineral sylvite found.

Organic carbon content. Low organic carbon content is typical of soils in arid regions (Hill and Schütt, 2000; Dixon, 2009), reflecting sparse vegetation cover, rapid rates of organic matter decomposition, and grazing activities (Khresat and Qudah, 2006). The observed low TOC content and its continuous decrease in proportion to depth suggest a rapid and progressively diagenetic decomposition of organic material (Schütt et al., 2010). Tread fill sediments of ancient agricultural terraces rich in organic matter, as described by Frederick and Krahtopoulou (2000) and Schütt (2006), were not detected. But this finding fits with the results of Beckers and Schütt (2013) and does not automatically exclude the previous agricultural use of these terraces. In addition to the possibility of decaying processes of soil organic matter in buried sediments (Schütt, 1998), the crop residues might have been grazed by livestock, which would have prevented their accumulation in the sediments (Beckers and Schütt, 2013). This is supported by a study from Sandor et al. (1990) showing that the TOC content obtained from terrace fills of ancient agricultural terraces in New Mexico is lower than that in sediments from uncultivated neighboring areas.

Magnetic susceptibility. Magnetic susceptibilities are a bulk signal and are - among others - controlled by sediment textures and organic matter contents (Hart, 1982; Rubio et al., 2000). The generally observable increasing magnetic susceptibility coincides with concentrations of organic and inorganic carbon increasing from bottom to top, as well as with near-surface coarser grain sizes. The significantly higher magnetic susceptibility values of the wadi terrace sediments might be explained by their origin from cut sandstone conglomerates underlying the basalts in the drainage basin of Wadi Rajil.

5.5.3. Biogenic microfossils

The documented phytolith concentrations are generally low, but they do correspond to those in soils and sediments presented by other studies, following a similar quantitative approach (e.g. Albert and Henry, 2004; Cabanes et al., 2012). In general, the phytolith concentrations of regional soils and sediments sampled outside of an ethnographic context or archaeological site are often much lower than in samples taken from inside the same context or site (Albert et al., 1999; Shahack-Gross et al., 2003; Albert and Henry, 2004; Tsartsidou et al., 2008; Cabanes et al., 2012; Portillo et al., 2014).

When interpreting phytolith records in soils and sediments, it is necessary to discuss their sources of origin. Although large proportions of phytoliths are generally deposited by plant release, representing *in situ* deposition, phytoliths may also be transported by water runoff (Piperno, 2006) and deposited by wind or animal droppings, especially in arid environments with open landscapes (Fredlund and Tieszen, 1994). The proximity of all profiles would anticipate the regional atmospheric input of phytoliths to be at a similar level across the sediments studied, even though the exact contribution remains undetermined. The input of phytoliths by dung seems to be generally low within the samples studied, indicated by the weak correlation of spherulite and phytolith numbers. Because spherulites are composed of the meta-stable carbonate *monohydrocalcite*, however, and therefore highly soluble (Shahack-Gross et al., 2003), they do not preserve in the sediments of open-air sites over long periods of time (Brochier et al., 1992). Thus, the presence and frequency of spherulites within the topmost sediments may indicate the deposition of dung by wild or domesticated animals (Canti, 1999, 1998, 1997) in the most recent past; the spherulite numbers do not tell us whether phytolith concentrations of ancient terrace fills are related to *in situ* production by plant growth or the deposition of dung by grazing activities or fertilization.

The detected diatom genus *Aulacoseira* is a common, freshwater, planktonic genus (Siver and Kling, 1997). The genus of *Hantzschia* occurs in marine and freshwater habitats (Stidolph, 1993; Aboal et al., 2003) but is characteristic of aerial and terrestrial environments (Johansen, 2010). The relatively high correlation between diatoms and spherulites in the samples studied therefore suggests a primary depositional input by animal dung, containing freshwater diatoms (Shahack-Gross, 2011). The almost complete absence of diatoms in deeper sediment levels, then, contrary to the phytoliths, might be either related to a reduced input by animal dung in the past or to higher dissolution rates for diatom frustules than for phytoliths in the buried sediments. The latter case is rather unlikely, given the experimental dissolution study of biogenic silica by Loucaides et al. (2008) that observes higher dissolution rates for fresh phytoliths than for fresh diatoms. However,—among other uncertainties—there are differences in phytolith stability between various morphologies and assemblages (Cabanes et al., 2011). Moreover, some types of diatoms are very fragile making them particularly vulnerable to the applied phytolith processing protocol which includes several centrifuging cycles (Crosta and Koç, 2007). To ensure an optimal diatom recovery a separate extraction by using their standard protocol would be required. Since their might also be small diatoms available that may not be visible at 400x magnification, an examination under a strong magnification (usually 1000x) is recommended (Crosta and Koç, 2007).

The input of fresh phytoliths by modern vegetation can be neglected, as vegetation cover is sparse under present-day climatic conditions, at least for all terrace and control profile locations. Plant (grass) growth occurs periodically in the wadi terrace system WTG-1, since the terraces are flooded by Wadi Rajil during the winter even though they are not actively in use today. This fact, coupled with the presumably young age of the wadi terrace system WTG-1, would indicate that the phytolith records of W1 and W2 contain fresh phytoliths and reflect modern rather than old phytolith assemblages, or a mixture of both. This may also explain their higher phytolith concentrations.

Aside from the topmost samples, which seem to be influenced by modern dung, we can assume that the majority of phytoliths within the studied terrace fills and in the sediments of the reference profiles are of local origin, released by plant decomposition. Phytolith preservation is generally poor, as evidenced by the high percentages of weathered morphotypes and the absence of multicellular phytoliths, likely in association with a varied range of depositional and post-depositional processes (Alexandre et al., 1997; Cabanes et al., 2009; Fraysse et al., 2009; Jenkins, 2009; Shillito et al., 2011; Madella and Lancelotti, 2012). For instance, phytoliths dissolve under alkaline conditions (Piperno, 1988), although they can preserve in large numbers within alkaline sediments (Lewis, 1981) over long periods of time (Strömberg, 2004). Corresponding to the similarity in physical and chemical properties for the studied sediments, however, similar levels of phytolith dissolution can be expected (Piperno, 2006). The observed differences in phytolith concentrations are therefore much more likely related to differential phytolith deposition than to differential dissolution. Thus, the observation of increased phytolith contents of terrace fills compared to the natural reference sediments suggest increased plant growth within the terraces as a consequence of their increased capacity for water storage. The decrease in phytolith concentration in proportion to depth is probably associated with the common sequence of tread fills with the cultivation layer located on top (see Fig. 5a). Phytoliths are either formed in roots released within the rooting zone, or in the above-ground parts of plants and are then returned to the soil in form of litter (Farmer et al., 2005). The decrease phytolith concentration with increasing depth may therefore simply reflect the distribution of organic matter in the sediment profile (Alexandre et al., 1997).

A reason for the differences in phytolith concentrations within terraces and terrace systems, besides differential taphonomy and deposition, could be differential phytolith production of plants (Fredlund and Tieszen, 1994). It is most likely that other food plants than cereals were cultivated within the terraces: pulses, such as *Cicer arietinum* (chickpea) and *Lens culinaris* (lentil), have been documented in plant macro-remains at Jawa (Willcox, 1981), as at many other Neolithic and Bronze Age sites in the Middle East (Zohary and Hopf, 1973; Zohary et al., 2012). Although phytoliths have been documented for numerous specimens from the *Fabaceae* (*Leguminosae*) family (Cummings, 1992), phytolith production varies substantially among different subfamilies (Piperno, 2006). Moreover, Hart (2014) investigated different plant parts of *Cicer arietinum* and *Lens culinaris* and observed no phytolith production at all, a fact which may be explained by environmental variability (Pearsall, 2000; Piperno, 2006) or plant part selection (Hart, 2014). The presence of woody and herbaceous flora within the studied terraces may be indicated by the observed amounts of dicotyledonous phytoliths. However, due to their limited taxonomic value and low number, further conclusions regarding their type or quantity cannot be drawn. Reliable statements about the application of farming strategies such as horticulture or polyculture at Jawa are therefore not possible.

5.5.4. Future research

The results from the integrated multi-proxy approach applied here provide possible starting points for further research. In order to better understand the early farming strategies at Jawa and its spatial and temporal variation, future research requires more excavation of these terrace systems and an intensified dating strategy. In particular, a combination of phytolith analyses and micromorphology could probably enhance identification of plant remains in these deposits and interpretation of their formation and post-depositional alteration (e.g. Shahack-Gross et al., 2005; Albert et al., 2008; Shahack-Gross and Finkelstein, 2008; Matthews, 2010; Matthews et al., 2014; Vrydaghs et al., 2016). Further research might also explore the potential contribution of other microfossils such as calcium oxalates that are common in woody and herbaceous dicotyledons (Canti and Huisman, 2015, and references therein). In future studies it will also be important to extend the grid beyond the terraces to provide more samples of regional sediments, especially from animal enclosures and modern arable land.

5.6. Conclusions

This study presents an interdisciplinary and multi-proxy approach to investigating ancient agricultural terrace systems in a systematic and integrated fashion, which has facilitated a better understanding of the agricultural activities carried out in the vicinity of the Early Bronze Age settlement of Jawa (Jordan). During the Early Bronze Age, irrigated terrace agriculture was practiced in this area on slopes, small plateaus, and valleys: floodwater from nearby wadis or runoff from adjacent slopes was collected and diverted via surface canals. The terraced fields were arranged in cascades, allowing for effective water exploitation through a system of risers, canals, and spillways.

The two OSL ages of terrace fills from the terrace systems TG-1 and TG-2 represent the first absolute datings available for this agricultural area in the vicinity of Jawa. They indicate that the construction of these terrace systems started as early as 5300 ± 300 a, which confirms the assumptions made by Müller-Neuhof (2014a) based on the archaeological record. Moreover, these data fit well into the chronology of Müller-Neuhof et al. (2015) which dates the beginning of the occupation phase at Jawa to around 3500 cal BCE. Regarding design, scale and sophistication, the Jawa terrace systems are therefore the oldest examples of its kind in the Middle East known to date, demonstrating that agriculture at Jawa was an important part of the settlement's economy. The overall agreement of the OSL data and the archaeological record suggests the general applicability of OSL dating in the Jawa region.

The terrace profiles studied have similar stratigraphic sequences of mixed unstratified fine sediments that are composed of small-scale relocated sediments with local origin and reflect low-energy fluvial deposition regimes. The accumulation of these fines was associated with the construction of agricultural terraces, forcing infiltration and storage of the water in the terrace fills. Calcite precipitation and deflation are the dominant post-sedimentary processes within these terrace sediments. Phytolith assemblages are dominated by Pooids which are common in well-watered woodlands, and contain some of the major Middle Eastern crops. Increased phytolith concentrations in terrace fills, as compared to regional sediments, suggest increased plant growth and thus water availability within the terraces. Whether the terrace systems were used for growing food crops only or whether they were additionally used for grazing cannot be ascertained.

Concerning methodology, the dung spherulites in ancient sediments at open-air sites in desert environments are difficult to extract information from because of their high solubility and the overlapping signals from modern dung input by wild animals and livestock. The same seems to be valid for diatoms, due to their potential deposition by animal dung. It is well established within phytolith studies that in semi-arid and arid environments, or in many other contexts where organic remains may be poorly preserved, quantitative phytolith analyses may provide a unique opportunity to investigate the spatial distributions of plant microfossil concentrations and their relation to human activity or paleoenvironmental conditions. While this has previously been shown within settlements and habitation areas in the southern Levant (e.g. Albert and Henry, 2004; Jenkins and Rosen, 2007; Portillo et al., 2009, 2014), this study has demonstrated that quantitative phytolith analyses can be very valuable in investigating spatial distributions in off-site areas. Future research of these agricultural terrace systems requires more excavations, sediment sampling and absolute datings. The integration of phytolith analyses and micromorphological techniques, as well as the examination of other microfossils, such as calcitic oxalate crystals, may result in a more comprehensive understanding of early farming in that region.

5.7. Acknowledgments

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CHAPTER 6

Ancient runoff agriculture at Early Bronze Age Jawa (Jordan): Water availability, efficiency and food supply capacity

Abstract

Located in the basalt desert of northeastern Jordan, Early Bronze Age (EBA) Jawa is regarded as one of the major settlements in the Middle East during the 4th millennium BCE. In addition to a sophisticated water storage system, the existence of three complex agricultural terrace systems based on runoff and floodwater irrigation in the close vicinity was recently revealed. This paper investigates the impact of these water management strategies on harvest yields and the scale of the 'on-site' crop production at Jawa by applying a crop simulation model (CropSyst). Simulations for the cultivation of winter barley, winter wheat and lentils were performed for the period from 1983 to 2014. To simulate the different runoff irrigation schemes, a curve-number-based rainfall-runoff model was applied. To estimate the number of people that could have been supplied by the local food production, simple calculations based on metabolic calorie requirements and agricultural and pastoral production rates were conducted. This study shows that the runoff farming systems of EBA Jawa are relatively effective under current rainfall conditions. Even during dryer seasons, the simulated crop yields are much higher under runoff irrigation/floodwater irrigation than under non-irrigated conditions. On average the crop yields increase by 1.5 to 6 times, depending on crop type and runoff irrigation level. Moreover, a marked decrease in crop failures could be observed. The total crop and animal production could have satisfied the nutritional requirements of about 500 to 1000 persons per year. Considering the estimated maximum population for EBA Jawa, ranging from 3400 to 5000 people (Helms, 1981), local production did not meet the basic needs of all inhabitants. This indicates that

trade might have been an important branch of Jawa's economy in order to supplement food resources. Moreover, former population estimates for ancient Jawa might be overstated.

Keywords

Ancient water management; Ancient desert agriculture; Runoff/floodwater irrigation; Rainfall variability; Rainfall-runoff analysis; Crop modeling

6.1. Introduction

The fortified ancient settlement of Jawa measures approximately ten hectares and is regarded as one of the major towns in the Middle East during the 4th millennium BCE (Helms, 1981). The well-preserved site was partly excavated by S. Helms between 1972 and 1976 (Betts et al., 1991; Helms, 1981). Based on ceramic evidence, two main occupation periods were defined, dating to (a) the EBA I (c. 3500–3000 BCE) and (b) the transition of the EBA IV to the Middle Bronze Age I (around 2000 BCE; Helms, 1989, 1981). First radiocarbon dates from Jawa support this chronology, indicating that the earliest occupation phase at Jawa started between 3500 and 3400 cal BCE (Levantine EBA IB; Müller-Neuhof et al., 2015). However, it remains unknown, exactly when this phase ended and whether or not the transition from Levantine EBA IB to EBA II at around 3000 BCE was reached (ibid.). Based on simple calculations taking the inhabited area of the town in relation to the estimated population density, ancient Jawa had its largest extent during this earlier phase and may have been inhabited by up to 3400 to 5000 people, while for the later phase only a small reoccupation is documented (Helms, 1989, 1981).

The inhabitants of the EBA settlement relied on agropastoralism for subsistence with some hunting (Köhler, 1981). Due to the arid environmental conditions, the people had to apply various water management strategies to secure their food and water supply. This is apparent from the existence of a highly elaborated water distribution and storage system, consisting of a series of pools, dams and canals utilizing surface and floodwater runoff—a hydraulic system which appears to be one of the earliest of its kind (Helms, 1981; Roberts, 1977; Viollet, 2007; Whitehead et al., 2008). Furthermore, the well-preserved remains of three abandoned agricultural terrace systems, utilizing floodwater from nearby wadis or runoff from adjacent slopes, mainly by collecting and diverting water via surface canals, document a sophisticated early water management system (Meister et al., 2017; Müller-Neuhof, 2014a,b, 2012). Following the archaeological record and OSL datings, these terraced systems also date to the Levantine EBA I, putting them among the oldest evidence of runoff and floodwater irrigation in the Middle East (Meister et al., 2017). The actual utilization of these terraces is indicated by increased phytolith concentrations of its sediment fills, as compared to non-terrace deposits nearby (ibid.). Overall, Jawa's society seems to have been highly organized and the scale of Jawa's water harvesting and supply system and its technology were unique during this time (Helms, 1981).

Following the assumptions of Helms (1981), Jawa's economy was essentially a self-supporting system that was able to meet basic needs. According to Müller-Neuhof (2014a) the agricultural systems at Jawa were even designed to create a surplus crop production that was probably traded in a regional exchange network. The production volume and supply capacity of these systems, however, have yet to be determined.

In order to assess the scale of 'on-site' crop production at Jawa this study applies the crop simulation model CropSyst (Stöckle and Nelson, 1994; Stöckle et al., 2003). It is intended to determine the impact of the applied water management techniques on harvest yields. To accomplish this, we use different runoff scenarios depending on rainfall intensity and the specific catchment area of each terrace system. To estimate the number of people that could have been supplied by the local food production we apply simple calculations based on metabolic calorie requirements and agricultural and pastoral production rates.

6.2. Study site

6.2.1. Geographical setting

The ancient city of Jawa (32.336 N, 37.002 E, 1002 m asl) is located in the basalt desert steppe of northeastern Jordan on the left bank of Wadi Rajil, about 7 km south of the present-day Syrian border (Fig. 6.1a). The region is part of the north Arabian volcanic province of Harrat Ash Shaam and composed of Quaternary and Neogene basalt (Allison et al., 2000; Bender, 1968; Taqieddin et al., 1995). The topography is flat to gently undulating and penetrated by depressions or pans filled with fine-grained sediments, locally called Qa'a (Al-Homoud et al., 1996). Hillslopes are slightly inclined and surfaces are usually extensively covered by basalt stones due to weathering of the volcanic rocks (Allison et al., 2000).

Natural springs are unknown and groundwater aquifers run deep (Helms, 1981). Wadi Rajil as one of the major ephemeral streams of the region comprises an upstream catchment area of about 270 km^2 at Jawa (Whitehead et al., 2008). With its headwaters in the sub-humid Hauran mountains of Syria, the wadi usually carries more water than the small tributaries from Jawa's surroundings and the variability of annual discharge is smaller (Helms, 1981). Since the Syrian government built a dam across the river in 1968, the wadi's natural downstream runoff behavior is disturbed (Lancaster and Lancaster, 1999). The entire region is only sparsely covered by vegetation which is dominated by grasses, herbs and shrubs (Al-Eisawì, 1996). Soils are generally poorly developed raw desert soils (Bender, 1968).

6.2.2. Present and past climate

At present, Jawa is located in the transitory zone between the Mediterranean climate in the west and the fully arid zone in northeastern Jordan (Al-Homoud et al., 1996). According to the Köppen-Geiger climate classification, the area corresponds to a hot desert climate (BWh)

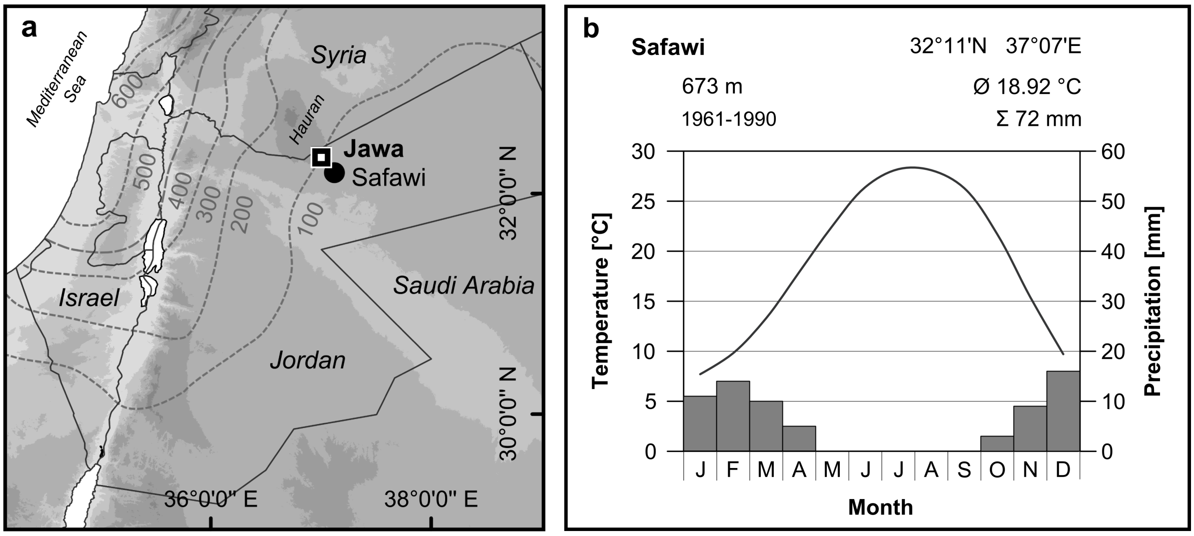

Figure 6.1.: 1a: Location of Jawa and the modern town Safawi in Jordan and isohyets in mm*a^{-1} (Database: SRTM 250; FAO 2001). 1b: Climate diagram of Safawi (modified after Meister et al. 2017; data source: FAO 2001).

(Kottek et al., 2006) characterized by hot, dry summers and cool, rainy winters (Allison et al., 2000). At the nearby Safawi climate station, mean annual rainfall totals about 70 mm*a^{-1} and the annual temperature averages 19 °C (Fig. 6.1b). Rainfall occurs mainly between November and March. The occurrence of strong winds is typical (Al-Homoud et al., 1996) and potential evaporation rates are high (Allison et al., 2000).

According to paleoclimate records from the Dead Sea area (e.g. Bar-Matthews et al., 1998; Frumkin et al., 1999a; Migowski et al., 2006; Neumann et al., 2007) these arid climatic conditions have prevailed approximately since the Mid-Holocene (Finné et al., 2011; Rambeau, 2010; Roberts et al., 2011; Robinson et al., 2006), whereby the transition to more arid conditions across many of the present-day arid and semi-arid areas of the northern hemisphere took place in the period from ∼6.4 to 5.0 ka BP (Clarke et al., 2016). With respect to the EBA occupation phase of Jawa between 3500 and 3000 BCE, annual rainfall was temporarily ∼100 mm higher than today (Issar and Zohar, 2004), estimated from isotopic data (Bar-Matthews et al., 1997, 1998). In contrast, a comparative study by Clarke et al. (2016) based on numerous terrestrial and marine climate proxies identified one distinct episode of heightened aridity in the southern Levant in the late 4th millennium BCE at 3300–3100 BCE. However, since there is a lack of high-resolution proxy records in the Jawa region detailed paleoenvironmental reconstructions for the Holocene are missing (Finné et al., 2011; Rambeau, 2010).

6.2.3. Present and past regional land use and Jawa's subsistence strategy

Modern land use in the surroundings of Jawa is dominated by mobile pastoralism based on mixed camel and sheep/goat herds (Al-Tabini et al., 2012; Lancaster and Lancaster, 1991; Müller-Neuhof, 2014a). Arable agriculture in the region is opportunistic (Lancaster and Lancaster, 1999) and rainfed agriculture is only practiced in some regions, including the northern areas towards the Hauran mountains (Helms, 1981) and e.g. the Qa'a ash Shubayka and Qa'a al Buqayawiyya, where the local hygric conditions of the endorheic depressions support the growth of crops (Tansey, 1999). At present the traditional Bedouin winter crop is barley, while wheat in Jordan is only cultivated in areas that receive > 350 mm*a^{-1} precipitation (Al-Bakri et al., 2011). Economically, crops are grown for household consumption and for animal feed (Lancaster and Lancaster, 1999).

The inhabitants of Early Bronze Age Jawa relied on agropastoralism for subsistence with some hunting (Köhler, 1981). According to the composition of animal remains at the excavation site (Köhler, 1981) and rough estimates of stock sizes, Jawa's inhabitants kept about 10,000 domestic sheep (*Ovis aries* L.) and goats (*Capra hircus* L.) and a herd of domestic cattle (*Bos taurus* L.) with about 800 animals for meat and milk production (Helms, 1981; Köhler, 1981). In addition to the existence of three agricultural terrace systems (Section 6.2.4) evidence for farming is also shown in a large number of grinding stones and sickle blades found at the excavation site (Helms, 1981). Macrobotanical analyses revealed the presence of several crop taxa such as six-row hulled barley (*Hordeum vulgare* L. emend. LAM), einkorn (*Triticum monococcum* L.), bread wheat (*Triticum aestivum* L. sensu lato), emmer (*Triticum dicoccum* Schrank), chickpea (*Cicer arietinum* L.), pea (*Pisum sativum* L.) and lentil (*Lens culinare* Medicus) (Willcox, 1981).

6.2.4. The agricultural terrace systems at Jawa

Located on slopes, small plateaus, or valleys in the direct vicinity of Jawa, each of the three terrace systems studied is assembled of several field units surrounded and partitioned by small stone walls. These walls retained and collected water and sediments from runoff events and facilitated the development of terraces (Meister et al., 2017). The cascade-like arrangement of fields promoted the flow of water and its distribution among the downstream areas which was frequently controlled by spillways and water inlets. Water collection and diversion among the fields was often controlled by surface canals constructed of stone walls or by trench-like structures resulting from clearing the ground of basalt boulders (see Meister et al. 2017 for a more detailed description). In total, the three terrace systems cover an area of about 38 ha (Figs. 6.2, 6.3). Terrace system TG-1, located on a plateau west of Jawa, comprises 24 ha and is supplied with water by a catchment area of c. 240 ha which is artificially subdivided by conduits into several smaller catchments. Terrace system TG-2 is located on a small plateau and covers an area of 8 ha. Its supplying catchment is difficult to ascertain since its main supply canal is only partially preserved. It seems to have either diverted floodwater from a small tributary wadi or captured water from a canal deflecting water from Wadi Rajil (Figs. 6.2, 6.3). Terrace system TG-3, located in a small valley, covers an area of 6.2 ha. Its fields were mainly fed by surface runoff from adjacent upslope areas covering about 40 ha.

A crucial factor for the water availability of such runoff systems is the relation between the catchment area, where the runoff is generated, and the area of cultivation, where the runoff is used for irrigation purposes; a relation which is described by the ratio R (Evenari et al., 1961). In the case of terrace system TG-1, the catchment area is tenfold bigger than the cultivation area, resulting in a ratio R of 10:1. With respect to system TG-2, the ratio directly depends on which wadi was tapped: for the tributary wadi the ratio is 7.5:1; in the case of Wadi Rajil we chose a value of 20:1 since only a limited amount of water could have been deflected from the main wadi into the canal. Moreover, this water was additionally used to fill five water reservoirs of Jawa's water storage system (Helms, 1981, Fig. 6.2). Terrace system TG-3 has a ratio R of 6.5:1.

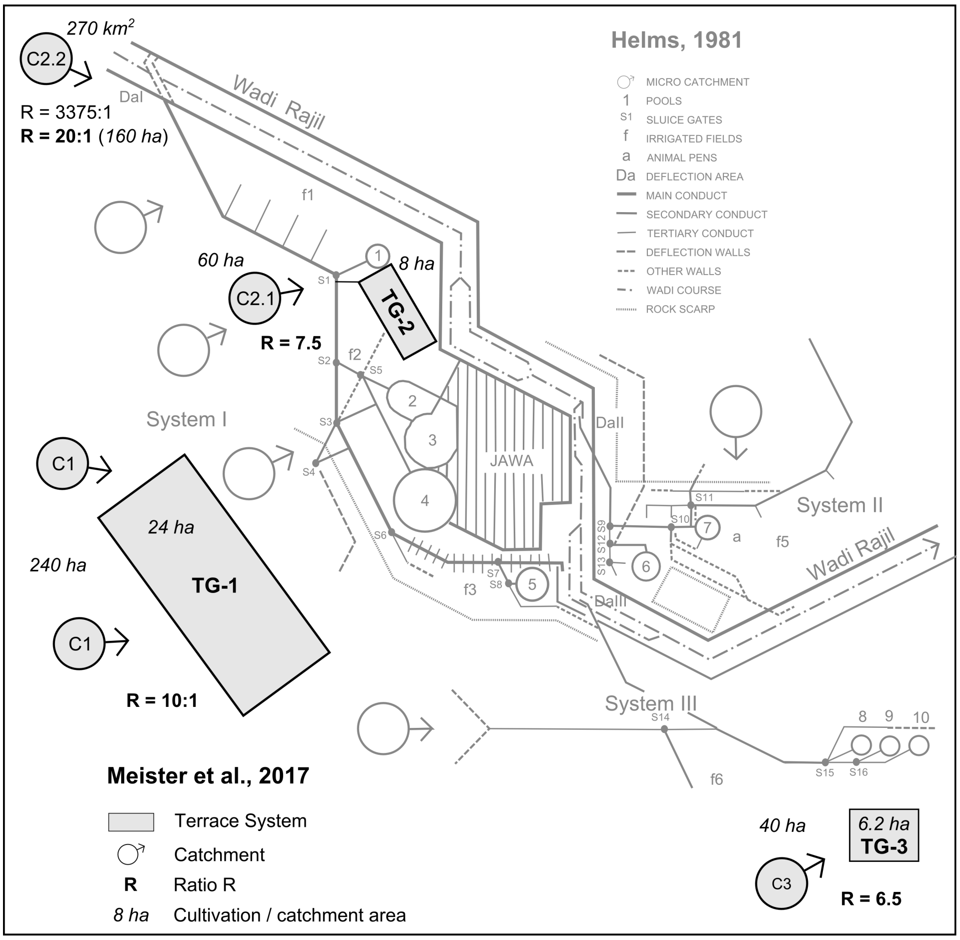

Figure 6.2.: Schema of the Jawa water management systems; modified after Helms (1981) and extended according to Meister et al. (2017).

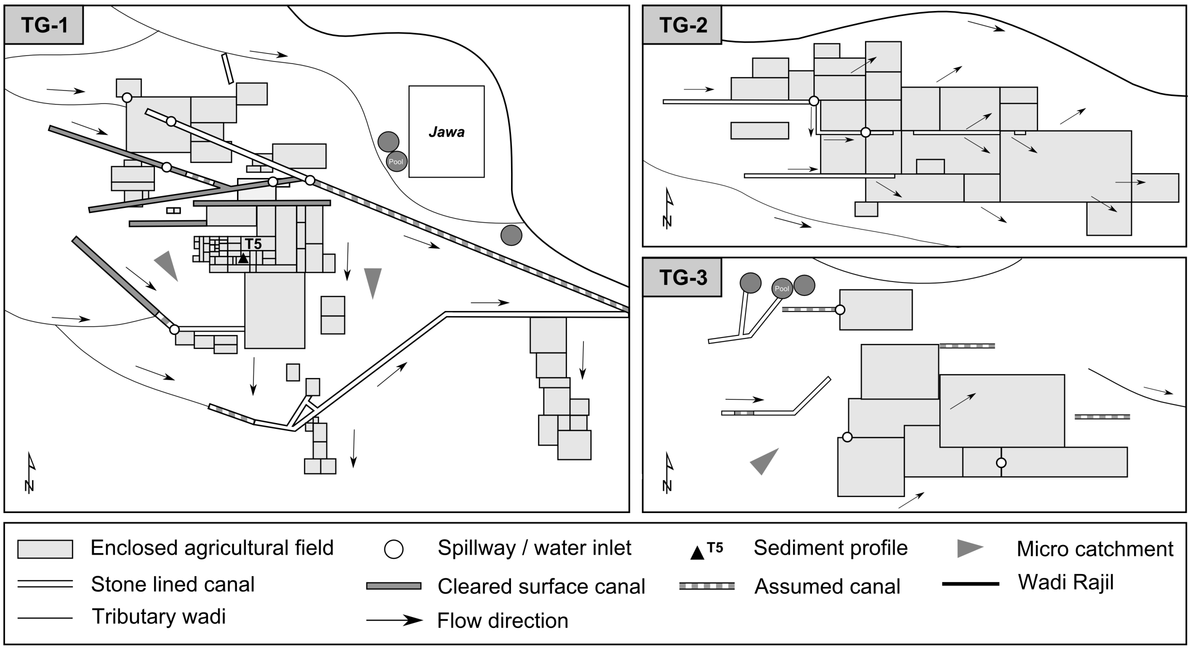

Figure 6.3.: Detailed sketches of the recorded agricultural systems at Jawa; modified after Meister et al. (2017).

6.3. Methods, data and analysis

6.3.1. CropSyst

CropSyst (Cropping Systems Simulation Model) is a complex functional crop growth simulation model which serves as an analytical tool to compute crop productivity in regard to crop management and the environmental conditions (Stöckle and Nelson, 1994; Stöckle et al., 2003). On the basis of fixed parameters (e.g. soil composition, plant phenology) and dependent stress parameters (e.g. soil water budget, nitrogen budget, thermal time, decomposition, erosion) the model simulates crop growth, crop development stages and the resulting crop yield in daily time steps and for multiple crops and years. Management options are diverse and include e.g. crop selection, irrigation, fertilization, tillage operations and residue management.

CropSyst is open source and written in C++. A detailed User's Manual is published by Stöckle and Nelson (1996); Stöckle et al. (1994); Stöckle and Nelson (2000). The model requires daily weather values of solar radiation, maximum and minimum temperatures and precipitation. Other input data for the model include soil properties, crop characteristics and management practices. The input parameters are given in four data files: Weather, Soil, Crop and Management, each containing numerous sub-parameters (Table 6.2). These parameters interact in various ways during the simulation, e.g. the nitrogen and water budgets influence the nitrogen transport as a function of the soil characteristics.

The model has been applied to several crops (e.g. corn, wheat, barley and soybean) and regions (e.g. US, Italy, Syria, Spain and Australia), generally with satisfactory results (e.g. Benli et al., 2007; Donatelli et al., 1997).

6.3.1.1. Study approach

One of the common crop modeling applications is the estimation of potential productivity under different environmental conditions or irrigation strategies. To assess the impact of seasonal rainfall and runoff variability on crop production and its variability, the yield potential of rainfed and runoff irrigated crops at Jawa was simulated for 1983–2014. We chose to run the crop simulation model (CropSyst, v4-19-06) under modern environmental conditions since modern climate data is more reliable than simulated paleodata from Global Climate Models (GCMs; Hemming et al., 2010). Moreover, small differences in climate variability, as expected for deserts, are often insufficiently depicted by GCMs (Gonzalez-Rouco et al., 2011).

In order to assess the efficiency of the agricultural terrace systems and their irrigation measures we assume that the given crop productivity of the terrace systems is exclusively on a rainfed basis, and thus without runoff/floodwater irrigation, reflecting the system's minimum productivity. Accordingly we assume that each runoff event that was harvested by irrigation measures and/or the choice of the terrace system's location increased crop yields. Since there are no gauging data of the wadis in the Jawa basin we generated a runoff time series for the individual catchments, based on rainfall and soil data in order to study the frequency and volumes of the runoff events. The resulting data served as input parameters in the cropping system model (cf. section 6.3.1.2). Consequently, the efficiency of the systems was evaluated by comparison of crop yields simulated under rainfed conditions and different runoff irrigation levels as resulting from the occurrence of effective rainfall. In order to assess the impact of rainfall and runoff variability, the relation between yield and total water amount was analyzed by calculating the Pearson product-moment correlation coefficient using the *cor.test* function of the *stats*—package (Team, 2013) in *R*.

With respect to the crop selection for the simulations, we chose winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.) and lentils (*Lens culinaris* Medikus) since they were commonly cultivated in the Middle East during the EBA (Zohary et al., 2012; Zohary and Hopf, 1973) and are documented for EBA Jawa (Willcox, 1981), although the exact races of Early Bronze Age cultivars are not known. During simulations we followed common agricultural practices of the modern Bedouins, assuming that they correspond to traditional practices. For sake of simplicity of the model, we neglected information on tillage operations or on crop rotations. Hence, the model presented here probably does not represent the full complexity of Early Bronze Age crop cultivation. Nevertheless, we believe that it is a valuable tool for understanding the role of runoff irrigation and describing the relation between water and crop yields.

6.3.1.2. Weather data and analysis

For simulation runs CropSyst requires comprehensive meteorological input data including precipitation, maximum and minimum temperatures and wind speed on a daily basis, while other parameters (e.g. solar irradiance) can be generated based on local information such as coordinates and altitude by the implemented climatic data generator ClimGen (Stöckle et al., 1999).

Only few climate stations cover the Jordanian desert steppe and adjacent areas. The meteorological station of Safawi is located in the vicinity of Jawa (Fig. 6.1a), but its records are fragmentary and daily data are inaccessible. The station provides long-term averages for the period from 1961–1991 (FAO, 2001, Fig. 6.1b). Monthly averages of wind speed, maximum and minimum temperatures are available for the period 1973–1992 (FAO, 2007). In the absence of available daily time series, we interpolated daily values by applying a quintic polynomial fitting-line on the monthly parameters of the aforementioned dataset (n = 12–16 for each month, $r^2 = 0.99$), being aware that this smooths the natural noise of the parameters. Since data on relative humidity and dew point are not available, these parameters were not considered.

To obtain daily precipitation data for Jawa we applied daily satellite precipitation estimates received from the daily gridded RFE (NOAA-CPC Rainfall Estimator) ARC 2 (African Rainfall Climatology Version 2.0), which were generated by merging gauge measurements and satellite infrared measurements using the RFE2 algorithm (Xie and Arkin, 1996). The dataset covers Jordan with a spatial resolution of 0.1° x 0.1°. It has the highest spatial resolution of comparable datasets (Love et al., 2004; Novella and Thiaw, 2012) and is frequently used in data-sparse regions, e.g. for hydrological modeling (Beckers et al., 2013b; Stisen and Sandholt, 2010). In addition, RFE data perform particularly well in homogenous, flat areas such as the Jawa region (Novella and Thiaw, 2010). We analyzed the available period from January 1983 to December 2014 for the cell of Jawa (37.0 E, 32.2 N). To validate the satellite precipitation estimates we compared them with the GPCC (Global Precipitation Climatology Centre) FDP v.6 dataset (Schneider et al., 2011) for gridded monthly time series by using the Pearson product-moment correlation coefficient. The GPCC dataset has a spatial resolution of 0.5° x 0.5° and is based on spatially interpolated meteorological station data (Rudolf et al., 2010). Due to the different temporal resolutions of both datasets, the higher-resolution ARC 2 daily time series was aggregated on a monthly basis before performing the calculations. Given the differences in spatial resolution, the ARC 2 data was spatially extended to the GPCC grid extent and subsequently averaged. All rainfall datasets were downloaded via the IRI/LDEO Climate Data Library (http://iridl.ldeo.columbia.edu/).

Regarding rainfall analysis we followed the approach of Beckers et al. (2013b). We defined the rainy season, i.e. the hydrological year and the agricultural growing season, lasting from October to May (Trigo et al., 1999). In the following we refer to the rainy season as 'season'. In order to classify the seasons regarding their magnitude in dryness or wetness we applied the standardized precipitation index (SPI) (McKee et al., 1995). Calculations were performed with the SPEI package v.1.6. in *R* (Vicente-Serrano et al., 2010) and categorized in accordance with McKee et al. (1995). Daily rainfall intensities were classified according to Gallego et al. (2005). To examine the relation to seasonal rainfall amounts the mean daily intensities of each season were calculated considering only days with precipitation values > 0.1 mm (Beckers et al., 2013b).

To generate runoff volumes for the different catchments we applied the SCS runoff curve number method (CN). The CN is an empirical parameter for estimating direct runoff or infiltration rates from rainfall excess, following the assumption that surface runoff or overland flow always appears when rainfall rates exceed infiltration rates (Mishra and Singh, 2013). Based on the hydrologic conditions, land cover and soil type, the CN method is commonly used in hydrological modeling, especially for small to medium-sized catchments in arid and semi-arid environments (e.g. Beckers et al., 2013b; Berking et al., 2010; El-Hames, 2012; Foody et al., 2004; Hammouri and El-Naqa, 2007; Krause, 2013).

Assuming similar hydrological and soil characteristics within the small-scale catchments of the terrace systems, the area's hydrological soil group, D, and curve number, 88, were picked from published tables (SCS, 1985). The resulting values of 34.5 mm for potential maximum retention (S) and 6.9 for initial abstraction (Ia) using an initial abstraction ratio of Ia/S = 0.20 (Table 6.1) is in accordance with values of other studies conducted in comparable environments (e.g. Beckers et al., 2013b; Berking et al., 2010). The relationship Ia = 0.2*S was empirically derived from the study of many small watersheds. A more recent analysis by Hawkins et al. (2002), however, found that this ratio is usually too high. Based on this study, the use of Ia/S ratios of 0.05 seems more appropriate, as supported by many other studies (e.g. Baltas et al., 2007; Lim et al., 2006). Therefore, we used an initial abstraction ratio of Ia/S = 0.05 and the runoff equation (P-0.05*S0.05)2/P+0.95*S0.05 for calculating runoff (with P = precipitation in mm). Runoff was estimated for each rainfall event with a value P>S0.05, driven by the ARC 2 daily rainfall estimates for the entire analysis period (1983–2014). The resulting amount of runoff per square meter was multiplied by the respective terrace system catchment and subsequently divided by its agricultural area, assuming that the generated runoff within the catchment was equally distributed within the fields. With respect to the terrace system TG-2 and the potential diversion of floodwater from Wadi Rajil, it seems reasonable to assume that the regional runoff amount estimated for a catchment area of 160 ha (C2.2, R = 20) is generated within the large catchment, although the runoff behavior probably changes within the upstream area and nowadays a dam disturbs the natural discharge. The specific objective in this case, however, is to estimate the impact of such a diversion in the past and, thus, the effect of an increase in water availability on harvest yields.

Table 6.1.: Hydrological properties of the Jawa region.

Terrain unit	Dominant Texture	Hydrolog. condition	Hydrolog. soil group	CN*	S0.20 [mm]**	Ia0.20 [mm]***
Terraces and slopes	Clay	Poor	D	88	34.5	6.9

* Curve Number for arid and semi-arid rangelands (SCS, 1985),
** Potential maximum retention, S0.20=25.4*(1000/CN-10), S0.05=1.33*S0.20,
*** Initial abstraction ratio, Ia=0.2*S

6.3.1.3. Soil, crop and management data

Data on soil types and their physical and chemical properties were obtained from a field campaign in 2013 (Meister et al., 2017). The sediments from profile T5 (32°19'56" N, 36°59'50" E, located in terrace system TG-1) were chosen as representative for the soils occurring in the terrace systems. The sediments of profile T5 consist of yellowish silty clay (average textual composition: 43 % clay; 43 % silt, 14 % sand) with an average pH of 7.9 (Table 6.2; see Meister et al. 2017 for detailed data and method descriptions). Soil organic matter and electrical conductivity average 0.8 % and 0.73 $mS*m^{-1}$. Soil hydraulic properties were estimated on texture after Saxton and Rawls (2006, Table 6.2). Because initial soil water contents were not determined, a reasonable value was chosen to match to the expected yields under rainfed conditions. The chosen value of 0.25 m^3/m^3 also matches with the measured values from an experiment conducted at Ramtha Station, northern Jordan (Al-Issa and Samarah, 2007). The crop growth parameters were set by using the default settings (Stöckle and Nelson, 1994). The beginning and end of the simulation period in October and September were chosen as per ethnographic observation of agricultural cycles in the area (Helms, 1981). The sowing date was set shortly after the first greater seasonal rainfall event (>5mm; Table 6.7), whereby the crop harvest date was determined by CropSyst based on a specified number of days after maturity (Stöckle and Nelson, 1994). As known from recent rainfed agricultural practices in the region, neither fertilization nor supplemental irrigation are applied and were therefore not simulated (Al-Bakri et al., 2011). Subsequently, the different levels of runoff irrigation depending on catchment size were considered in the model runs.

6.3.1.4. Model validation

Model calibration was not conducted due to missing field observations and regional data on annual grain yields both in general and for the modeled period. However, the model was validated by comparing simulated crop yields with available data for the region or from areas with similar environmental conditions. In particular we used estimated crop production values of wheat cultivated in Jordan by rainfall regimes (Table 6.5) and production rates for wheat

Table 6.2.: Used input data and settings for the CropSyst modeling approach. Non-listed parameters were used in the default setting.

Data-file / parameters	**Activity**	**Value / method description**
Weather		
Precipitation	Estimated (ARC 2, Jawa)	Section 6.3.1.2; Fig. 6.4a; Table 6.7
Irrigation	Calculated (SCS runoff curve number method)	Section 6.3.1.2; Fig. 6.4c; Appendix A.5
Max. and min temp.	Interpolated from monthly means of Safawi weather station	Section 6.3.1.2; Table 6.4
Solar irradiance	Calculated by CropSyst (Location file)	
Maximum solar irradiance	Calculated by CropSyst (Location file)	
Daylight (h)	Calculated by CropSyst (Location file)	
Relative humidity	Not used	Missing data
Dew Point	Not used	Missing data
Wind speed	Interpolated from monthly means of Safawi weather station	Section 6.3.1.2; Table 6.4
Soil		
Albedo	Given by CropSyst	Dry: 0.16; wet: 0.09
Clay	Observed	43 %; Section 6.3.1.3
Silt	Observed	43 %; Section 6.3.1.3
Sand	Observed	14 %; Section 6.3.1.3
pH	Observed	7.9; Section 6.3.1.3
Hydrologic group	Estimated from soil texture	D; Section 6.3.1.2
Hydrologic condition	Estimated from soil texture	Poor; Section 6.3.1.2
Permanent wilting point	Estimated from soil texture	0.260 m^3/m^3; Section 6.3.1.3
Field capacity	Estimated from soil texture	0.41; Section 6.3.1.3
Bulk density	Estimated from soil texture	1.21; Section 6.3.1.3
Sat. hydr. cond.	Estimated from soil texture	0.141 $m*day^{-1}$; Section 6.3.1.3
Saturation	Estimated from soil texture	0.54 m^3/m^3; Section 6.3.1.3
Management		
Sowing date	Extracted from rainfall data	1-2 days after the first greater rainfall event (>5mm) of every year; Table 6.7
Land treatment	Assumed	Straight row
Fertilization	Not set	No fertilization
Initialization		
Water content	Estimated	0.25 m^3/m^3; Section 6.3.1.3
NO_3/NH_4	Not set	Missing data
Salinity	Observed	0.73 $mS*m^{-1}$; Section 6.3.1.3
Organic matter	Observed	0.83 %; Section 6.3.1.3
Submodels		
Precipitation	Precipitation event duration	240
Freezing	No snow pack	On
Chemistry	Nitrogen / salinity	On
Evapotranspiration	Penman-Monteith	On
Soil	Infiltration (FD)	On
	Runoff model (FD)	On
	Subdivide soil layers	On
	Erosion	On
Organic matter	Single organic matter pool	On

and barley in the Negev desert as expected by Bedouin farmers (Table 6.6), given by Russel (1988). Validation for lentil production used the average crop yield data from 1994 to 2013 for Jordan provided by the Jordanian Department of Statistics (DOS, http://web.dos.gov.jo/).

6.3.2. Food supply capacity

The food supply capacity by crop production from the terrace systems was estimated based on the ratio of the mean and maximum crop yields for all three crops and each irrigation level (terrace system) as well as the annual calorie consumption per person. The latter is calculated from the ratio of the current daily calorie consumption rate per person in Jordan (2270 kcal*day^{-1}; Roser, 2015) and the average caloric value of each crop, using the modern values of 3.5 kcal*kg^{-1} for barley and lentils and 2.7 kcal*kg^{-1} for bread wheat (USDA, 2015). In addition, the supply capacity of Jawa's sheep, goat and cattle herds was calculated based on estimated flock sizes (Helms, 1981, section 6.2.3) and annual caloric herd productivity values, including milk and meat production (Russel, 1988, p. 75; Appendix A.3).

6.4. Results and discussion

6.4.1. Meteorological data and water availability

6.4.1.1. Precipitation

The GPCC and the temporally and spatially averaged ARC 2 dataset for Jawa are positively correlated (r = 0.73, α<0.05). The ARC 2 estimates exceed the GPCC precipitation amounts by about 10 %, possibly resulting from the sparse distribution of GPCC stations in northern Jordan and across the Arabian Peninsula and their fragmentary datasets (Hemming et al., 2010). Moreover, the differences might be due to the different spatial scales of both datasets (Stisen and Sandholt, 2010). Overall, the precipitation totals are consistent with the regional precipitation data computed by Tarawneh and Kadıoğlu (2003). Furthermore, Beckers et al. (2013b) reported good statistical properties of the ARC 2 rainfall estimates for the city of Palmyra in Syria by comparing the dataset with directly measured rainfall data.

At Jawa the total seasonal rainfall amounts varied significantly in the period 1983–2014, ranging from 56.7 to 175.2 mm (mean = 116.2 mm; Fig. 6.4a, Table 6.7). The high rainfall variability is also documented by the SPI values which show repeated changes from wetter to dryer periods and vice versa within the observation period (Fig. 6.4b). Furthermore, the distribution of rainfall events varies seasonally. Overall, these results are in good accordance with Tarawneh and Kadıoğlu (2003) who state that the precipitation regime of Jordan is highly variable and not durable.

The season totals and the mean daily intensities of precipitation correlate weakly (r = 0.44, α<0.05), while there is a strong correlation between seasonal rainfall amounts and the amounts of heavy rainfall events (r = 0.76, α<0.01). This indicates an increased contribution of heavy rainfall events to annual precipitation in normal to wet years, which is in agreement with several studies, reporting positive correlations for different regions worldwide (Easterling et al., 2000). In wetter years therefore, large quantities of water are usually available for only a short period of time (Helms, 1981).

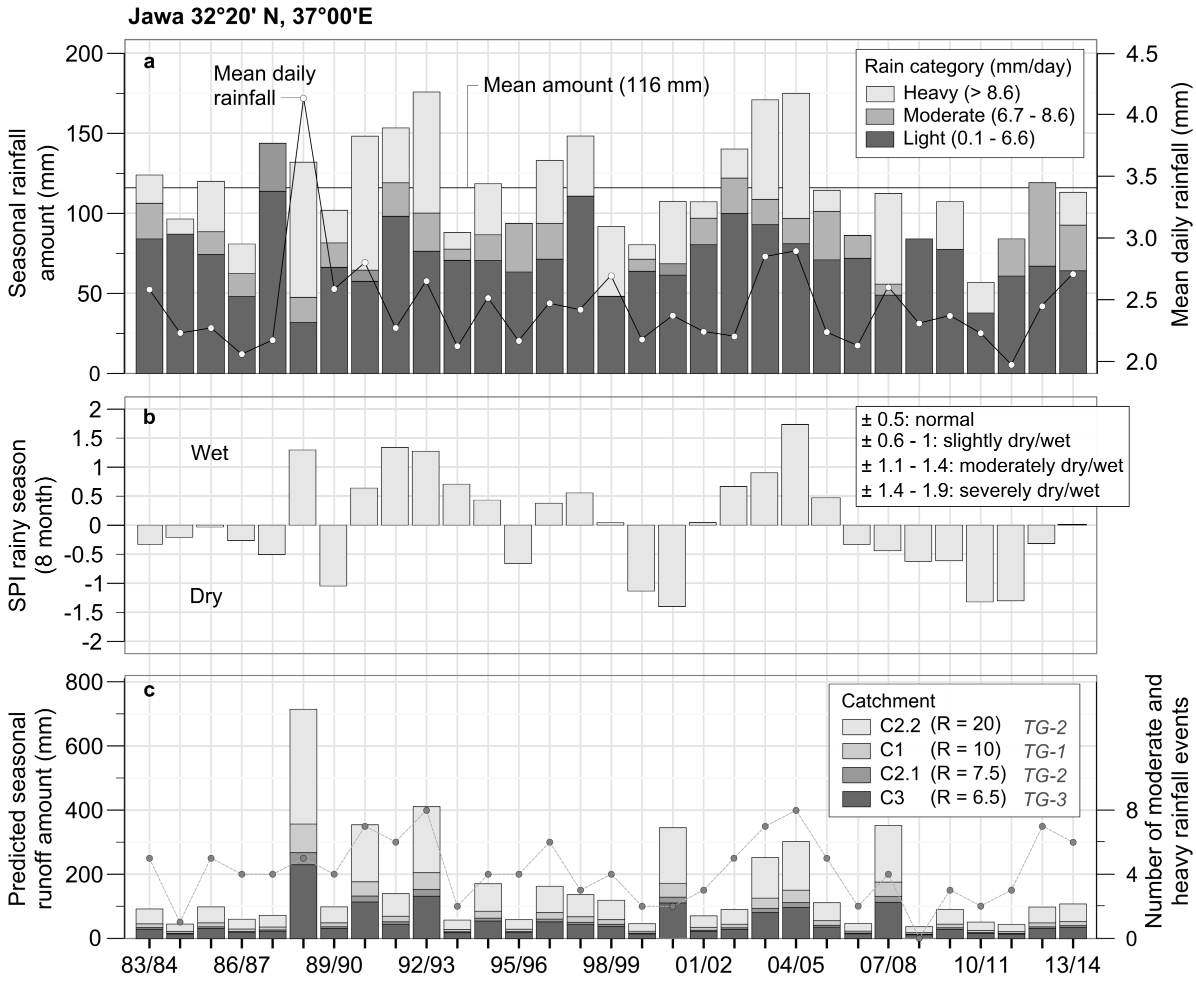

Figure 6.4.: Results of the rainfall and runoff analysis. 4a: Seasonal rainfall amounts with volumetric contribution of rainfall category and mean daily rainfall (see Appendix A.4 for additional data); 4b: Standardized precipitation index (SPI) of the rainy seasons. c: Total seasonal runoff depth which each square meter of arable land receives in addition to the water it receives as direct rain, and number of moderate to heavy rainfall events. Note that the runoff volumes are illustrated in stacked bar plots by terrace system (catchment size).

6.4.1.2. Runoff

Owing to the event-based and deterministic runoff modeling approach, there is a relation between the number of moderate to heavy runoff events and the predicted seasonal runoff amounts (Fig. 6.4c). While on average four moderate to heavy rainfall events occur per season, in normal to severely wet seasons up to eight strong rainfall events might occur. The seasonal runoff depths range from 1.9 to 35.8 mm, averaging 7.8 mm; this depth multiplied by the R factor of the respective terrace systems gives the total seasonal runoff amount that each system derives additionally to rainfall (Fig. 6.4c; Appendix A.5). In the case of the smallest catchment (C3) the runoff depth averages 51 mm within the simulation period, while the biggest catchment (C2.2) gained an average of 157 mm. In the severely wet season of 1988/1989 a maximum runoff depth of 716 mm is estimated for catchment C2.2, while a minimum of only 12 mm was obtained in the dry season of 2008/2009 for catchment C3. Overall, the runoff estimates provided by this study are consistent with the experimental study by Evenari (1982) conducted in the Israeli Negev desert. Based on modern observations from two ancient runoff-farms (Avdat and Shivta) they revealed similar mean runoff coefficients ($\alpha = 0.05$) to those estimated by the SCS runoff curve number method applied for Jawa, although the average runoff coefficient at Jawa is slightly lower (Table 6.3). The local variability of runoff, however, can be high and is influenced by several factors such as slope inclination, soil cover and precipitation intensity (Cooke et al., 2006).

6.4.1.3. Temperatures and wind speed

With respect to the temperature data of the Safawi weather station, the highest monthly maximum temperature averages 36.4 °C and occurs in July, while the lowest monthly maximum temperature averaging 14 °C is reached in January (Table 6.4). Associated average monthly minimum temperatures reached 20.8 °C and 2.8 °C respectively. These temperature data are in good agreement with averaged seasonal data for Ramtha station (32°30'N, 36°00'E; 595 m. a.s.l) in northern Jordan (Al-Issa and Samarah, 2007), located about 110 km northwest of Safawi, indicating that temperature profiles within northern Jordan have very similar characteristics. In the absence of local data for Jawa it therefore seems reasonable to use temperature data from Safawi station for crop simulations at Jawa. Regarding wind speed at Safawi station, values range from 2.09 km*h^{-1} in November to 5.12 km*h^{-1} in June, averaging 4.0 km*h^{-1} annually (Table 6.4).

6.4.2. Crop production modeled by CropSyst

Altogether, 465 model simulations were performed based on calculations for three crops, a simulation period of 31 years and five different rainfall and runoff scenarios. The simulated mean grain yields for the various treatments and for all crops and cropping seasons are summarized in Table 6.7 and illustrated in Figs. 6.5 and 6.6.

Table 6.3.: Comparison between seasonal precipitation (Prec) and runoff coefficients* (RC) at Jawa and the modern experimental runoff-farms Avdat- and Shivta in Israel (adapted from Evenari 1982, 146 ff; Table 12; 13).

	Jawa**		**Avdat farm*****		**Shivta farm******	
	Prec (mm)	RC	Prec (mm)	RC	Prec (mm)	RC
Min	57	0.02	26	0.00	28	0.03
Max	175	0.27	160	0.21	165	0.23
Mean	116	0.06	87	0.08	93	0.11

* Defined as the ratio of the total seasonal runoff and the total seasonal rainfall.,
** Rainfall data from the ARC 2 rainfall estimates (1983 to 2014) and runoff coefficients, estimated by the SCS runoff curve number method.,
*** Observed from 8 watersheds (1 to 345 ha in size) in the period from 1960 to 1968,
**** Observed from one watershed ($\sim$ 1 ha in size) in the period from 1960 to 1968.

Table 6.4.: Summary of long-term climate data. Monthly averages of rainfall data at Jawa (1983–2014) and temperature and wind speed data from the Safawi weather station (1973–1992).

Month	**Rainfall (mm)**	**Max. temp. (°C)**	**Min. temp. (°C)**	**Wind speed (km*h^{-1})**
January	17.3	13.97	2.75	3.28
February	16.0	16.02	4.48	3.83
March	19.1	19.42	7.09	4.53
April	15.4	25.08	11.37	4.69
May	12.4	30.40	15.66	4.89
June	0.5	34.26	18.67	5.12
July	0	36.42	20.78	4.70
August	0	36.25	20.29	4.20
September	1.0	34.15	18.72	3.66
October	7.8	28.63	14.69	3.33
November	11.7	21.43	8.95	2.91
December	16.0	15.45	4.46	3.08
Total/Mean	117.1	26.0	12.3	4.0

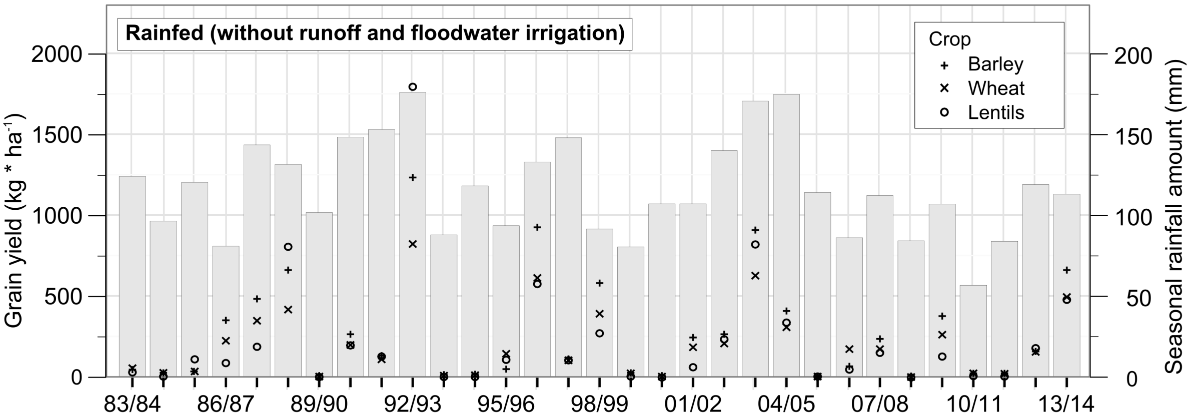

Figure 6.5.: Seasonal rainfall and simulated grain yield for barley, wheat and lentils under rainfed conditions.

6.4.2.1. Rainfed agriculture

The simulation results applying the CropSyst model assuming rainfed agriculture show strong variations in the production yields among the different years (Fig. 6.5, Table 6.7). Annual crop yields range from 10–1239 kg*ha^{-1} for barley, from 5–829 kg*ha^{-1} for wheat and from 2–1798 kg*ha^{-1} for lentils. The overall mean of rainfed crop yield totals 276 kg*ha^{-1} for barley, 224 kg*ha^{-1} for lentils and 205 kg*ha^{-1} for wheat.

The results of the correlation analysis reveal that there was a positive relationship between the seasonal rainfall amounts and the yield of barley, wheat and lentils (r = 0.57–0.60, $\alpha<0.05$, Table 6.7). Thus, high rainfall rates usually resulted in high crop yields (e.g. 1992/1993), while particularly dry conditions coincide with low yields (e.g. 2010/2011). In contrast, however, there are seasons characterized by high yields for all three crops although the total rainfall amounts were below the long-term average (e.g. 1998/1999); this signifies the role of an optimal rainfall pattern throughout the season in boosting the yield of rainfed crops.

Regarding the occurrence of harvest failures (<50 kg*ha^{-1}) within the simulation period, for lentils and wheat a total of 12 harvest failures were simulated, while for the more robust barley 11 harvest failures were simulated.

The simulated yields for wheat cultivation fit well to the Jordanian wheat production values given by Russel (1988, Table 6.5), as for the ‘desert region’ (150–250 mm*a^{-1} annual rainfall) he states an average wheat yield of about 400 kg*ha^{-1}. Corresponding to the noticeably lower seasonal rainfall amounts within the Jawa region ($\sim$ 116 mm), a reduction of simulated crop yields to about 200 kg*ha^{-1} seems reasonable. Moreover, the simulated yields for barley range roughly between 400 and 600 kg*ha^{-1} in ‘wet’ years and correspond to Helms (1981) findings.

The data on crop production in the Negev desert presented by Russel (1988, Table 6.6) match perfectly with the simulated yields of wheat and barley, not only in terms of the range of yields but also in terms of the ratio of yields between both crops. Thus, barley yields are slightly higher than wheat yields in 'satisfactory' and 'good' years but notably higher under 'exceptional good' rainfall conditions.

Since lentil cultivation in Jordan is nowadays restricted to rainfed areas where annual rainfall exceeds 300 mm (Momany, 2001), data on lentil yields for the Jawa region are unavailable. However, simulated yields are low and the rate of harvest failures high, reflecting the high vulnerability of this crop to water scarcity.

Table 6.5.: Estimated production of wheat cultivated in Jordan by rainfall regimes (adapted from Russel 1988.

Region	**Rainfall (mm)**	**Average yield ($kg*ha^{-1}$)**	**Range of yields 'bad' – 'good' ($kg*ha^{-1}$)**
Desert	150–250	400	100–700
Eastern Plain	250–300	640	350–900
Western Plain	300–400	810	500–1170
Upland	400+	1050	750–1460

Table 6.6.: Wheat and barley yield expectations of Bedouin farmers in the Negev (adapted from Russel 1988.

Informant yield evaluation	**Wheat ($kg*ha^{-1}$)**	**Barley ($kg*ha^{-1}$)**
Exceptional	1000	2000
Good	500–700	700–800
Satisfactory	300–500	400–600
Poor	0–200	0–200

Table 6.7.: Seasonal rainfall amounts, sowing dates and simulated grain yields (kg*ha^{-1}) for the cultivation of winter barley, winter wheat and lentils under rainfed conditions (RF) and different irrigation scenarios or catchments (C). The R factor is given in brackets. Maximum yields of each crop and season are highlighted in grey.

Season	SRA	Sowing date	Barley					Wheat					Lentil				
				TG-1	TG-2		TG-3		TG-1	TG-2		TG-3		TG-2		TG-3	
			RF (0)	**C1 (10)**	**C2.1 (7.5)**	**C2.2 (20)**	**C3 (6.5)**	**RF (0)**	**C1 (10)**	**C2.1 (7.5)**	**C2.2 (20)**	**C3 (6.5)**	**RF (0)**	**C1 (10)**	**C2.1 (7.5)**	**C2.2 (20)**	**C3 (6.5)**
83/84	124	28.10.1983	53	268	224	413	201	60	196	169	307	159	32	156	131	339	120
84/85	96	14.12.1984	32	278	183	559	154	32	231	187	419	163	7	128	106	277	85
85/86	120	04.11.1985	42	53	52	228	51	40	52	48	199	47	112	452	340	993	311
86/87	81	09.11.1986	358	849	713	897	664	231	536	465	643	431	91	494	343	1200	295
87/88	143	21.12.1987	490	838	742	1120	701	355	567	513	730	490	189	591	440	808	376
88/89	132	19.10.1988	668	452	501	405	530	424	376	405	335	410	809	3554	3642	2738	3660
89/90	102	07.11.1989	16	101	49	372	39	9	96	46	247	34	3	63	24	188	16
90/91	148	19.10.1990	270	645	615	662	574	206	406	390	509	367	198	723	559	2540	520
91/92	153	14.10.1991	139	509	413	666	368	117	348	292	503	277	129	837	461	2770	366
92/93	175	15.12.1992	1239	767	927	597	805	829	555	623	440	654	1798	3119	3192	2930	3211
93/94	88	22.10.1993	22	28	26	37	26	14	22	19	30	18	3	4	3	9	3
94/95	118	11.10.1994	25	37	34	51	32	19	31	28	50	35	3	11	7	43	6
95/96	94	03.11.1995	56	253	218	391	208	149	199	187	292	183	110	267	218	1078	203
96/97	133	20.11.1996	931	860	895	795	913	618	616	637	567	649	579	1926	2100	1582	2017
97/98	148	19.10.1997	119	477	378	706	353	111	329	281	473	263	107	525	435	1950	389
98/99	92	13.12.1998	586	1248	1131	1232	1060	397	845	778	846	739	274	1597	1193	3354	1020
99/00	80	23.10.1999	32	63	50	181	48	28	130	88	162	66	7	130	87	178	56
00/01	107	14.10.2000	15	19	17	30	17	9	13	11	26	11	2	3	2	9	2
01/02	107	29.12.2001	251	544	467	779	436	190	374	325	558	305	65	353	267	652	225
02/03	140	02.11.2002	272	556	487	859	464	212	411	370	561	351	237	418	526	2631	418
03/04	170	25.11.2003	915	866	907	813	932	634	622	648	565	662	823	1985	1912	1731	1905
04/05	174	20.11.2004	415	939	803	970	743	313	630	565	700	538	339	2405	1625	1972	1182
05/06	114	26.12.2005	10	30	26	46	24	10	36	28	66	26	5	55	30	375	24
06/07	86	28.12.2006	72	643	527	1014	483	180	441	374	700	344	50	306	238	569	215

07/08	112	22.11.2007	241	602	511	963	469	178	462	394	660	362	152	744	472	2052	414
08/09	84	30.10.2008	11	22	18	51	16	5	15	11	51	10	2	2	2	24	2
09/10	107	20.12.2009	383	1182	985	1295	888	267	767	659	890	609	130	874	665	2245	576
10/11	57	01.01.2011	29	324	159	685	105	28	277	227	474	204	8	153	96	346	72
11/12	84	17.11.2011	30	248	152	458	81	27	206	180	350	166	6	248	204	679	185
12/13	119	28.10.2012	164	357	298	627	286	163	262	221	404	209	183	1061	528	2490	437
13/14	113	15.11.2013	668	966	977	847	958	500	657	651	609	639	482	1533	1386	1696	1342
Min			10	19	17	30	16	5	13	11	26	10	2	2	2	9	2
Max			1239	1248	1131	1295	1060	829	845	778	890	739	1798	3554	3642	3354	3660
Mean			276	485	435	605	407	205	345	317	431	304	224	797	685	1305	634
Mean ratio (C/RF)			1.00	1.76	1.58	2.19	1.48	1.00	1.68	1.55	2.10	1.48	1.00	3.56	3.06	5.83	2.83
PCC r (WA vs. CY)			0.57	0.24	0.36	0.02	0.40	0.57	0.26	0.36	0.05	0.40	0.60	0.76	0.76	0.52	0.75

6.4.2.2. Runoff/floodwater irrigation agriculture

Average grain yields of barley, wheat and lentils are higher under supplemental runoff/floodwater irrigation, demonstrated also by the fact that more water availability generally correlates positively with higher yield (Fig. 6.6; Table 6.7). These parameters, however, do not always correlate strongly due to the influence of plant properties, soil characteristics and rainfall patterns.

For lentils, there is a normal to strong correlation between yields and the total water amount, supplied by rainfall and runoff ($r = 0.52–0.76$, $\alpha<0.05$). The average yields increased by almost 3 to 6 times compared to rainfed yields, ranging from 634 kg*ha^{-1} (C3) to 1305 kg*ha^{-1} (C2.2). Lentil yields > 2000 kg*ha^{-1} were usually reached when seasonal water amounts well exceeded 250 mm (Fig. 6.6c, d), demonstrating that the crop responds favorably to irrigation (Yadav et al., 2007).

For barley and wheat there is a weak to normal positive correlation ($r = 0.24–0.40$, $\alpha<0.05$) for the catchments C1, C2.1 and C3, while there was no linear relationship between the available water amount and the yields for catchment C2.2 ($r = <0.06$, $\alpha<0.05$). Nevertheless, average yields are approximately 1.5 times (C3) to > 2 times (C2.2) higher under different levels of runoff irrigation, reaching average yields of 305–345 kg*ha^{-1} for wheat and of 407–605 kg*ha^{-1} for barley. The weak correlation between yield and total water amount for the highest irrigation level (C2.2) is probably related to the fact that CropSyst is not able to simulate drainage, resulting in the simulation of extremely wet soil conditions and water logging and a decrease of yields (e.g. 1992/1993). Regarding crop losses, there is a marked reduction in the number of harvest failures under runoff irrigation. For barley and wheat cultivation the number fell to c. 30 %, for lentils to c. 25 % with only 3 and 4 harvest failures within 31 years.

Taking into account the seasonal water supply of the terraced systems by rainfall and runoff irrigation, the simulated yields of wheat and barley are consistent with the production values given by Russel (1988) for Jordan and the Negev desert (Tables 6.7, 6.5, 6.6; Fig. 6.6d; Appendix A.5). In turn, the simulated yields of lentil cultivation are in good agreement with the average crop yield data given by the Jordanian Department of Statistics, according to which lentil crop production in Jordan averaged 700 kg*ha^{-1} in the period from 1994 to 2013.

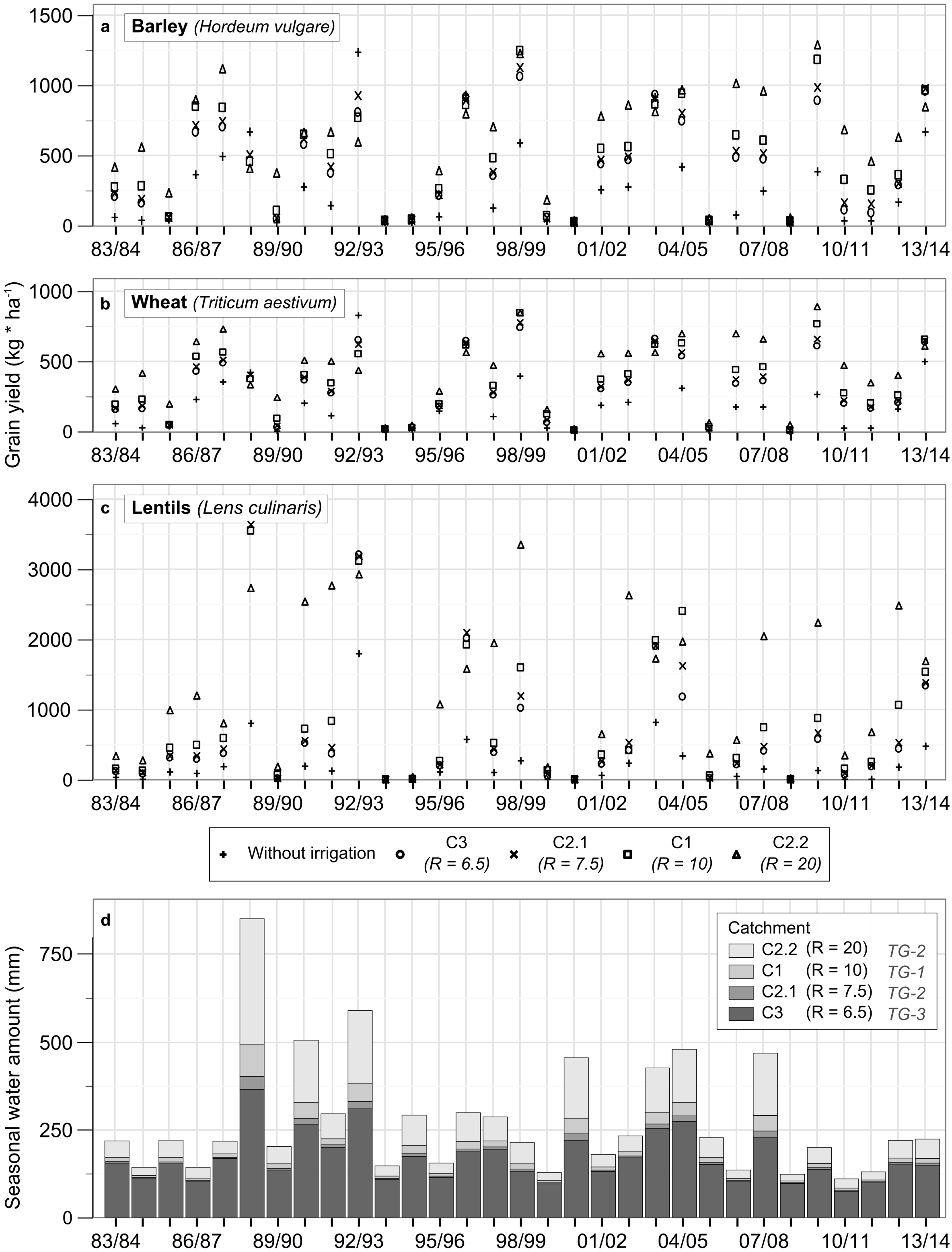

Figure 6.6.: 6a, b, c: Simulated grain yield for barley (a), wheat (b) and lentils (c) under rainfed conditions and different irrigation levels. Note the different scales; 6d: Seasonal water amount (sum of seasonal rainfall and runoff amounts) that reaches each terrace system illustrated in stacked bar plots.

6.4.3. Food supply capacity by pastoral and agricultural production

Under today's environmental conditions about 142 people can be annually supplied by the average lentil production of all three irrigated terrace systems combined; in 'exceptional' good years this supply capacity increases almost fivefold (Table 6.8). The supply capacity of barley and wheat production is generally lower: average barley production can support 81 people per year, while this number drops to about 44 people under wheat cultivation; in 'exceptional' years these values more than double as well. Assuming mixed cultivation of cereals and legumes around Jawa (Meister et al., 2017) the food supply capacity would feed somewhere between 40 and 140 people, taking average yields of all three crops into consideration.

In view of crop productivity, it is reasonable to assume that the runoff/floodwater irrigated terraced fields at Jawa would have been mainly utilized for the cultivation of pulses, such as chickpeas, peas and lentils, to reduce cultivation risks (Yadav et al., 2010). Since the simulated crops have been subject to modern breeding, however, it must be assumed that plant properties of modern barley, wheat and lentil plants have changed compared to Early Bronze Age plants and yields were even lower than today. Overall, the local crop production at Jawa was not sufficient to secure food supplies for all inhabitants, even when the small agricultural field areas documented by Helms (1981, cf. Fig. 6.3) are taken into account. Therefore, it seems likely that other arable areas in the greater vicinity of Jawa existed and were additionally used for the production of staple crops. The mudpan area around Qa'a ash Shubayka, for example, is located only 25 km east of Jawa and covers over 1000 ha. Since it is used by Bedouins living near Jawa for agriculture even today it was probably also important for food production during the 4th millennium BCE (Helms, 1981).

The animal herds at Jawa, assuming a total number of about 11,000 animals, could have met the nutritional requirements of only about 400 persons per year (Table 6.9). Considering the estimated maximum population for EBA Jawa, ranging from 3400 to 5000 people (Helms, 1981), the significance of this is that neither the animal production nor the local crop production created any surpluses or provided the necessary nutrition for Jawa's inhabitants. Thus, the estimated number of animals is either too low and the agricultural areas too small to comprise an economic base for such a large population, or the town's population estimates by Helms (1981) are overstated.

However, in the likely case that the number of people living at Jawa was > 1000, one can assume that trade was an important economic branch, supplementing pastoral and agricultural production. Recent archaeological surveys in the northern Badia have revealed abundant traces of Chalcolithic/ Early Bronze Age socio-economic activities, ranging from the exploitation of large flint mines with associated export-oriented cortical flake production, through abundant indications of ancient pastoralism Müller-Neuhof (2014a, 2013a). At Jawa, numerous imported flint tools were found (Helms, 1981), indicating that the town was part of a supra-regional exchange network focused on the distribution of flint (Müller-Neuhof, 2014a). Moreover, expanding the ideas of Müller-Neuhof (2014a), it may be hypothesized that Jawa was an EBA trading center on a regional scale, connecting the non-urban pastoralists of the basalt desert with groups living in the more fertile Hauran mountains, which, owing to their respective specialization on agriculture and pastoralism, may have relied upon the purchase of animal and crop products. Pottery, crop seeds or hunting products may have been additional trading goods.

Table 6.8.: Total number of people that can be annually supplied according to modern calorie requirements by the simulated mean and maximum yields of each crop and terrace system.

Terrace system	Cultivation area (ha)	Irrigation level / catchment	Number of people					
			Barley		Wheat		Lentil	
			Mean	Max	Mean	Max	Mean	Max
TG-1	24	C1	49	127	27	66	81	361
TG-2	8	C2.1	15	38	8	20	23	123
		C2.2	21	44	11	23	44	114
TG-3	6.2	C3	11	28	6	15	17	96
	Total (38 ha)	with C2.1	75	193	41	101	121	581
		with C2.2	81	199	44	104	142	571

Table 6.9.: Total number of people that can be annually supplied by an estimated number of about 11,000 domestic animals at Jawa.

Herd animal	Estimated flock size	Number of people
Cattle	800	93
Sheep	8000*	265
Goat	2000*	49
Total	**10,800**	**407**

* Based on bone remains the sheep to goat ratio at Jawa is estimated at 4:1 (Köhler, 1981)

6.5. Conclusions

Rainfall variability is an important characteristic of the arid climate in the Jawa region that imposes crop production risks, especially on rainfed cultivation systems. This study shows that the runoff farming systems of EBA Jawa are relatively effective under current rainfall conditions. Even during dryer seasons, the simulated crop yields produced in these terrace systems are much higher under runoff/floodwater irrigation than those of non-irrigated fields. On average the crop yields increase by 1.5 to 6 times under runoff irrigation. Moreover, it is shown that the application of these water management techniques reduces the number of crop failures considerably. This success might be related to the fact that Jawa is located at the margin of a climate region whose precipitation regime has a strong Mediterranean character, which means that sufficient rainfall events triggering runoff occur quite regularly.

According to estimated stock sizes and the crop modeling results, however, neither animal production nor local crop production satisfied the basic nutritional requirements of Jawa's inhabitants, indicating that trade might have been an important branch in Jawa's economy in order to supplement the locally produced food resources. Moreover, former population estimates for ancient Jawa might be too high. In any case, if the water management system failed and severe droughts occurred, the inhabitants could have traveled to the more humid Hauran mountains, which was a one- to two-day journey by foot.

In terms of methodology, the application of a rainfall-runoff model combined with a crop simulation model in order to test the impact of runoff irrigation on harvest yields in ancient runoff farming systems proves to be a valuable tool and may also be applied in other regions. With respect to EBA Jawa additional modeling and validation, including a wider range of conditions and crop properties, should be conducted. Moreover, estimates concerning food supply capacities may provide useful information for a thorough understanding of food security and the supply situation of archaeological sites, since it is often impossible to reconstruct the economy of an ancient site using archaeological data alone.

6.6. Acknowledgments

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CHAPTER 7

A pastoral landscape for millennia: Investigating pastoral mobility in northeastern Jordan using quantitative spatial analyses

Abstract

Northeastern Jordan is one of the few remaining regions in the Middle East where pastoral nomadism is still practiced. In this desert region, pastoral mobility is an adapted land use able to cope with low rainfall rates, great seasonal and annual rainfall variations and thus heterogeneous vegetation and water availability. During winter, herders and their livestock move into the desert; in summer they move to the desert margins to places with perennial water supply. First traces of mobile pastoralism date back to the beginning of the Late Neolithic.

Within the basaltic region of northeastern Jordan, there is a dense distribution of archaeological remains; some of them can be linked to pastoral groups due to the herders' ancient practice of building agglomerations of sub-circular enclosures ('clustered enclosures') made of basalt boulders for corralling their flocks and domestic activities. The resulting features provide an excellent opportunity to investigate a pastoral landscape that has been frequently used by herders during the last eight to nine millennia.

In this study, 9118 clustered enclosures in the northeastern Jordanian basalt desert have been systematically recorded using satellite imagery. In order to investigate potential migration or communication routes, grazing lands and social interactions of former pastoralists, we examine their first- and second-order characteristics using distance and density based approaches of point pattern analyses by integrating geomorphometric and geomorphological site properties. The results of this spatial analysis are combined with available archaeological data and a review on traditional herding practices in northeastern Jordan. Overall, the results demonstrate that the observed spatial distribution of clustered enclosures is influenced locally by natural characteristics but regionally by cultural practices.

Keywords

Mobile pastoralism; Pastoral campsites; Clustered enclosures; Point pattern analyses; Traditional herding practices; Migration pattern

7.1. Introduction

Northeastern Jordan is climatically classified as desert (BWh after the Köppen-Geiger classification; Kottek et al., 2006). With annual average rainfall rates of 50–150 mm, the hot and arid climate of the area leads to water scarcity (Dottridge and Abu Jaber, 1999) and generally poor biomass production. It is one of the few remaining regions in the Middle East where nomadism is still practiced (Tansey, 1999), being the predominant land use (Roe, 2000). Due to strong annual climatic variations with pronounced seasonality, pastoral mobility is essential in order to respond to spatio-temporal changes in vegetation and water availability (Betts, 1998) and represents an adapted form of land use. It seems likely that mobile pastoralism was introduced to the area during the 2nd half of the 7th millennium BCE (Rollefson et al., 2014a). Today, the pastoral system is mainly based on sheep and goat herding (Betts et al., 2013; Roe, 2000) and the herders and their livestock move within the desert area during the winter, while they traditionally spend the summers at places with perennial water supply (Roe, 2000).

The landscape of northeastern Jordan is divided into a basalt desert (*harra* in Arabic) and a limestone desert (*hamad* in Arabic; Fig. 7.1). Within these regions there is a dense distribution of archaeological remains which greatly vary in their form and function. Particularly common architectural structures within the *harra* are simple stone circles (or enclosures) which are scattered throughout the region in a large variety of sizes and shapes (Betts, 1982b, p. 23). Made of stockpiled basaltic stones, they usually occur in clusters of sub-circular structures (Betts et al., 2013, p. 175, Fig. 7.2). In the archaeological record, these sites are commonly linked to previous pastoral activities since the larger structures appear to be animal enclosures (also known as corrals or pens; Betts, 1982b, p. 23) used by herders for corralling their flocks of sheep and goat during the night to prevent straying. Sheltering the animals from wind is especially important in winter and early spring (Betts et al., 2013, p. 175). Evidence for this interpretation is given by modern Bedouins who apply the same technique, often re-using earlier structures (Betts, 1982b, p. 25). In the past these corrals were most likely also used to protect the herds against wild animals (Betts et al., 2013, p. 175). Comparable structures smaller in size are commonly attached to the larger ones and are usually interpreted as being simple windbreaks or huts used by the shepherds (Betts, 1982b, p. 23; Rollefson, 2013, p. 215). The abundant occurrence of artefacts in and around such enclosures in the Jebel Qurma region as well as the occasional occurrence of fireplaces suggests that they were also used for habitation and the related domestic activities of mobile pastoralist groups, rather than being simply corrals (Akkermans et al., 2014).

An additional and important characteristic of the enclosures that indicates their use by herders is their location, which is often linked to periodic water sources, e.g. along wadis or the shorelines of mudpans (Akkermans et al., 2014; Müller-Neuhof, 2014b).

A distinctive and elaborate version of roughly circular structures of various forms made of basalt stones are termed 'jellyfish' (Betts, 1982b,a), 'wheel houses' (Kempe and Al-Malabeh, 2013, 2010a) or 'wheels' (Kennedy, 2011; Rollefson et al., 2016). While many of these sites consist of a roughly circular structure, with numerous enclosures in the center, surrounded by small 'huts', others are segmented by radiating walls. Moreover, cairns occur frequently within the wheels or in their direct vicinity (cf. Akkermans et al., 2014; Betts, 1982b,a; Kennedy, 2011; Rollefson et al., 2016). Although the use of the wheels is still unknown, one hypothesis given by Betts (1982a, p. 185) is that the interior divisions may have functioned as animal pens, whereas the huts provided protection and shelter for herders and their family (see also Rollefson et al., 2016, p. 949 for other explanations). Surface findings and OSL dates of such sites in the *harra* indicate that these wheel-structures originate from the Late Neolithic to Chalcolithic/Early Bronze Age (Akkermans and Huigens, in press; Athanassas et al., 2015).

The basic form of sub-circular stone enclosures has been in use in the Jordanian desert from the earliest prehistoric times (Betts, 1982b, p. 23). However, an exact age determination is often difficult since these structures were commonly rebuilt and reused in later periods (Betts, 1982b). This was also confirmed most recently by the findings of two archaeological transect surveys conducted within the *harra*, documenting that the majority of the clustered enclosures investigated were already occupied by pastoral groups during the Late Neolithic or the Chalcolithic/Early Bronze Age and were commonly reoccupied in historical periods and modern times (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013). Since the basic architecture of the enclosures has not changed since prehistoric times and the structures are in some cases in use today it is difficult to categorize them (Betts, 1982b, p. 23). Because of their typical design and location in the northeastern Jordan desert the enclosures are also well visible on aerial photographs and satellite imagery (Fig. 7.2). Their often exceptionally good preservation might be related to the arid environmental conditions in this region during the Holocene (Frumkin et al., 2008). However, although Betts (1982b, p. 23) mentions the presence of thousands of these enclosures in the northeastern Jordanian desert, archaeological research in the region has mainly focused upon the many other prehistoric and historical archaeological features, e.g. 'desert kites' (e.g. Helms and Betts, 1987; Kempe and Al-Malabeh, 2013, 2010a), dwellings, tombs and cemeteries (e.g. Rollefson et al., 2014a, 2013; Rowan et al., 2015a), Safaitic rock inscriptions (e.g. Macdonald, 1993, 1992) or the specific type of wheel enclosures (e.g. Betts, 1982a; Rollefson et al., 2016). Except for the surveys undertaken by Müller-Neuhof and colleagues (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013) and Akkermans and colleagues

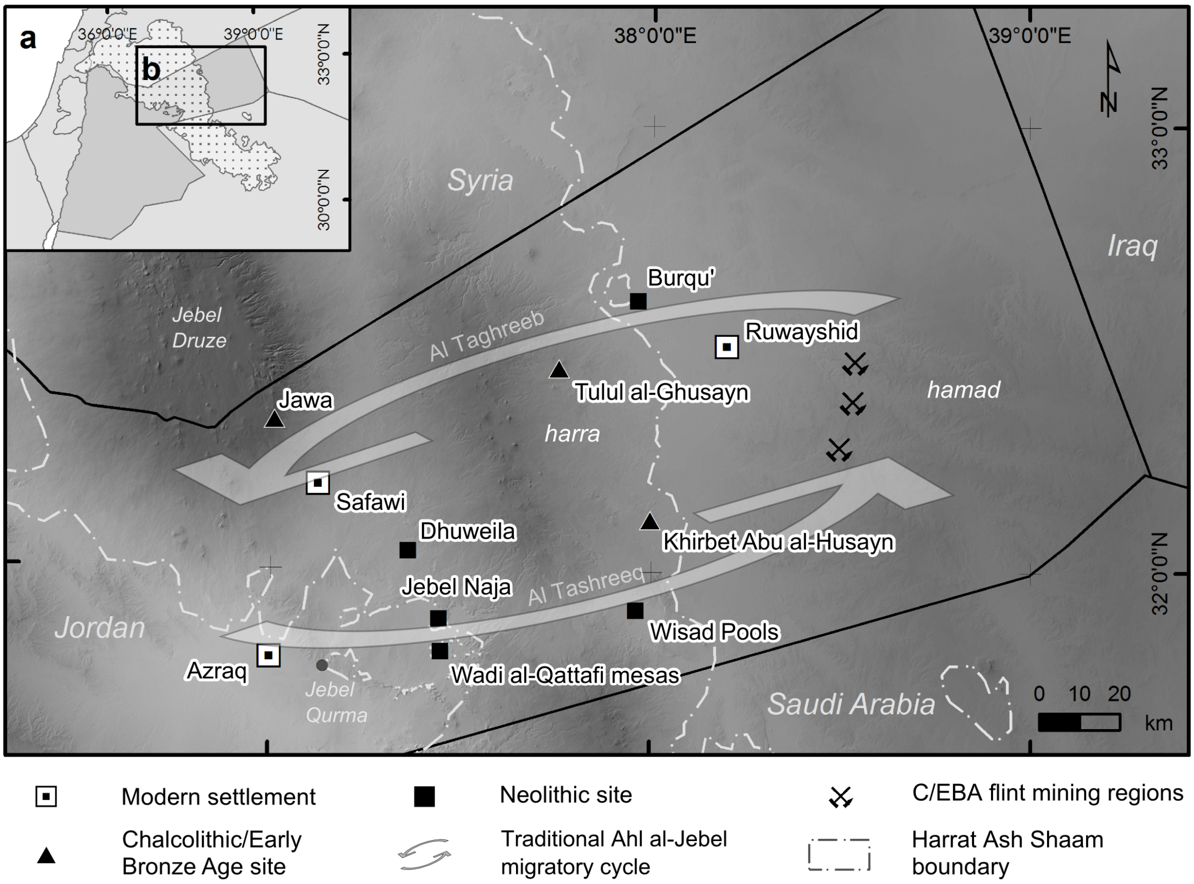

Figure 7.1.: 1a: Location of the 'Harrat Ash Shaam' basaltic region within Jordan and neighboring countries; 1b: Location of northeastern Jordan, modern settlements, selected prehistoric archaeological sites (after Betts, 1998; Müller-Neuhof, 2014b; Rollefson et al., 2014a) and traditional annual migration routes of the Ahl al-Jebel tribe (after Roe, 2000) in the *harra* and the *hamad*.

(Akkermans et al., 2014; Akkermans and Huigens, in press; Huigens, 2015) little or no attention has been given to (clustered) enclosures aside from major archaeological sites and other remains.

The common interpretation is thus that these clustered enclosures were primarily used by mobile pastoralists on a short-term or seasonal basis—either for domestic or herd-management purposes (e.g. Akkermans et al., 2014, p. 196; Betts et al., 2013, p. 186; Müller-Neuhof et al., 2013, p. 127; Rollefson, 2013, p. 215; Tarawneh and Abudanah, 2013, p. 239)—and that the sites seem to be commonly reused after their construction (e.g. Müller-Neuhof et al., 2013). This makes them particularly interesting for the investigation of a pastoral landscape that has been used by herders over the last eight to nine millennia. Their distributional pattern at a local and regional scale is expected to provide information on how mobile groups interacted with (a) the landscape and (b) each other. However, to interpret this distributional pattern further information on favored pastureland's, migration pattern, and social interactions need to be considered.

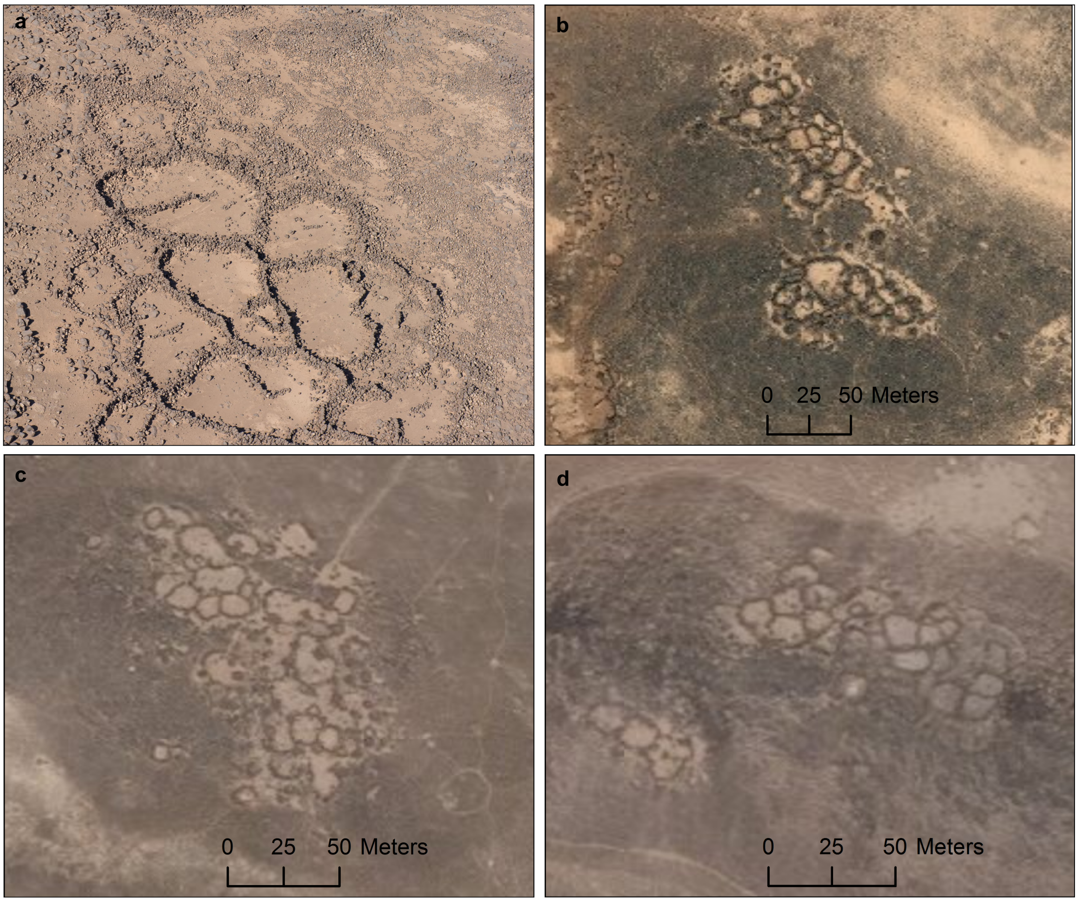

Figure 7.2.: 2a: Aerial photograph of clustered enclosures, ©*APAAME, Photo: APAAME_20120522_DDB-0374, by permission*; 2b, c, d: Satellite images of clustered enclosures, ©*Esri, Source: Esri, DigitalGlobe.*

Therefore, all clustered enclosure sites which are composed of more than two enclosure-like structures and that exceed a size of 20 meters in diameter were systematically recorded based on satellite imagery. The mapping focused on the basaltic *harra* since enclosures only rarely occur in the limestone desert of the *hamad*. In the *hamad* enclosures are predominantly linked to limestone outcrops and the constructions are usually smaller and lower than in the *harra* (Betts et al., 2013, p. 175). In order to investigate the absolute and relative spatial locations of the recorded enclosure sites in the *harra* their first- and second-order characteristics (O'Sullivan and Unwin, 2010, p. 124) are examined using distance and density based approaches of point pattern analyses by including geomorphometric and geomorphological site characteristics. The results of this spatial analysis are combined with available archaeological data and a review on traditional herding practices in northeastern Jordan. This investigation is a first attempt to investigate the spatial distribution of clustered enclosures throughout the area of the northeastern Jordanian *harra*. In this way it is intended to complement knowledge on the settlement history of the northeastern Jordanian desert, which is predominantly based on archaeological surveys focusing on small areas along the fringes of the *harra* (e.g. Akkermans et al., 2014; Akkermans and Huigens, in press; Betts et al., 2013; Rollefson et al., 2014a; Rowan et al., 2015a).

7.2. Study area

7.2.1. Regional setting

The northeastern part of Jordan, called northern Badia, is bounded by the Azraq basin and the current national borders of Syria, Iraq and Saudi Arabia. In the Middle East, the term Badia refers to 'badlands' (Rowan et al., 2015a, p. 176), an arid, desert environment with little or no vegetation cover, low precipitation rates and periodic surface water (Allison et al., 2000).

Climatically, the northern Badia is located in the transition zone between the Mediterranean environments along the Jordan valley and the fully arid zone of the Syrian Desert (Al-Homoud et al., 1996). Classified as hot desert climate (BWh; Kottek et al., 2006), the climate is characterized by marked seasonal variations, with hot, dry summers and cooler, moister winters (Allison et al., 2000). In the northwest of the study area average annual rainfall rates exceed 150 mm due to the westerly location and orographic effects at the Jebel Druze. Towards the south and east, rainfall rates decline, reaching less than 50 mm in the southern regions close to the border with Saudi Arabia (Tansey, 1999). Rainfall occurs mainly between November and March. The mean annual maximum temperatures reach 35°C to 38°C in summer and mean annual minimum temperatures range from 2°C to 9°C in winter (Allison et al., 2000). The mean annual temperature in Safawi is about 18.9°C (Meister et al., 2017). Strong winds occur frequently; during summer northwestern winds prevail, caused by troughs of the Indian Monsoon, and during winter the dominant direction is west/southwest due to cyclonic disturbances from the Mediterranean Sea (Al-Homoud et al., 1996).

The landscape is geologically divided into two main areas (Fig. 7.1): the *hamad* in the east, which is composed of Cretaceous to Tertiary limestone and covered by chert gravels (Bender, 1968, 1974); and in the west the northern Badia basalt plateau, called *harra*. The *harra* is part of the North Arabian Volcanic Province 'Harrat Ash Shaam' that extends from southern Syria to Saudi Arabia and consists of several Quaternary and Neogene volcanic basalt lava flows that extruded from widely spread volcanic centers (Allison et al., 2000; Bender, 1968; Taqieddin et al., 1995). Within the *harra* the relief declines gradually from north to south, with elevations ranging from around 1200 to 400 m asl (Al-Homoud et al., 1995; Allison et al., 2000). The topography is gently undulating and dominated by low hills; many slopes are slightly inclined and show a concavo-convex profile curvature (Al-Homoud et al., 1995). The distribution of the basalt flows and their age significantly determines surface topography, landform development and drainage network connectivity (Allison et al., 2000; Fig. 7.3). The channel network that drains the area is extensive with ephemeral discharge (Tansey, 1999). On the older basalt flows, the landscape is characterized by gentle surfaces and well-developed drainage patterns.

In contrast, the youngest basalt flows feature rugged topography with poorly linked surface drainage and many small silt-filled depressions (Al-Homoud et al., 1996; Allison et al., 2000). In the *harra* the underground is generally covered by basalt boulders of varying size and shape due to weathering of the volcanic rocks, forming extensive stone pavements (Allison et al., 2000). Fine-grained sediments occur in depressions, located between the basalt hills (Al-Homoud et al., 1996). These locally called 'Qa'a' are flat mudpans and similar to playas due to their endorheic character (Tansey, 1999); in contrast to most playa lake deposits (Schütt, 2004), sediments deposited in these mudpans of the Badia are seldom saline (Tansey, 1999). The largest qa'a depressions are located along the *harra/hamad* boundary, often extending over 10 km in length and 1 km in width (Bender, 1968). Besides, another geomorphological feature that is locally called 'marab' refers to depressions with a well-defined inflow and outflow, normally in the form of a wadi channel (Tansey, 1999).

Groundwater is available from three aquifers. The uppermost aquifer is located at depths of 450 to 50 meters below surface (Allison et al., 2000)—making it inaccessible to human communities until the most recent past (Dottridge and Abu Jaber, 1999).

The current soils are poorly developed (Al-Eisawì, 1996). The natural vegetation cover of northeastern Jordan belongs to the Saharo-Arabian plant region which is characterized by sparse vegetation consisting of grasses, herbs, and shrubs (Al-Eisawì, 1996). Vegetation growth is mostly restricted to qa'a, and wadi areas since these are flooded regularly during the winter rainy season and, thus, provide essential moisture reserves (Tansey, 1999). Within the last decades the vegetation cover of the region has been considerably reduced due to overgrazing (Roe, 2000) and the destruction of bushes and shrubs for fuel (Betts, 1998).

7.2.2. Occupation history and the development of mobile pastoralism in northeastern Jordan

Little is known about periods prior to the 10th millennium BCE regarding human activities in northeastern Jordan. Epipaleolithic occupation in the *harra* is documented by small scatters of microliths, small camps and knapping sites dating to the Geometric Kebaran and Natufian periods (Betts, 1993, p. 43). While there is little evidence for the Pre-Pottery Neolithic A period, hunting camps such as Dhuweila I and the construction of 'desert kites', used for the hunting of wild animals (Helms and Betts, 1987; Kempe and Al-Malabeh, 2013), are evidence for an expansion of hunting groups in the *harra* in the Late Pre-Pottery Neolithic B period towards the end of the 7th millennium BCE (Betts, 1993, p. 52).

Regarding the late prehistoric periods, there are a large number of archaeological sites and remains dating from the 7th to the late 4th millennia BCE, which indicate extensive human activities (cf. Akkermans et al., 2014; Betts et al., 2013; Müller-Neuhof, 2014b; Rollefson et al., 2014a; Rowan et al., 2015a) and a relatively large and rapid population increase, especially during the Late Neolithic (Rollefson et al., 2014a).

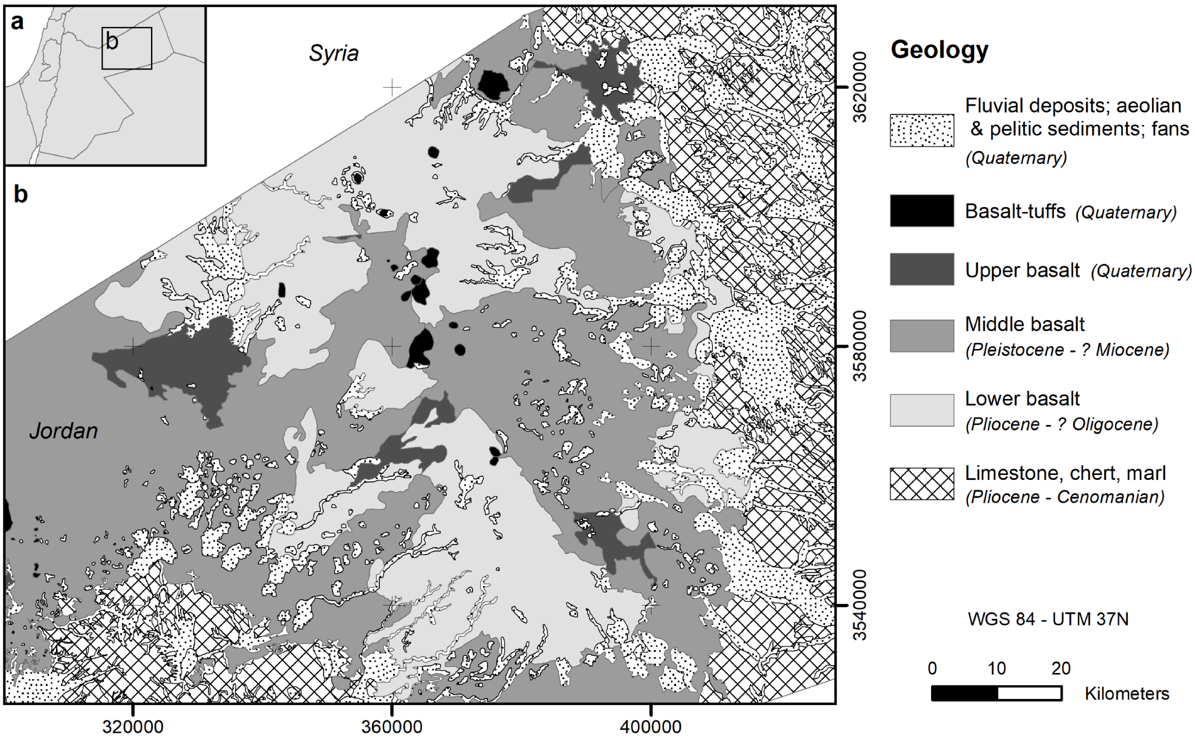

Figure 7.3.: Geological map of the *harra* and surrounding regions (scale: 1:250,000); modified after Bender et al. (1968).

Evidence for the first moves towards herding in eastern Jordan has been found at sites in al-Azraq (Azraq 31) and Wadi Jilat (Wadi Jilat 13/25), situated to the west of the *harra*, where Pre-Pottery Neolithic C/Early Late Neolithic seasonal camps of a hunter-forager-herder population show signs of domestic sheep and goats (Garrard et al., 1999, 1996; Martin, 1999). In northeastern Jordan, the Late Neolithic appears to be an intermediate stage representing a change from hunting to herding. The observation of an architectural shift from clustered room architecture to corrals with attached rooms around the Late Neolithic to Chalcolithic is interpreted as a change to a lifestyle prioritizing pastoralism, and probably reflects the gradual introduction of dairying (Betts et al., 2013, p. 189 ff.).

There is still an ongoing debate about exactly how specialized pastoral nomadism emerged in the region. Based on the investigation of relatively small Late Neolithic/Chalcolithic sites, such as Jebel Naja and sites in the Burqu' region (Fig. 7.1), Betts and her colleagues suggest a transitional subsistence strategy where local hunter-gatherers adopted domestic caprines; they assume once pastoralism was introduced it gradually grew in importance over time (Betts et al., 2013; Garrard et al., 1999; Martin, 1999). In contrast, Rollefson et al. (2014a) assume that the process of the emerging herder-hunter exploitation of the northern Badia during the Late Neolithic was more dynamic and marked by more interactions. Their ongoing research at Wisad Pools and the Wadi al-Qattafi mesas has provided evidence that the onset of mobile pastoralism in the *harra* can be dated to the Pre-Pottery Neolithic C/Early Late Neolithic by showing that during the 2nd half of the 7th millennium and the early 6th millennium considerable numbers of pastoralists probably already occupied the regions at Wisad Pools and the Wadi al-Qattafi mesas. Living in villages on a seasonal basis, the settlers relied to a great extent on hunting and seem to have practiced opportunistic agriculture as well as herding caprines (Rollefson et al., 2014a). Noting that nomadic pastoralism may have contributed to a population growth of the former hunter-gatherer groups, Rollefson et al. (2014a) argue that it seems much more likely that the Late Neolithic population was heavily composed of members of a farming population, who moved seasonally from farming areas such as 'Ain Ghazal' into the Badia in order to protect the resources of the arable land by removing the animals until the harvest was completed (see also Köhler-Rollefson, 1988, 1992). Since it is difficult "(. . .) to declare that the development of pastoral nomadism was either one or the other", probably both models are correct (Rollefson et al., 2014a, p. 15). Once mobile pastoralism was established as a reliable economic subsistence strategy in the Badia, there may have been interaction between these two arrangements and a subsequent social merging into one population (Rollefson et al., 2014a, p. 16).

The Chalcolithic/Early Bronze Age period has been investigated by Müller-Neuhof in extensive surveys in northeastern Jordan between 2010 and 2016, revealing abundant traces of socio-economic activities, such as the exploitation of large flint mines in the *hamad* (Müller-Neuhof, 2014b, 2013b, 2006, Fig. 7.1). In addition to the well-known Early Bronze Age settlement of Jawa (Betts, 1991; Helms, 1981; Müller-Neuhof et al., 2015), another two Chalcolithic/Early Bronze Age settlements, Tulul al-Ghusayn and Khirbet Abu al-Husayn, have been discovered, strongly suggesting the presence of permanent settlements in the *harra* during that period (Müller-Neuhof, 2014b, p. 238). The identification of terrace agricultural systems at Jawa (Meister et al., 2017; Müller-Neuhof, 2014a, 2012) and Tulul al-Ghusayn (Müller-Neuhof, 2014b) documents the application of an agropastoral subsistence strategy at these sites. Moreover, abundant indications of ancient pastoralism in the *harra* have been found by two transect surveys along a system of wadis and mudpans from the southeast to the northwest, and from the east to the west, where surface finds from about 200 sites, the majority of them clustered enclosures, were investigated. The finds indicate occupation phases during the Late Neolithic, the Chalcolithic/Early Bronze Age, the Roman/Byzantine period, the Umayyad, the Abbasid, the Mamluk, the Ayyubid, the later Islamic/Ottoman periods and modern times. While surface finds from the majority of these clustered enclosures suggest an initial occupation in the Chalcolithic/Early Bronze Age many of them were re-used in later periods, testifying the presence of herders at the same locations throughout (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013). Pastoral activities during the Chalcolithic/Early Bronze Age period, especially those producing secondary products (see also Sherratt, 1983), were probably linked to a medium-range exchange or trade network, connecting pastoral groups of the *harra* with societies in the more fertile region which may have relied upon the import of animal products (Müller-Neuhof, 2014b, p. 246).

For post-Early Bronze Age periods there is little evidence for human activities until the Safaitic period (Rollefson et al., 2014a, p. 196; cf. Huigens, 2015; Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013). For the Safaitic period, dating from the 1st century BCE to the 4th century CE (Betts et al., 2013), an extensive collection of Safaitic rock inscriptions provides evidence for abundant activities by mobile pastoralists (Macdonald, 1993, 1992, 1983, 1982). The vast majority of these inscriptions have been found in the *harra* of southern Syria and northeastern Jordan and the *harra* and *hamad* of northern Saudi Arabia. From a total of 18,000 inscriptions (identified by 1993) more than 12,000 were found in northeastern Jordan (Macdonald, 1993, p. 304). In addition to the description of pastoral practices and seasonal migration routes (Macdonald, 1993), they also document the rise of camel pastoralism by the 1st century BCE, which might also have increased the trading possibilities on a supra-regional scale (Betts et al., 2013, p. 189) and the number of sheep and goats in the *harra* due to the use of camels as water carriers (Lancaster and Lancaster, 1991, p. 132). Since the references to camels exceed those to sheep and goats within the inscriptions, it is supposed that the herders were predominantly camel-breeders. Nonetheless, it is reasonable to assume that some groups were specialized in sheep and goat herding and that others were mixed pastoralists (Macdonald, 1993, p. 319).

According to the survey results of the Jebel Qurma Archaeological Landscape Project in the Jebel Qurma region, the occupation history during the Late Antiquity is divided in phases with very high human activity and phases with very low human activity (Akkermans and Huigens, in press). After a phase of local habitation roughly dating from the 2nd century BCE to the 8th century CE (as indicated from campsites, tombs and rock art), there was a period of local abandonment until the late 13th to 14th century Mamluk epoch (as indicated from campsites and Arabic inscriptions). The short-lived Mamluk period was followed by another local abandonment between the 15th to the late 19th or even the early 20th century. From that time human activity in the Jebel Qurma region significantly increased before it declined again at the beginning of the 21st century (Akkermans and Huigens, in press).

7.2.3. Traditional herding practices in the northern Badia

The current population of the northern Badia belongs almost exclusively to the 'Ahl al-Jebel' Bedouin tribe that has resided on the southwestern foothills of the Jebel Druze and within the area of the *harra* and the *hamad* for a long time, as documented by oral history and available documents (Roe, 2000, p. 63). Traditionally, these herders of goats and sheep follow a common pattern of annual migration in the northern Badia involving two constituent movements which are described as 'al tashreeq' ('the easting') and 'al taghreeb' ('the westing') (Roe, 2000, p. 56; Fig. 7.1). During *al tashreeq* in late autumn (late October and early November) the

Bedouins traditionally move rapidly east towards the *hamad* plains where they scatter across the desert-steppe during the winter and spring months, following the rainfall and resulting plant growth patterns (Betts, 1998; Roe, 2000). By late spring (from late February onwards), as these pastures are grazed out, *al taghreeb* starts, corresponding to a slow westerly movement back into the *harra* where, owing to the shading of boulder cover and general inaccessibility, perennial plants can be found locally (Roe, 2000). The movement ends at the fringes of the desert steppe and the settled areas where the herders are based during the summer (Betts, 1998). In order to prevent an early over-exploitation of grazing lands around water sources the herders usually postpone their return to the summer residence sites for as long as possible (Roe, 2000). Traditional summer residence sites in the Badia include the Azraq oasis and its outlying springs, and the southern foothills of the Jebel Druze. Here, the pastoralists co-reside with sedentary agrarian communities, exchanging pastoral products for goods they require (Roe, 2000). Generally, migration patterns are spatially and temporally variable and depend on the availability of water and rainfed pastures, factors which can vary greatly from year to year (Betts, 1998).

The migration cycle described above was roughly followed until the 1980s (Roe, 2000, p. 84). Since that time pastoral production in Jordan has altered significantly (Roe, 2000), mainly caused by changes in herding and settlement practices, political borders, increases in population and a greater demand for meat and dairy products (Tansey, 1999). As a result, the pastoral system has become monetized, market-oriented and the overall numbers of animals have increased considerably (Al-Tabini et al., 2012; Roe, 2000).

7.3. Material and methods

7.3.1. Clustered enclosures mapping

Satellite data were used in order to map the clustered enclosures in the study area, covering in total c. 10,000 km^2. The sites were systematically recorded from satellite images applying the World Imagery web service of *Esri* using *ArcMAP* (v. 10.0). This service provides about one-meter high-resolution satellite imagery for Jordan. Site mapping was conducted on a dataset updated on 17th March 2016 for a fixed scale of 1:8000. To avoid the mapping of other enclosure-like structures, such as dwellings (cf. Rollefson et al., 2014a), small (hunting) camps (cf. Betts, 1998) or single/double enclosures associated with desert kites (cf. Helms and Betts, 1987; Kempe and Al-Malabeh, 2013), only sites with more than two enclosure-like clustered structures and a minimum site size of 20 meters in diameter were recorded. Potential 'wheels' were recorded when they were characterized by clustered enclosures, fulfilling the criteria described above.

Mapping was confined to the area of the basaltic *harra* due to the restricted detectability of clustered enclosures in the *hamad*. The research area is delimited to the east by the transition to the limestone plateau of the *hamad* and to the south by a cover of aeolian sediments. The northern boundary is set artificially, including parts of southern Syria. The western boundary is determined by the change towards limestone bedrock in the south and modern agriculture and settlement activities in the north.

7.3.2. Data processing, remote sensing and geomorphometric approaches

In order to investigate possible relationships between locations of clustered enclosures and their environmental conditions, geological maps (scale of 1:250,000; sheets: El Azraq, Mahattat el Jufur; source: Bender et al., 1968) were digitized (Fig. 7.3). Additionally, geological features on a smaller scale were identified by applying band ratios after Inzana et al. (2003), using three scenes of Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), recorded in June/July 2015 (available from http://glovis.usgs.gov/). To identify areas of fine-grained deposits the Landsat band ratio SWIR1/NIR*red/NIR was used to discriminate mafic from non-mafic rocks (Inzana et al., 2003, Table 7.1). The band rationed image corresponds well with geologic maps of the area showing different basalt flows, fluvial deposits and limestones. To extract the mudpan and wadi deposits (subsequently recapped as 'mudpan class') from other geological units the transformed multispectral image was classified by applying a supervised random forest classification after Breiman (2001). The required training and test datasets were digitized using ten polygons for the total of nine identified classes corresponding to the geological basic information. Each polygon was filled with 20 randomly distributed points, ten as training data and ten as test data. A total number of 200 trees were selected using expert knowledge based on variogram analysis. The calculations were conducted in R using the package *randomForest* (Liaw, 2015; Liaw and Wiener, 2002). With an overall accuracy of 96.5 %, the Random Forest classifier performed well. With a user's accuracy of the mudpan class of 91.9 %, representing the fraction of correctly classified pixels with regard to all pixels of that ground truth class, the classification result is reasonably reliable.

The GRASS r.watershed module (Metz et al., 2011) was applied using elevation data from the Shuttle Radar Topography Mission (SRTM) 1 (resolution: 30 m * 30 m, available at http://earthexplorer.usgs.gov/) to delineate catchments and channel networks. In order to determine the distance from pastoral sites to the closest potential periodic water source the spatial information on the occurrence of 'mudpans', as deduced from satellite images, and to 'river channels', as derived from the morphometric analysis of the digital elevation model, were merged. After reclassification, a raster of the cumulative distance from mudpan/river pixels was created using the *gridDistance* function of the *raster*–package (Hijmans, 2015). The 'clustered enclosures to water source' distance was extracted by using the *extract* function of the same package.

Table 7.1.: Band designations for the Landsat TM and OLI/TIRS satellites. Since the band designations differ between Inzana et al. (2003; Landsat 4/5) and the present study, the Landsat 8 bands with the most similar wavelength characteristics were selected.

Landsat 4/5 TM		Landsat 8 OLI/TIRS	
Band	**Wavelength (µm)**	**Band**	**Wavelength (µm)**
3	0.63 - 0.69	4 (red)	0.64 - 0.67
4	0.76 - 0.90	5 (NIR)	0.85 - 0.88
5	1.55 - 1.75	6 (SWIR 1)	1.57 - 1.65

7.3.3. Spatial point pattern analyses

In order to determine the processes that affected the spatial distribution of clustered enclosures within the study area spatial point pattern analyses were carried out. A spatial point pattern consists of locations of a set of point objects, representing the simplest possible spatial data (O'Sullivan and Unwin, 2010, p. 121; Nakoinz and Knitter, 2016, p. 129-131). Point pattern analyses focus on the spatial distribution of known events and aim to identify the factors controlling the processes that generated them (e.g. Bivand et al., 2013, p. 178). Emphasis was put on the analysis of (1) the distribution of clustered enclosures in space, i.e. their absolute location, and (2) potential interactions between clustered enclosures, i.e. their relative location (see O'Sullivan and Unwin, 2010, p. 124).

Based on the analysis of the clustered enclosures, i.e. their spatial distribution, first- and second-order effects were traced (O'Sullivan and Unwin, 2010). First-order effects describe the locations of points and the influence of different parameters (covariates) on point locations. This is assessed by investigating the intensity of events within the region, i.e. their density distribution. In contrast, second-order effects are present when the occurrence of points is influenced by the occurrence of other points; this effect is analyzed using distance-based approaches (O'Sullivan and Unwin, 2010).

In cases where the distribution of known events is independent from site-related factors and regional characteristics, e.g. the distances to river channels and mudpans or bedrock characteristics, complete spatial randomness (CSR) prevails. The mathematical representation of CSR is the homogeneous Poisson process that assumes a constant intensity function. In contrast, an inhomogeneous Poisson distribution assumes that the intensity varies from place to place (Bivand et al., 2008; for detailed descriptions on method and theory see Baddeley et al., 2015; Diggle, 2013).

7.3.3.1. Density based analyses of clustered enclosures

Kernel density estimation: In order to detect first-order effects and obtain information about the spatial density of the clustered enclosures their intensity functions were assessed using kernel density estimations (KDE). This enabled a differentiation between high and low-density areas to be made. The resulting intensity surface depends strongly on kernel type and its bandwidth (for a more detailed description see Bivand et al., 2008; Nakoinz and Knitter, 2016). In this study, an isotropic Gaussian probability density kernel was applied (Baddeley et al., 2015, pp. 168-170). The bandwidth of the kernel determines the level of smoothing; small values produce very tapered surfaces, while large values produce very smooth functions (Bivand et al., 2008). To determine the appropriate empirical kernel bandwidth the likelihood cross-validation approach was used, which assumes an inhomogeneous Poisson distribution (Baddeley et al., 2015, p. 171). Depending on the data the optimal bandwidth can also be selected by experiments and based on expert knowledge (Bivand et al., 2008; Nakoinz and Knitter, 2016). In line with this and to obtain information on the general data trend a large bandwidth was additionally selected. The calculations were conducted applying the software *R* using the *density* function of the *spatstat*-package (Baddeley et al., 2016; Baddeley and Turner, 2005; details on the method: Baddeley et al., 2015).

The density of clustered enclosures as a function of a covariate: In order to identify whether the density of clustered enclosures is influenced by the water availability, i.e. whether first-order effects prevail, their spatial relation to the 'distance to river channels and mudpans' was analyzed. However, since natural springs and lava tubes are largely unknown and near surface groundwater aquifers are absent these factors were not integrated into the analyses. The calculations were conducted in *R* using the spatstat function *rhohat* with a bandwidth of 100 m (see Baddeley et al., 2015, pp. 179-180). The resulting covariate function was used to predict a density raster that mirrors dependence on the covariate. This raster was subtracted from the empirical density of the clustered enclosures in order to identify areas where the dependence of the covariate is strong or weak.

7.3.3.2. Distance based analyses of clustered enclosures

In order to identify an interaction between the recorded sites three types of analyses, namely the G, F and K functions, were conducted. These functions demonstrate whether the interactions lead to an aggregated or regular pattern of clustered enclosures (Diggle, 2013). The resulting empirical distributions of G, F and K functions are compared to two theoretical models that assume independence: (1) a homogeneous Poisson distribution, and (2) an inhomogeneous Poisson distribution, considering the influence of a covariate, e.g. water availability.

The G function is the cumulative frequency distribution of the nearest-neighbor distances (O'Sullivan and Unwin, 2010, p. 132). The F function is the cumulative frequency distribution function of the nearest-neighbor distance between locations where points occur and locations where no points occur. The non-point locations are selected at random and their nearest-neighbor distance to a known point is determined (O'Sullivan and Unwin, 2010, p. 133). Since the F function is a measure of the space left between points it is also called the empty-space function (see Baddeley et al., 2015, p. 264).

A shortcoming of the G and F functions, especially in clustered point patterns, is that they only use nearest-neighbor distances (Bivand et al., 2008; Nakoinz and Knitter, 2016). Therefore, the K function was additionally applied, also known as Ripley's K (Ripley, 2004). The K function measures the fraction of all points found within a given distance by drawing circles with increasing radii around points (Bivand et al., 2013, p. 191).

The calculations of the G, F, and K functions were conducted applying the software package *R* using the appropriate functions provided by the *spatstat*–package (Baddeley and Turner, 2005). More detailed method descriptions of the applied functions are given e.g. by Baddeley et al. (2015); Bivand et al. (2013); Diggle (2013); O'Sullivan and Unwin (2010).

7.3.4. Frequency distribution of clustered enclosures within different geological units

In order to investigate the frequency distribution of clustered enclosures within different geological units, the area of each geological unit and the number of clustered enclosures per geological unit was calculated for the Jordanian part of the study area in *R* using the *gArea* and *poly.counts* functions provided by the *rgeos* and *GisTools*—packages (Bivand and Rundel, 2016; Brunsdon and Chen, 2016). The geological units were differentiated according to petrographic (e.g. limestone, basalt) and stratigraphic characteristics (e.g. different basalt flows) based on the geological maps (Bender et al., 1968).

7.4. Results

7.4.1. Clustered enclosures

Altogether, 9118 clustered enclosures were localized, digitized and geocoded for an area of about 10,000 km^2 based on satellite imagery (Fig. 7.4a). The recorded sites consist of groups of enclosures of varying shapes and sizes. The majority of enclosures were oval or circular; others were roughly rectangular. The larger structures were often associated with smaller oval structures (cf. Fig. 7.2b-d). The number of enclosures in a cluster varies between 3 to over 30. The resulting sizes of the clustered enclosures of round to oval shape range from over 20 meters to about 250 meters in diameter.

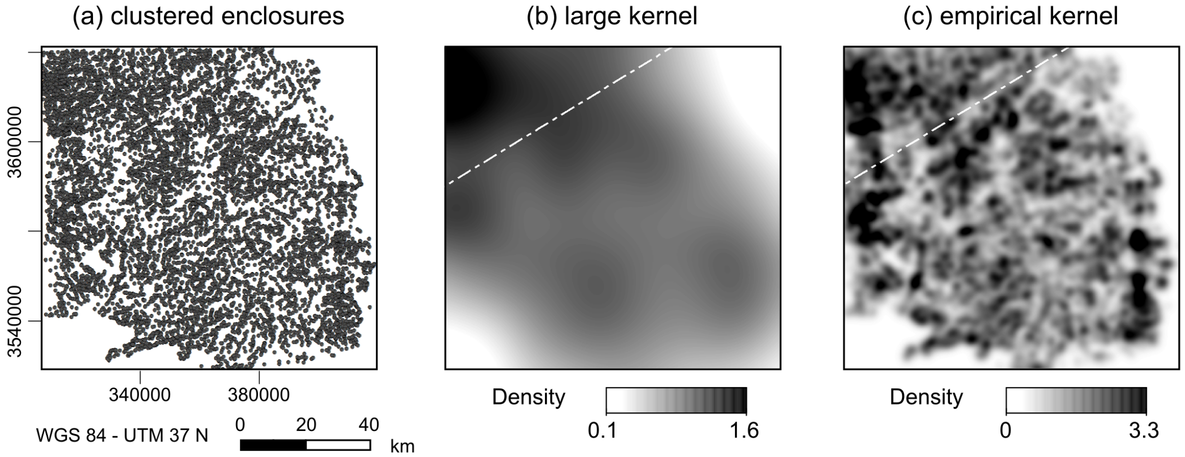

Figure 7.4.: 4a: Location of clustered enclosures in the *harra* of northeastern Jordan recorded from satellite images; 4b, c: Kernel density estimations of clustered enclosures calculated with a large kernel (b; k=10 km) and an empirical kernel (c; k=1314 m); density values correspond to clustered enclosures per square kilometer; different absolute values result from the kernel weighting process; the state border to Syria is illustrated by a white dashed line.

7.4.2. Density based analyses of clustered enclosures

The spatial distribution of clustered enclosures in the study area shows an overall high density with an average of about one clustered enclosure site per square kilometer (Fig. 7.4a). Elongated, corridor like zones can be observed that, however, lack a predominant direction. In contrast, the results of the kernel density estimation indicate different density patterns: the large kernel with a bandwidth of 10,000 m (Fig. 7.4b) indicates a general trend with decreasing intensity from northwest to southeast. The empirical kernel with a size of 1314 m that results from the likelihood cross-validation approach reveals areas of high density in the northwest and the southeast but also along the southern edge of the state border to Syria (Fig. 7.4c). Zones of moderate density stretch throughout the region, although they mostly surround areas of high density. Between areas of high and moderate density, zones of low density occur frequently. The low-density areas in the south and east coincide with geologic transitions, and thus reflect the methodological issue of mapping enclosures in areas where the bedrock is formed by limestone or covered by aeolian sediments.

The occurrence of clustered enclosures in the harra is strongly related to the presence of river channels or mudpans; highest densities of clustered enclosures can be observed at distances between 0 and 200 m from periodic water sources (Fig. 7.5). Comparing the empirical density distribution (Fig. 7.4c) with a predicted spatial density distribution that is based on the distances to periodic water sources, it can be recognized that (1) a correspondence between areas of moderate density of clustered enclosures and the density distribution is exclusively influenced by distance to water sources; (2) a deviation from this general rule appears in areas of high empirical density of clustered enclosures, e.g. the surroundings of the Chalcolithic/Early Bronze Age settlements of Jawa and Khirbet Abu al-Husayn (Fig. 7.6). Negative values occur in areas of zero empirical density of clustered enclosures, although the distance to periodic water sources is given.

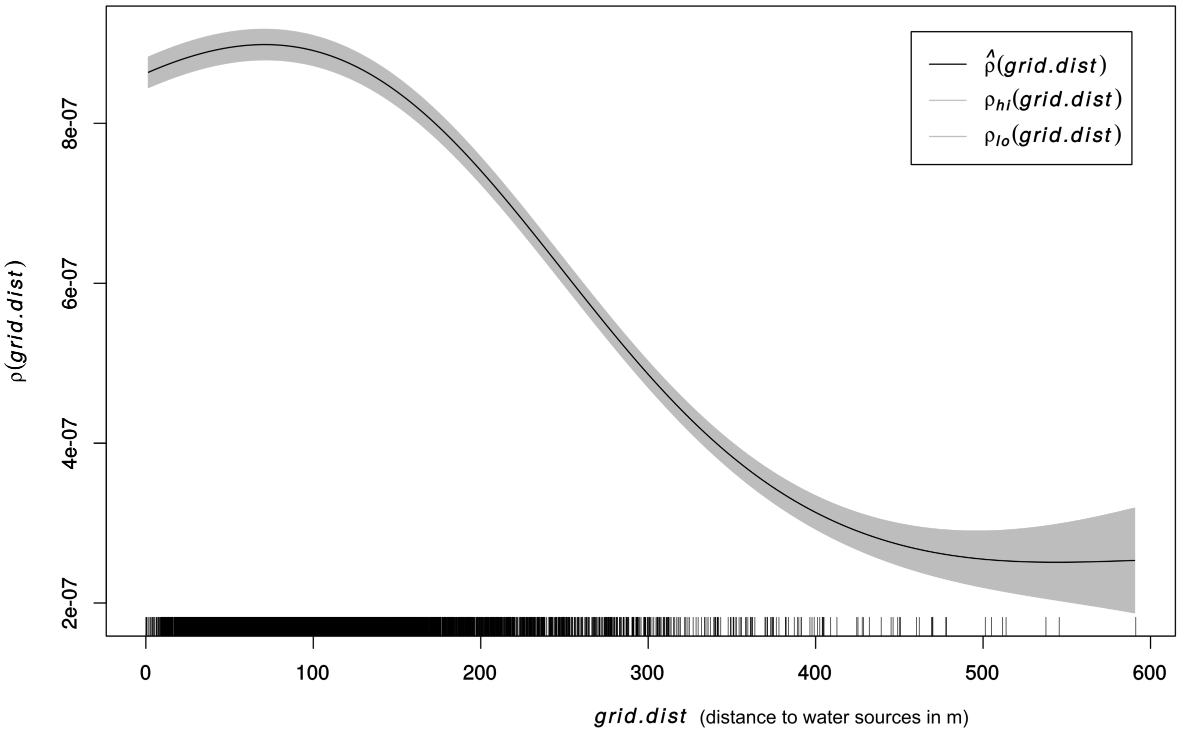

Figure 7.5.: Intensity as a function of distance to river channels and mudpans for the clustered enclosures. The solid line shows the function estimate together with the 95 % confidence bands assuming an inhomogeneous Poisson point process (Baddeley et al., 2015, p. 180).

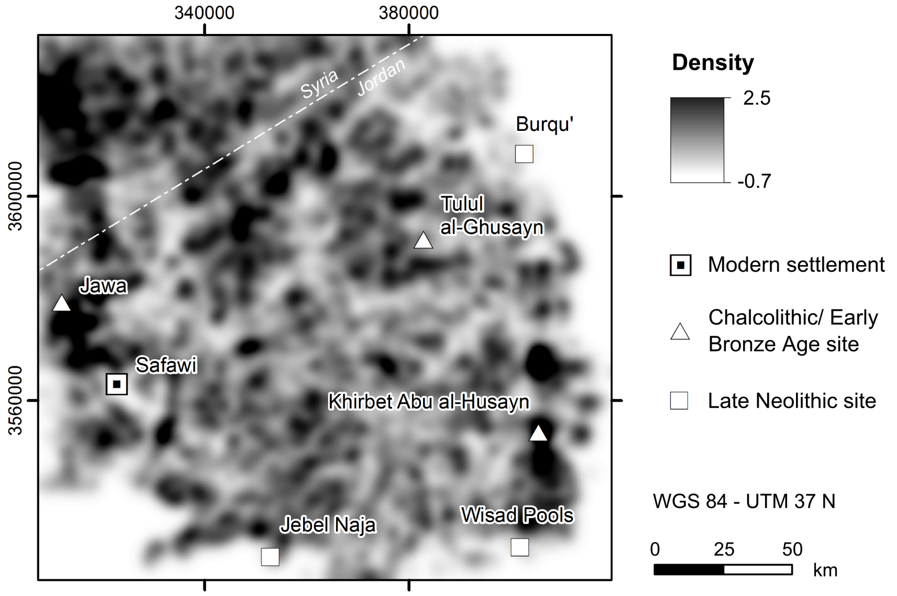

Figure 7.6.: Intensity function estimate for the covariate 'distance to river channels or mudpans' compared to the empirical distribution; density values correspond to clustered enclosures per square kilometer. Resulting values around 0 indicate that the density of clustered enclosures is a function of the covariate while areas with positive values indicate that the covariate is not able to completely explain the intensity of the observed sites.

7.4.3. Distance based analyses of clustered enclosures

The results of the G, F and K functions provide a homogeneous picture: the empirical distributions deviate from the theoretical distributions. The results of the G function calculations illustrate that clustered enclosures have their nearest neighbor at shorter distances (at distances over 100 m) than expected by the theoretical model. This holds true for the homogeneous as well as the inhomogeneous Poisson distribution and indicates an aggregation of clustered enclosures (Fig. 7.7). The results of the F function calculations show a reverse pattern: the amount of nearest neighbors between arbitrary points and clustered enclosures is smaller than expected by the homogeneous as well as inhomogeneous theoretical models (Fig. 7.8). This indicates empty spaces and thus an aggregation of clustered enclosures. The results of the K function show strong positive deviations from the theoretical models at very small distances ($<$ 50 m) and at distances between 100 and 1000 m with a maximum at about 200 m; between these positive deviations, which are indicative of an aggregation of clustered enclosures, there is a small negative deviation at 80 m (Fig. 7.9).

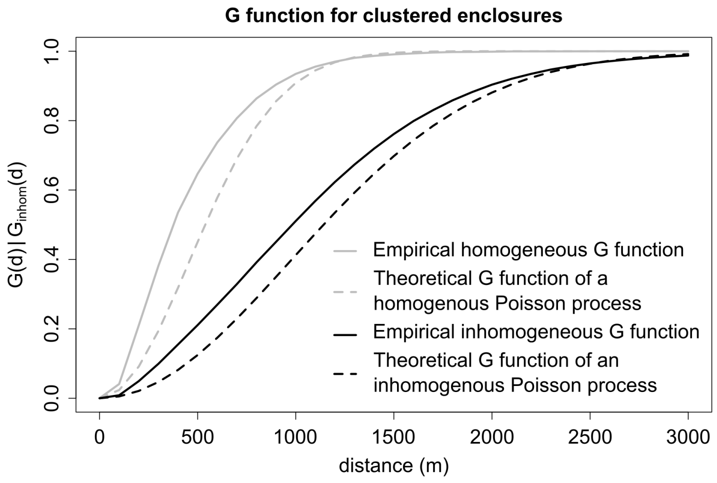

Figure 7.7.: Results of the nearest-neighbor based G functions for clustered enclosures in northeastern Jordan. The homogeneous and the inhomogeneous G functions show deviation from the theoretical models and illustrate that the distribution of clustered enclosures is aggregated.

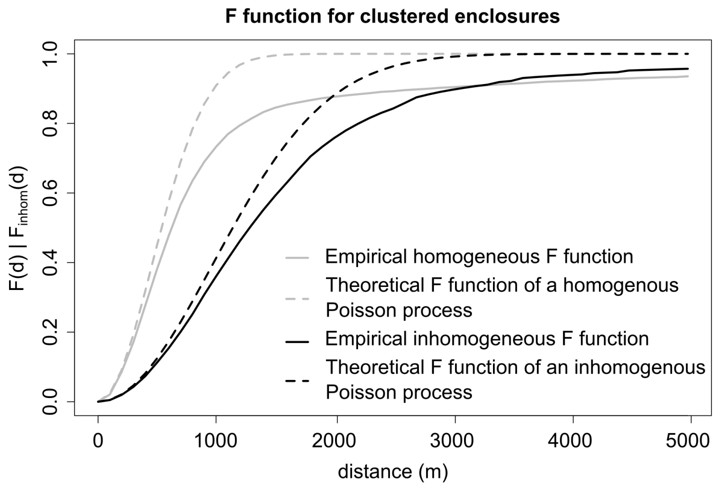

Figure 7.8.: Results of the nearest-neighbor based F functions for clustered enclosures in northeastern Jordan. The homogeneous and the inhomogeneous F functions show deviation from the theoretical models and illustrate that the distribution of clustered enclosures is aggregated.

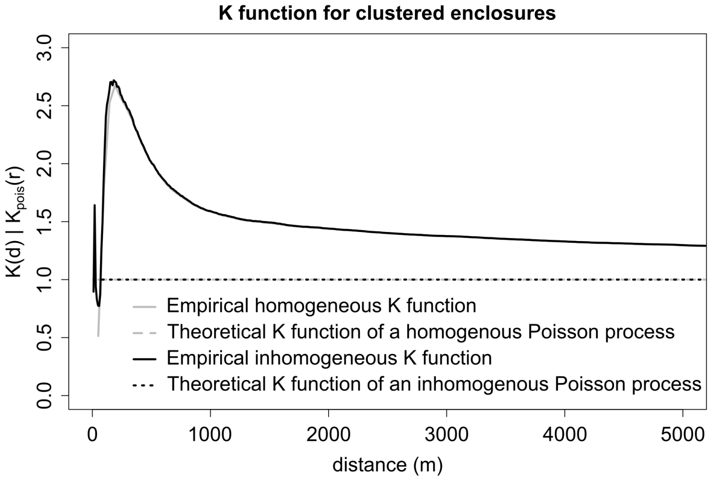

Figure 7.9.: Empirical K functions for clustered enclosures in northeastern Jordan. The homogeneous and the inhomogeneous K functions show deviation from the theoretical models and illustrate that the distribution of clustered enclosures is aggregated.

7.4.4. Distribution of clustered enclosures within geological units

The clustered enclosures-to-area ratio for different geological units of the Jordanian part of the study area shows that the number of clustered enclosures found within the lower and middle basalt flows (B4, B5) is proportional to the areal extent of these units (Fig. 7.10). In relation to the areal extent, fewer clustered enclosures are found within areas underlain by the youngest basalt flows and tuffs (B6; B't), different Quaternary deposits (q3-q4), limestone, marl, conglomerate and sandstone (q2, tt1, tt2, tt4). In contrast, areas comprised of Quaternary fluvial deposits, aeolian deposits and mantle rocks (q5) show disproportionally high numbers of clustered enclosures relative to their areal extents.

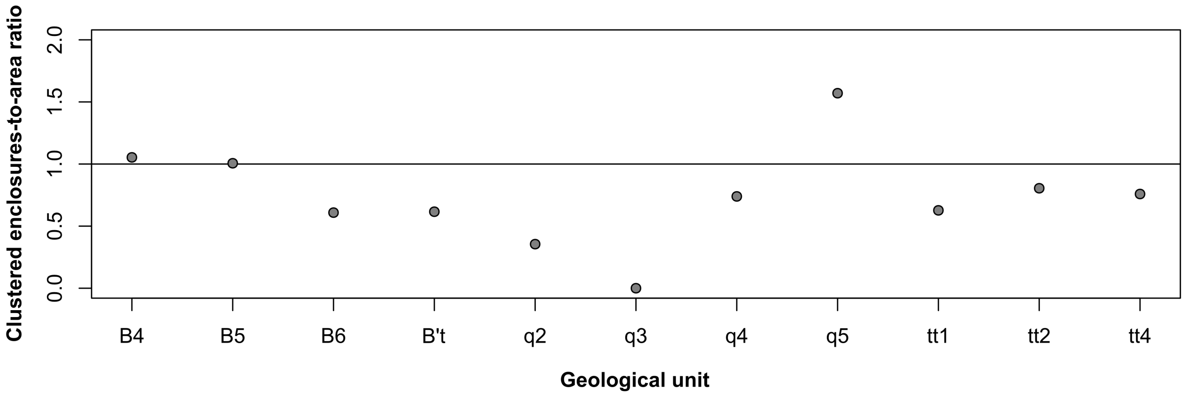

Figure 7.10.: Clustered enclosures-to-area ratio for different geological units of the Jordanian part of the study area based on geological maps (scale = 1:250.000; Bender et al., 1968). The value 1.0 corresponds to the relative amount of clustered enclosures in relation to the relative area of the specific geological unit. The number of clustered enclosures within the Jordanian study area is 7150.
(B4 = Pliocene to ? Oligocene lower basalt flows; B5 = Pleistocene to ? Miocene middle basalt flows; B6 = Quaternary upper basalt flows; B't = Quaternary basalt-tuffs; q2 = Pleistocene lacustrine limestone, sandy marls; q3 = Quaternary fans; q4 = Quaternary pelitic sediments in mudflats; q5 = Quaternary fluvial deposits, aeolian deposits, mantle rocks; tt1, tt2 = Eocene to Paleocene limestones with chert, marls; tt4 = Pliocene to ? Oligocene sandy limestones, conglomerates, white marls with cherts).

7.5. Discussion

In the archeological records of the Badia, clustered enclosures are described as seasonal camps of pastoral groups used for domestic activities and penning flocks (e.g. Akkermans et al., 2014, p. 196; Betts et al., 2013, p. 186; Müller-Neuhof et al., 2013, p. 127; Rollefson, 2013, p. 215; Tarawneh and Abudanah, 2013, p. 239). This interpretation is deduced from the utilization of enclosures by modern Bedouins. The following discussion and conclusions are based on this assumption, although alternative usages of these sites cannot be ruled out. Whether the sites were used only on a short-term seasonal basis or whether they may have been used for an extended period remains uncertain.

The sheer number of 9118 recorded clustered enclosures indicates that the *harra* was extensively used by mobile groups in the past (Fig. 7.11). Their distribution demonstrates that pastoral activity covered the whole area and was by no means restricted to the fringes of the *harra*. The observed differences in site sizes and numbers of associated enclosures within a cluster might be linked to variations in the herd numbers kept inside the enclosures and varying numbers of occupants (Tarawneh and Abudanah, 2013, p. 241). As only enclosure sites larger than 20 m in diameter were recorded it should be noted that the number of smaller enclosure sites remains unclear. Due to the absence of extensive archaeological surveys and excavations there is no chronology of the recorded sites.

Based on the clustered enclosures recorded here, there are multiple factors that influence location (Fig. 7.11). One important factor is the regional distribution of rainfall. As the rainfall rates in the *harra* gradually increase from the southeast to the northwest (Tansey, 1999), caused by the orographic effects of the Jebel Druze, high-density areas of clustered enclosures in the northwest reflect the increased value of this region for pastoral communities.

Furthermore, the locations of clustered enclosures within the *harra* are related to the hydrological characteristics of the different geological and geomorphological units. Especially the older basalt flows, characterized by well to moderately developed stream networks (Al-Homoud et al., 1996; Allison et al., 2000) appear to be preferred for building clustered enclosures and, thus, for pastoral use. In contrast, areas underlain by younger basalt flows and tuffs have poorly developed surface drainage with only a few larger streams and overall rugged topography (Al-Homoud et al., 1996; Allison et al., 2000). Due to the lack of concentrated runoff these areas were less frequently visited by mobile pastoralists.

Probably the most important factor is the distance of clustered enclosures to periodic water sources or water bodies. Distances to river channels and mudpans of up to 200 m seem to be particularly favorable for the construction of clustered enclosures (Fig. 7.5). The availability of water in these storage bodies secures water availability and, thus, extends the grazing period after the rainy season. This spatial connection additionally supports the assumption that clustered enclosures were primarily used by pastoral groups (cf. Akkermans et al., 2014; Müller-Neuhof, 2014b).

Another factor that influences the location of high-density areas of clustered enclosures in particular is the overall size of mudpans. The size of the mudpan is usually directly related to the amount of water that can be stored in it, which in turn is positively related to the duration of water availability during the dry season. This applies e.g. for the Qa'a Shubayka located about 25 km east of Jawa and the Qa'a Abu al-Husayn along the southeastern border of the *harra* (Fig. 7.3; Fig. 7.6). Both mudpans cover an area of several square kilometers and are periodically filled up during the winter rainy season. According to the observed high density of clustered enclosures in their close vicinity, these large mudpans seem to have been a center of attraction for pastoralists and their livestock.

However, the Burqu' region (Fig. 7.1), located along the northeastern margin of the *harra*, is characterized by a considerably lower density of clustered enclosures compared to the shore areas of Qa'a Abu al-Husayn and Qa'a Shubayka. This is surprising as the Burqu' region is characterized by a high number of mudpans and river channels. Moreover the 'lake' at Qasr Burqu' was artificially enhanced by ancient dams and is still in use today, including the use of modern dams (Betts et al., 1991). Thus, the 'lake' at Qasr Burqu' must always have been an important water source (Betts et al., 1991), demonstrated also by the fact that the area has been regularly settled since the earliest times (Betts, 1990, p. 471). This shows that an interpretation that solely considers hydrological characteristics is insufficient.

One factor that helps to provide a more comprehensive understanding of the regional density distribution of clustered enclosures is the traditional migration cycle of the Ahl al-Jebel tribe as described by Roe (2000). According to this, the herders pass the region around the Qa'a

Abu al-Husayn on their way to the *hamad* in early winter, at the beginning of the rainy season. Water resources provided by the Qa'a Abu al-Husayn and neighboring mudpans were used extensively, complementing the food supply of the grazing land – probably extending the utilization period and, thus, increasing the numbers of clustered enclosures. In contrast, the Burqu' region is visited by the herders in late spring. At this time the *hamad* is already grazed out (Roe, 2000), a fact which probably prevents a longer stay in this area. Moreover, in the *harra* annual plants still provide fodder on the grazing grounds. A subsequent slower westward movement (Roe, 2000), passing the Qa'a Shubayka, would also explain why there are more high-density areas of clustered enclosures in the northern regions of the *harra* than in the south (Fig. 7.6). The fast eastern movement towards the *hamad* in early winter (Roe, 2000) is probably related to poor grazing grounds in the *harra* at that time.

The traditional practice of herders of the Ahl al-Jebel tribe to follow a seasonal migration cycle in the northern Badia is indicative of the herders' fundamental understanding of the regional environmental setting and its dynamics. This is also illustrated by a vast indigenous terminology, e.g. for features associated with water availability and storage (Lancaster and Lancaster, 1997, p. 372). The targeted utilization of the *harra* and the *hamad* considered the availability and efficient use of water and vegetation as well as the susceptibility to over-exploit pastures. Following this kind of migration cycle allowed the flora to recover (Roe, 2000) and probably enabled the sustainable exploitation of the region over long periods.

Given the depth of knowledge of the landscape (Lancaster and Lancaster, 1997), the length of time herders have been living there – stretching back over 8 to 9 thousand years e.g. (cf. Betts et al., 2013; Rollefson et al., 2014a; Müller-Neuhof, 2014b) – and the observation that this traditional migration cycle corresponds well with the overall distributional pattern of the recorded clustered enclosures, we assume that pastoralists might have followed similar migration patterns in earlier times. At least under climatic conditions similar to those of today, mobility in herd management – characterized by a seasonal movement into the *harra* and the *hamad* in winter and spring, and to areas with permanent water supply in summer – is essential to meet the requirements of the flocks (Betts and Russell, 2000, p. 31). However, "pastoral nomadic systems over the longue durée reflect a deep and complex dynamic of social and ecological adaptation" (Rosen, 2008, p. 115). Hence, differences in the social and economic structure have certainly influenced pastoral movements over time (Betts and Russell, 2000, p. 32).

The mobility model of the Ahl al-Jebel tribe is supported by Safaitic inscriptions (1st century BCE – 4th century CE). These written sources describe nomads moving to the fringe of the *harra* by the end of the dry season and camping in areas with periodic water resources (Macdonald, 1992, p. 9ff.). The nomads waited there for the first rains of the rainy season. After the onset of the rainy season herders migrated to the inner desert of the *hamad* to the east or south of the *harra* for the winter and spring. In dry years many of the nomads stayed along the fringe of the desert or spent these seasons in the *harra* close to reliable water resources. In early summer they most likely returned to the *harra* searching for water and grazing areas close to the places where they had spent the dry season, before starting the next migration cycle (Macdonald, 1992, p. 9ff.).

Besides this specific form of subsistence economy, there might be other factors influencing the pastoral movement and the observed pattern of clustered enclosures. On a supra-regional level, one such factor is the introduction of camel-herding within the first millennium BCE, which enhanced trading activity throughout the Arabian Peninsula and caused an upswing of nomadic tribes (Betts and Russell, 2000, p. 32). Moreover, there may have been interactions between different great tribes and their cycles of migration. For example, the camel herders of the Rwala and associated tribes traditionally spent their summers in Syria, Iraq or oases in Saudi Arabia, preferentially migrated through the *hamad* of northeastern Jordanian in autumn or spring, and stayed in Saudi Arabia during winter (Lancaster and Lancaster, 1997, p. 368).

On a regional level, it is also known that early food producing strategies usually involved a mixture of subsistence options and resource exploitation (Betts and Russell, 2000, p. 24). For the Chalcolithic/Early Bronze Age period, for example, surveys in northeastern Jordan have revealed abundant traces of socio-economic activities that are best described as indicating a multi-resource economy based on agriculture, pastoralism and (flint) mining (Müller-Neuhof, 2014b). This is mirrored by the first permanently settled, fortified C/EBA archaeological sites of Jawa (Helms, 1981), Tulul al-Ghusayn, Khirbet Abu al-Husayn (Müller-Neuhof, 2014b) and Khirbet al-Ja'bariya (Müller-Neuhof and Abu-Azizeh, 2016) which relied at least partly on herding. They are mainly located in areas with high densities of clustered enclosures, indicating increased interactions in the environs of these archaeological settlements and highlighting their potential function as economic centers, preconditioned of a similar age of these structures, which is not proven yet. It remains unclear whether some clustered enclosures were related to the semi-nomadic herding activities of the agro-pastoral settlers themselves (e.g. as part of the subsistence strategy) and also whether others were linked to nomadic herding groups who were attracted by the settlements (e.g. for trading purposes). All in all, interactions between the nomadic and sedentary groups in the Chalcolithic/Early Bronze Age can be presumed, which also incorporate supra-regional contacts in the Middle East especially in the 4th millennium BCE. These contacts stretched from the Levantine coast in the west via the northern Badia to the Euphrates and Mesopotamia in an east-west direction, as well as from Saudi Arabia to Syria in north-south corridors (Helms, 1981, p. 54f.), although only interactions in the northerly and westerly directions have been proven; "Arabia to the south is still virtually unexplored" (Helms, 1981, p. 56).

An economic linkage between the *harra* and the *hamad* during the Chalcolithic/Early Bronze Age is demonstrated by the fact that the products of flint mines in the Wadi Ar-Ruwayshid hamad region can be found in the *harra* and in other regions of SW-Asia (Müller-Neuhof, 2013b, 2006; cf. Fig. 7.1). Regarding the question of how the production and distribution of cortical scraper blanks was organized, a possible scenario presented by Müller-Neuhof (2014b, p. 232) is that pastoral groups conducted the mining and subsequently exchanged the blanks within a supra-regional exchange system. Due to the location of these mines in an arid environment, the clear export orientation of the production and the high output, it is assumed that the exploitation of these mines did not started before the donkey as a beast of burden was introduced into the Levant, which happened within the 4th millennium BCE (Müller-Neuhof, 2013b, see also Quintero et al., 2002).

For the Late Neolithic period it remains uncertain whether the migration of mobile groups was influenced by pastoral or hunting activities. In general the Late Neolithic is characterized by hunter-herder-forager groups, where herding was a new component among a number of established subsistence strategies (Betts, 2008, p. 37). A large variety in site types and artifact assemblages indicates heterogeneous responses of hunter-gatherers to the new subsistence practice (Betts, 2008, p. 36). Besides, the numerous and large hunting structures of 'desert kites' reflect a high level of planning and cooperative activity (Rosen, 2008, p. 120). Since pastoralism also necessitates societal interaction and organization it can be assumed that hunting played a social role among many pastoralists. Therefore, "the simultaneous occurrence of increased sophistication in hunting and the adoption of herd animals need not be seen as contradictory" (Rosen, 2008, p. 120).

In the light of economic activities during the Late Neolithic, it is assumed that the inhabitants of the northern Badia belonged to distinct groups who followed different strategies, such as nomadic hunter-gatherers, nomadic hunter-herders and settled populations with seasonal pastoralism (Betts et al., 2013, p. 186ff.). A regular migration between the *hamad* and the *harra* during the Late Neolithic is indicated by several flint scatters in the *hamad*, which was, according to Betts et al. (2013, p. 167), most likely related to the introduction and subsequent development of specialized pastoralism (see also Huigens, 2015, p. 192 for similar observations in the Hazimah plains). Supra-regional exchange is attested by imported items, such as stone rings and beads (Betts, 1998, p. 229).

The prolonged use of certain sites during the Late Neolithic on a seasonal basis or even more permanently is indicated by hundreds of dwelling structures at Wisad Pools and the Wadi al-Qattafi mesas, as well as in the Jebel Qurma region (cf. Akkermans et al., 2014; Rollefson et al., 2014a). This was probably due to less arid climatic conditions as evidenced at Wisad Pools by (a) reddish-brown sediments underneath Late Neolithic structures that have been interpreted as possible topsoil (Rowan et al., 2015b); as well as (b) scattered pieces of charcoal from deciduous oak and tamarisk in a building dated to c. 6500 cal BCE (Rollefson et al., 2016, Rowan et al., 2015b).

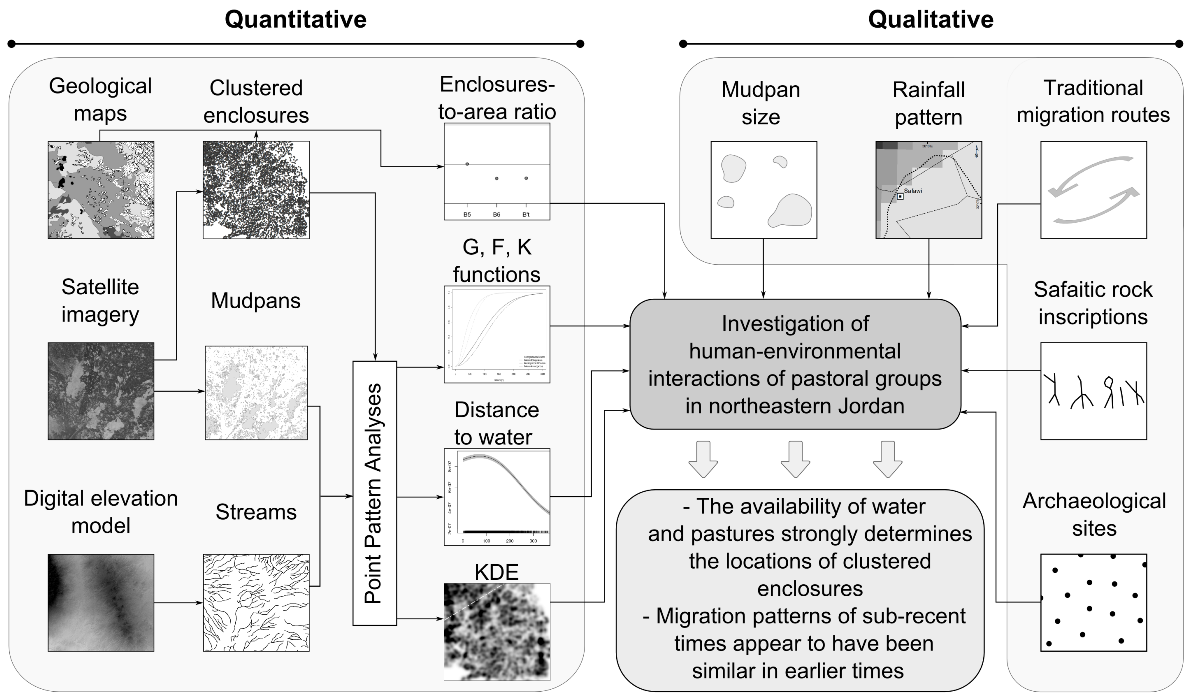

Figure 7.11.: Qualitative and quantitative data basis and methods applied in the investigation of human-environmental interactions of pastoral groups in northeastern Jordan.

7.6. Conclusions

In the study at hand more than 9000 clustered enclosures were recorded for the basaltic region of northeastern Jordan based on visual analysis of satellite imagery. The recorded sites are characterized by clusters of small and large enclosures that are commonly interpreted as animal enclosures or the habitation sites of mobile pastoralists. The sheer number of these clustered enclosures and their concentration in the *harra*, the basalt desert of the northern Badia, suggest that a relatively large number of people temporarily resided in this area. The scattered datings of the clustered enclosures of the *harra* span distinct occupation phases from the Late Neolithic to the present day (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013), documenting that the area was frequently utilized by herders, among others. It also demonstrates that ecological marginality is not necessarily accompanied by cultural or economic marginality (Bebermeier et al., 2016).

Overall, the distribution of clustered enclosures within the *harra* of northeastern Jordan mirrors complex social, socio-economic and socio-environmental relationships. In particular with regard to the latter, their distributional pattern is strongly related to the availability of water and thus grazing opportunities. The distance to periodic water resources and water bodies, i.e. wadi channels and mudpans, seems to be the most important locational factor for the construction of clustered enclosures. Further influencing factors are the hydrological characteristics of the landscape, in particular the development of the drainage network as caused by the age of the underlying basalt flows and the size of mudpans. Both hydrological features are – like the availability of grazing land – highly dependent on the regional and temporal rainfall pattern. All these factors are linked to the importance of the availability of water and pastures, and strongly support the hypothesis that the clustered enclosures were primarily used by pastoral groups.

Besides these natural environmental features, it appears that the overall distribution of clustered enclosures in the *harra* is related to the traditional pastoral migration cycle as observed for the modern Bedouin Ahl al-Jebel tribe. The general behavior of herders was to move fast to the east and south towards the *hamad* in late autumn/winter and afterwards to move slowly backwards to the north and west towards the Jebel Druze and the Azraq Basin in late spring/early summer (Roe, 2000). Given the pastoral activities during distinct late prehistoric and historical periods as indicated from the archaeological records (cf. Akkermans et al., 2014; Akkermans and Huigens, in press; Betts et al., 2013; Macdonald, 1992; Müller-Neuhof, 2014b; Rollefson et al., 2014a), as well as the fact that clustered enclosures in this region seem to be frequently re-used after their initial construction (Akkermans et al., 2014, p. 200; Betts, 1982b, p. 25; Müller-Neuhof et al., 2013, p. 127), it can be expected that many of the recorded sites were previously in use during late prehistoric and/or historical periods. The high conformity between the density pattern of the recorded clustered enclosures and the traditional pastoral migration cycle of the Ahl al-Jebel tribe, in conjunction with regional environmental characteristics and some archaeological data, indicates that the migration patterns of the recent past might have been similar throughout distinct historical and maybe late prehistoric times.

However, due to the absence of a temporally and spatially explicit and comprehensive chronology of the recorded clustered enclosures, it is not possible to derive relationships to varying migration routes during certain archaeological periods. Moreover, other factors and influences on the movement of pastoral groups must be considered, i.e. mixed subsistence strategies, exploitation of resources as well as regional to supra-regional trade and exchange. For instance, the Chalcolithic and Early Bronze Age shows high levels of flint mining, agriculture and herding at selected spots in the research area; selected high density areas of clustered enclosures point to interactions or relations between the more nomadic and more sedentary herding groups. In the Late Neolithic the area is characterized by diverse economic activities incorporating hunting and herding.

Further research is necessary to better understand the migration routes of early pastoralists. Clustered enclosures should be examined in greater depth by archaeological excavations and surveys in order to gain enhanced understanding of the functions of the individual structures and their chronology – knowledge which is required to understand the nature of past pastoral societies in northeastern Jordan.

7.7. Acknowledgments

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CHAPTER 8

Conclusions

8.1. Major conclusions of the case studies

8.1.1. Agricultural systems at Early Bronze Age Jawa

In the vicinity of the ancient city of Jawa, located in the basaltic desert of northeastern Jordan, the well-preserved remains of several abandoned agricultural terrace systems were recently discovered by geoarchaeological surveys (Müller-Neuhof, 2014a,b, 2012). The major research questions are how they functioned in detail, how efficient they were and how many people could have been supplied by the crop production.

The results of this study revealed that ancient agriculture in the environs of Jawa was practiced within three agricultural terrace systems, located on slopes, small plateaus, and valleys. The utilized agricultural area covered about 38 ha. The water supply of these systems was largely controlled by surface canals, which collected and diverted floodwater from nearby wadis or runoff from adjacent slopes. Runoff was mainly exploited from small watersheds of several tens to hundreds of hectares. The single terrace systems were composed of several field units, surrounded and divided by dry walls of basalt stones. On slope positions, these dry walls naturally caused siltation and the consequent development of terraces by retaining and collecting water and sediments from episodic floods and runoff events. Along the slopes the single terraced fields were arranged cascade-like, allowing the water—often controlled by spillways and water inlets—to flow from the upper terraces downslope to the lower terraces (Meister et al., 2017, cf. chapter 5).

The terrace fill sequences are composed of mixed unstratified fine sediments of local origin. The phytolith record is dominated by Pooid grasses. Increased phytolith concentrations in the terrace fill sediments, as compared to samples from non-terrace deposits nearby, suggest increased water availability and plant growth within the terraces. Two OSL ages of terrace fills from two terrace systems indicate that the construction of these terraces started as early as 5300 ± 300 a (1σ), dating them roughly to the Early Bronze Age I. This is in general agreement with the archaeological evidence for all three terrace systems investigated and fit well into the chronology of Müller-Neuhof et al. (2015), which dates the beginning of the occupation phase at Jawa to around 3500 cal BCE. Regarding design, scale and sophistication, the Jawa terrace systems are thus the oldest examples of their kind in the Middle East known to date, demonstrating that agriculture at Jawa was an important part of the settlement's economy (Meister et al., 2017, cf. chapter 5).

The runoff terrace systems of Jawa are considered to be effective under current rainfall conditions. The rainfall time series for the period 1983–2014 displays that rainfall patterns are erratic with most of the annual rainfall falling in torrential events, followed by short intensive runoff events. The modeled rainfall-runoff time series for this period demonstrates that the environmental conditions were favorable for floodwater/runoff harvesting in terms of water availability. The average seasonal runoff amounts generated and diverted to the terrace systems ranged—dependent from the catchment size—from 51 to 157 mm within the simulation period. Crop simulations for the period 1983–2014 show that even during dryer seasons, the simulated crop yields are much higher under runoff/floodwater irrigation than under non-irrigated, rainfed conditions. On average, the crop yields increased by 1.5 to 6 times, depending on crop type and catchment size of the terrace systems. The number of crop failures under runoff irrigation dropped by c. 70 %; with crop failures occurring in only 3 to 4 of 31 modeled years (Meister et al., in press-a, cf. chapter 6).

Assuming a mixed cultivation of cereals and legumes at Jawa the food supply capacity of all three irrigated terrace systems would feed somewhere between 40 and 140 people, taking simulated average yields of winter wheat, winter barley and lentils into consideration. In 'exceptional' good years this supply capacity increases almost fivefold. In total, crop production at these terrace systems was not sufficient to secure food supplies for all inhabitants, even by taking the small agricultural field areas documented by Helms (1981, cf. Fig. 3.20) into account. Therefore, it seems likely that other arable areas in the greater vicinity of Jawa existed which were additionally used for the production of staple crops, e.g. the Qa'a Shubayka located only 25 km east of Jawa (Meister et al., in press-a, cf. chapter 6).

Relying on an agropastoral subsistence strategy, the animal herd size at Jawa is roughly estimated at 11,000 animals (Helms, 1981). On this basis, the herds of cattle, sheep and goat could have met the nutritional requirements of about 400 persons per year. If total annual crop and animal production are taken together, about 500 to 1000 persons could have been supplied. Considering the estimated maximum population for Early Bronze Age Jawa, ranging from 3400 to 5000 people (Helms, 1981), it becomes apparent that neither animal production nor the local crop production created any surpluses or provided the necessary nutrition for

Jawa's inhabitants. This indicates that the estimated number of animals is either too low and the agricultural areas too small to comprise an economic base for such a large population, or the town's population estimates by Helms (1981) are overstated. Moreover, trade might have been an important branch of Jawa's economy in order to supplement food resources (Meister et al., in press-a, cf. chapter 6).

8.1.2. Mobile pastoralism in northeastern Jordan

Pastoral mobility is one way to respond to the spatio-temporal changes in vegetation and water availability resulting from strong annual climatic variations with pronounced seasonality (Betts, 1998), and represents an adapted form of land use. Pastoral mobility in northeastern Jordan can be traced by clustered enclosures. It is assumed that these structures were used by mobile pastoralists for corralling flocks and domestic purposes. To investigate the relation between pastoral camps and their environment in a landscape that has been used by herders for thousands of years, clustered enclosures and their spatial distribution were investigated (Meister et al., in press-b, cf. chapter 7).

For the basaltic *harra* of northeastern Jordan more than 9000 clustered enclosures were recorded in an area of about 10,000 km^2. The sheer number of them clearly demonstrates that the *harra* was extensively used by mobile groups in the past. Their distribution shows that human activities covered the whole area and was by no means restricted to the fringes of the *harra*. The recorded features are characterized by groups of small and large sub-circular enclosures of oval to round shape. The number of enclosures in a cluster varies between 3 to over 30; their overall size ranges from over 20 meters to about 250 meters in diameter. The observed differences in site sizes and numbers of associated enclosures within one cluster might be linked to variations in the herd numbers kept inside as well as a varying number of pastoralists (Meister et al., in press-b, cf. chapter 7).

The spatial distribution of the clustered enclosures shows areas of high density in the northwest and the southeast of the *harra* but also along the southern edge of the modern state border to Syria. Although a detailed chronology is missing—and it is unclear to which degree the individual enclosures sites were used repeatedly—the scattered datings of the clustered enclosures of the *harra* span distinct occupation phases from the Late Neolithic to the present day (Müller-Neuhof, 2014b; Müller-Neuhof et al., 2013). This documents that the area was frequently occupied by herders and that ecological marginality is not necessarily accompanied by cultural or economic marginality (Meister et al., in press-b, cf. chapter 7).

The locations and distributional pattern of clustered enclosures are strongly related to the availability of water and grazing opportunities. The distance to periodic water resources and water bodies, i.e. wadi channels and mudpans, seems to be the most important locational factor for the construction of these sites. Further influencing factors are the hydrological characteristics of the landscape, in particular the development of the drainage network as caused by the age of the underlying basalt flows and the size of mudpans. Both hydrological features are—like the availability of grazing land—highly dependent on the regional and temporal rainfall pattern. All these factors show the importance of the availability of water and pastures for the pastoral groups (Meister et al., in press-b, cf. chapter 7).

Furthermore, the overall distribution of clustered enclosures seems to be related to the traditional pastoral migration cycle as observed for the modern Bedouin Ahl al-Jebel tribe: The general behavior of herders was to move fast to the east and south towards the *hamad* in late autumn/winter and afterwards to move slowly backwards to the north and west towards the Jebel Druze and the Azraq Basin in late spring/early summer (Roe, 2000). Given the pastoral activities during distinct late prehistoric and historical periods as indicated from the archaeological records (cf. Akkermans et al., 2014; Akkermans and Huigens, in press; Betts et al., 2013; Macdonald, 1992; Müller-Neuhof, 2014b; Rollefson et al., 2014a), it is expected that many of the recorded sites were previously in use during late prehistoric and/or historical periods. The high conformity between the density pattern of the recorded clustered enclosures and the traditional pastoral migration cycle of the Ahl al-Jebel tribe, in conjunction with regional environmental characteristics, indicate that the migration patterns of the recent past might have been similar through distinct historical and late prehistoric times. For historical times this is supported by Safaitic inscriptions (1st century BCE – 4th century CE) that describe fairly similar migration patterns (Macdonald, 1992). For late prehistoric times possible indications for similar migration patterns are given by the fact that the locations of major prehistoric sites are usually particularly favorable and their surroundings are commonly characterized by increased pastoral activities. The observation of high density areas of clustered enclosures in the surroundings of the Chalcolithic/Early Bronze Age sites of Jawa, Khirbet Abu al-Husayn and Tulul al-Ghusayn point to interactions or relations between the more nomadic and more sedentary herding groups. Moreover, an economic linkage between the *harra* and the *hamad* during the Chalcolithic/Early Bronze Age is demonstrated by the fact that the products of flint mines in the Wadi Ar-Ruwayshid *hamad* region can be found in the *harra* and in other regions of SW-Asia (Müller-Neuhof, 2013b, 2006; cf. Fig. 7.1). A migration between the *harra* and the *hamad* during the Late Neolithic period is indicated by several flint scatters in the *hamad* (Betts et al., 2013; cf. Meister et al., in press-b, chapter 7).

However, due to the absence of a temporally and spatially explicit and comprehensive chronology of the recorded clustered enclosures, it is not possible to derive relationships to varying migration routes during certain archaeological periods. Moreover, other factors and influences on the movement of pastoral groups must be considered, i.e. mixed subsistence strategies, exploitation of resources as well as regional to supra-regional trade and exchange. For instance, the Chalcolithic and Early Bronze Age shows high levels of flint mining, agriculture and herding at selected spots in the research area. In the Late Neolithic the area is characterized by diverse economic activities incorporating hunting and herding. Overall, the results show that the observed distribution of clustered enclosures is influenced by natural characteristics as well as cultural practices (Meister et al., in press-b, cf. chapter 7).

8.2. Human-environmental interactions in northeastern Jordan—a synopsis

When dealing with human occupation in marginal habitats one is often confronted with the ecological concepts of resilience and vulnerability (e.g. Nelson et al., 2012; Redman and Kinzig, 2003; Schoon et al., 2011; Widlok et al., 2012). Resilience is the magnitude of disturbance that can be absorbed by a system before it is unable to sustain its structure (Gunderson and Holling, 2002). Vulnerability measures the resilience of a system to unexpected or unpredictable events (Gunderson and Holling, 2002). The terms are loose antonyms (Adger, 2000) focusing on persistence, adaptiveness, variability, and unpredictability (Gunderson and Holling, 2002). Based on these definitions it becomes clear that arid environments are highly vulnerable and little resilient. Societies that live under these conditions have to cope with the unpredictability of environmental dynamics and develop specific adaptation strategies. Strategies are successful when they decrease the vulnerability of the human-environmental system—a system that secures food and water supply.

The different case studies of this thesis display two kinds of adaptation applied by past societies living in the deserts of northeastern Jordan:

1. the application of different water management techniques by sedentary groups living in the Early Bronze Age settlement of Jawa;
2. the application of mobile pastoralism by mobile groups that have utilized the northeastern Jordanian regions of the *harra* and the *hamad* since late prehistory.

Both strategies were developed to cope with the unfavorable conditions in a desert environment and its climatic dynamics. Besides cultural and economic factors, the success of both adaptation strategies certainly relied on the societies understanding of their natural environment, as demonstrated by the fact that the investigated ancient built environment relates to the natural environment in several aspects.

In the absence of permanent water resources and with little potential for cultivation, the decision to found a city like Jawa in a desert environment is a risky endeavor with regard to food and water security. The habitation of Jawa during the 2nd half of the 4th millennium BCE and the construction of highly elaborated water storage and diversion systems (Helms, 1981, cf. section 3.2.4), as well as the agricultural terrace systems in its environs (Meister et al., in press-a), are therefore exemplary of how early societies in marginal desert regions adapted to environmental conditions and the risk of climate variability by implementing different water management strategies and technologies. While the water diversion and storage systems provided essential drinking water resources for people and livestock (Helms, 1981), the agricultural terrace systems enhanced crop yields (Meister et al., in press-a). The simultaneous application of these techniques decreased the vulnerability and increased the resilience of Jawa's inhabitants to the effect of climatic fluctuations. This in turn, allowed the occupation of Jawa in an unfavorable settlement area on a permanent basis.

The strong relation between the cultural and natural environments at Jawa is made clear by the design and location of these water management systems. The water diversion and storage systems as well as the agricultural terrace systems are constructed in accordance with the topography and hydrology of the region, enabling the collection and diversion of water. From a management and engineering point of view it has to be noted that both systems were not built directly within the watercourse of the major Wadi Rajil. Instead, Jawa's water engineers built the systems only within or close to small tributaries to which water from Wadi Rajil or tributaries was diverted. This is probably attributable to the runoff behavior of Wadi Rajil. Characteristic for dryland catchments of this dimension are unpredictable, short lasting floods that are occasionally of high magnitude (Beckers, 2014). Therefore, the operation and maintenance of such systems located within the watercourse of this wadi would have been much more challenging in order to avoid overfilling of the pools or the erosion of built structures, i.e. terraces, dams and canals. Moreover, it can be assumed that the systems would have had to be maintained and cleaned from sediments more frequently. Thus, the construction of terraces and water reservoirs in favorable locations in terms of water availability and maintainability displays a good understanding of the local hydrology, geomorphology and sedimentology.

Concerning the food supply, the application of a mixed farming/herding strategy at ancient Jawa probably also decreased the impact of droughts by making the food supply system more flexible (cf. Adger, 2000). If there was not enough rainfall to carry out agriculture on the terrace systems or in the close vicinity, Jawa's inhabitants could have moved further away to practice agriculture. If agriculture was completely impossible, they could have still relied on their livestock. If ancient Jawa was integrated into a functioning trade or exchange network, additional food resources could possibly have been imported. Potential contacts between the more sedentary and more nomadic Early Bronze Age pastoral groups illustrate possible collaborations (Meister et al., in press-b), e.g. the exchange of goods, as another form of adaptation to enhance the security of supply in this desert environment.

The implementation of the water management strategies accompanied by the availability of water and crops as well as the integration of different forms of subsistence decreased vulnerability and obviously led to an increase in Jawa's population, which is estimated at a maximum of about 5000 persons (Helms, 1981). A large population like this, however, also leads to an increase in vulnerability to climate deterioration due to enhanced requirements for nutrition and water. Whether the abandonment of Jawa was potentially influenced by the impact of paleoenvironmental conditions or whether it was influenced by other factors, e.g. political or economic changes, cannot be answered with the current state of knowledge. To date, information about the social and political organization of the town is missing and there is a lack of high-resolution palaeoenvironmental data for the eastern Jordanian deserts. Moreover, how long Jawa was occupied and when exactly the city was abandoned is as yet unknown. In view of the insufficient water and food supply capacity of Jawa's water storage and agricultural systems during dryer periods (cf. Whitehead et al., 2008; Meister et al., in press-a), however, it can be reasonably assumed that in the case of extremely dry conditions that lasted for a prolonged period of time, the maintenance of supply security for thousands of people would have been extremely difficult, if not impossible.

Another way to cope with the harshness of the arid conditions in the northern Badia is to follow a mobile lifestyle that relies on pastoralism. Mobile pastoralism is a form of economy that exploits drylands by taking advantage of the dynamic variability of rainfall and pastures (Krätli et al., 2013). Due to the high level of movement the vulnerability of herders and their flocks to climate variability is decreased. The sheer number of clustered enclosures in the northern Badia used by mobile pastoralists during the last eight to nine millennia demonstrates that this lifestyle is a successful form of adaption. The locations and distributional pattern of clustered enclosures close to periodic water resources and water bodies display the importance of the availability of water and pastures for pastoral groups (Meister et al., in press-b). The cultural practice of herders to follow a seasonal migration cycle seems to be a long-lasting phenomenon in the northern Badia. This is indicative of the herders' fundamental understanding of the regional environmental setting and its dynamics. The associated targeted utilization of the *harra* and the *hamad* considered the availability and efficient use of water and vegetation as well as the susceptibility to over-exploit pastures. Following this kind of migration cycle allowed the flora to restore (Roe, 2000) and probably enabled the sustainable exploitation of the region over long periods.

It was only with the establishment of the modern states, accompanied by several infrastructural developments, that these traditional pastoral practices started to change significantly. The pastoral system became monetized, market-oriented and the numbers of animals have increased considerably (Al-Tabini et al., 2012; Roe, 2000). The construction of roads, the digging of deep wells and the introduction of motorized transport enabled the supply of large herds with water and fodder for long periods in specific areas, irrespective of natural grazing conditions (Roe, 2000). Thus, the pastoral system became more independent of environmental conditions and even less vulnerable to climatic fluctuations. As a result the human-environmental system became unbalanced. While in the past the traditional migration pattern with its shifting pastures permitted the recovery of the flora, the modern shift to increased herd sizes and the year-round grazing possibilities disturbed the natural balance (Roe, 2000). As a result, the grasslands of northeastern Jordan have been substantially degraded over the last decades (Juneidi and Abu Zanat, 1993).

Overall, the different case studies of this thesis demonstrate how the development of techniques (e.g. floodwater/runoff harvesting; Meister et al., 2017), the integration of different subsistence strategies (e.g. herding and farming; Meister et al., in press-a), and different forms of lifestyle (e.g. mobile; Meister et al., in press-b) successfully decreased the vulnerability of past societies investigated in the deserts of northeastern Jordan. The adaptation strategies were adjusted to the local environmental conditions, thus revealing the population's in-depth knowledge of the natural environment and its local specificities. Their success is indicated by the vast amount of traces of human occupation in this region, documenting increased human activities during distinct late prehistoric and historical periods. All in all, this landscape archaeological study nicely illustrates how past societies adapted to marginal environments and lowered their marginality through technical measures and cultural practices.

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APPENDIX A

Appendix

A.1. Supplementary information to chapter 4.2

Table A.1.: Estimated production of wheat cultivated in Jordan by rainfall regimes; adapted from Russel 1988.

Region	**Rainfall (mm)**	**Average yield (kg*ha-1)**	**Range of yields 'bad' – 'good' (kg*ha-1)**
Desert	150-250	400	100-700
Eastern Plain	250-300	640	350-900
Western Plain	300-400	810	500-1170
Upland	400+	1050	750-1460

Table A.2.: Wheat and barley yield expectations of Bedouin farmers in the Negev; adapted from Russel 1988.

Informant yield evaluation	**Wheat (kg*ha-1)**	**Barley (kg*ha-1)**
Exceptional	1000	2000
Good	500-700	700-800
Satisfactory	300-500	400-600
Poor	0-200	0-200

A.2. Supplementary information to chapter 6

Table A.3.: Comparative caloric productivity for pastoral herds containing exactly 100 head when potential post-Pleistocene size reductions are accounted for; adapted from Russel (1988).

Source of calories	Cattle (kcal/yr)	Sheep (kcal/yr)	Goats (kcal/yr)
Slaughter	4,104,576	968,990	519,583
Milk	5,497,065	1,780,189	1,524,987
Total	**9,601,641**	**2,749,179**	**2,044,570**

Table A.4.: Summary of the rainfall analysis at Jawa based on the ARC 2 dataset. Q refers to the % quantile [mm*d-1].

Mean rainy days per season*	Mean daily rainfall per season**	50 % Q	75 % Q	90 % Q	95 % Q	Max Q***
41	2.8	1.7	3.7	6.6	8.6	54.2

* Mean number of rainy days per season (>0.1 mm) in the period from 01.01.1983 to 31.12.2014.,
** Mean rainfall on rainy days (>0.1 mm) in the period from 01.01.1983 to 31.12.2014.,
*** Maximum rainfall amount recorded in the period from 01.01.1983 to 31.12.2014.

Table A.5.: Seasonal sums of runoff and rainfall volumes of each terrace system and catchment.

Season	**Rainfall (mm)**	**Runoff (mm)**	**Rainfall + runoff (mm)**			
			TG-1/C1 (R=10)	TG-2/C2.1 (R=7.5)	TG-2/C2.2 (R=20)	TG-2/C3 (R=6.5)
1983/1984	124	4.6	170	159	217	154
1984/1985	96	2.3	119	113	142	111
1985/1986	120	5.0	170	157	219	152
1986/1987	81	3.0	111	104	142	101
1987/1988	143	3.7	180	170	216	167
1988/1989	132	35.8	490	400	848	363
1989/1990	102	5.0	152	139	201	134
1990/1991	148	17.8	326	281	503	263
1991/1992	153	7.0	223	206	294	198
1992/1993	175	20.6	381	329	587	308
1993/1994	88	2.9	117	110	146	107
1994/1995	118	8.6	204	182	290	173
1995/1996	94	3.0	124	117	154	113
1996/1997	133	8.2	215	194	297	186
1997/1998	148	6.9	217	200	285	192
1998/1999	92	6.0	152	137	212	131
1999/2000	80	2.4	104	98	127	95
2000/2001	107	17.3	280	237	453	219
2001/2002	107	3.6	143	134	178	130
2002/2003	140	4.6	186	174	231	169
2003/2004	170	12.7	297	265	424	252
2004/2005	174	15.2	326	288	477	272
2005/2006	114	5.6	170	156	226	150
2006/2007	86	2.4	110	104	134	101
2007/2008	112	17.7	289	245	466	226
2008/2009	84	1.9	103	98	122	96
2009/2010	107	4.6	153	141	198	136
2010/2011	57	2.6	83	77	109	74
2011/2012	84	2.2	106	101	129	98
2012/2013	119	4.9	168	156	218	151
2013/2014	113	5.4	167	154	222	148
Min	57	1.9	83	77	109	74
Max	175	35.8	490	400	848	363
Mean	116	7.9	195	175	273	167

APPENDIX B

Curriculum vitae

Der Lebenslauf ist in der Online-Version aus Gründen des Datenschutzes nicht enthalten.

Der Lebenslauf ist in der Online-Version aus Gründen des Datenschutzes nicht enthalten.

APPENDIX C

Affidavit/Eidesstattliche Erklärung

Hiermit erkläre ich, dass ich die Dissertation *Human-Environmental Interactions in Northeastern Jordan* selbständig angefertigt und keine anderen als die von mir angegebenen Quellen und Hilfsmittel verwendet habe.

Ich erkläre weiterhin, dass die Dissertation bisher nicht in dieser oder in anderer Form in einem anderen Prüfungsverfahren vorgelegen hat.

Berlin, den Julia Meister

....