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The Emergence of Terrace Farming in the Arid Zone of the Levant—Past Perspectives and Future Implications

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Abstract: Terrace farming installations occupy vast desert areas in the Southern Levant. Their construction in harsh environments raises critical questions focusing on the natural, political, and economic circumstances promoting their construction and operation. The present review, based on new observations and previously published materials, focused on three different arid regions located across the Southern Levant, namely the Eastern Marmarica of Northwestern Egypt, the Negev Desert of Israel, and the Petra region in Jordan. The comparison between the regions allows us to uncover the forces behind this vast phenomenon, and to draw conclusions on the relevance of these arid zones to past and present agricultural productivity. The results of this study showed that the environmental conditions in the Southern Levant provided soil and water throughout the entire Holocene, and that terrace farming was a well-known method to the early inhabitants of the region. However, the actual implementation of the vast phase of terrace farming was diachronic across the region, according to the political and economic circumstances promoting their construction at each location. As enhanced desertification is expected to accelerate during the coming decades, the maintenance of agricultural terraces is vital for the conservation of agricultural productivity in the forthcoming warming world, especially in arid lands.

Keywords: terrace farming; ancient agriculture; arid environments; Southern Levant; Negev Desert

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1. Introduction

1.1. The Importance of Terrace Farming in Arid Environments

All global agricultural initiatives must meet two basic requirements, namely soil suitable for cultivation and sufficient water for irrigation. These preconditions are better provided in temperate and tropical regions, but in arid zones receiving annual precipitation below 250–200 mm/y, these are challenging requirements to meet. Without methods of additional irrigation, most of the agricultural production in arid regions is restricted to natural oases fed by ground water or is confined to the banks of rivers with permanent flow, penetrating the arid zone from remote humid areas. Examples of such cases are widespread on all continents, such as the Sahara Desert traversed by the Nile River in Africa, the oasis and rivers surrounding the Taklamakan Desert in central Asia, and the streams crossing the Atacama Desert in South America.

In antiquity, additional large-scale agriculture enterprises were constructed in arid environments by the utilization of occasional rains, generating surface flow. These periodical events were targeted by runoff-harvesting systems constructed along valleys and ephemeral stream channels, aiming to irrigate agricultural plots organized as staircases of terraces [1,2]. These terraced plots are among the various implementations of the terrace farming method and are widespread globally in all climatic zones ([3–5] and references cited).

In most cases, the terraces constructed in arid environments were built from local raw materials, mostly stones and earth, and were assembled as dry stone terraces and earth embankments. These relatively simple installations aimed to level the valley bottoms and to ease their gradient to spread the infrequent overland flow to the maximum width of the valleys to receive sufficient irrigation [3,4]. However, when these structures occupy vast desert areas, their massive attendance opposes the basic characteristics of any arid zone; this is not the preferable region for large-scale agricultural production in terms of soil fertility and water availability. In most cases, large-scale stone works and vast labor investments were required to construct these installations. Therefore, their construction in these harsh desert environments raises several critical questions that focus on the natural conditions promoting the construction and operation of these agricultural enterprises in each desert zone, as well as issues regarding the political and economic circumstances promoting their initial construction, followed by long maintenance over a considerable historic time. These cardinal queries are at the core of the present study, focused on three different arid regions located across the Southern Levant, namely the Eastern Marmarica region of Northwestern Egypt, the Negev Desert of Southern Israel, and the Petra region in Southern Jordan (Figure 1). Together, these regions form a long transect, stretching over 800 km, between the Mediterranean coast in Northern Egypt and the deep inland desert of Southern Jordan (Figure 1).

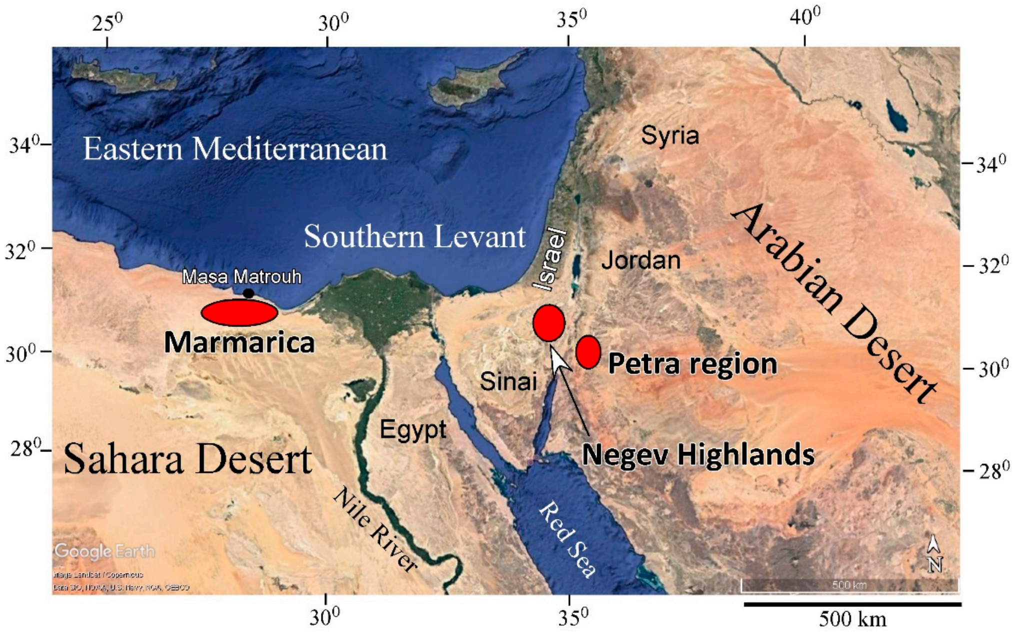

Figure 1. Location map of study sites on a Google Earth image.

1.2. Terrace Farming in the Arid Levant

The Southern Levant deserts occupy large areas in Northeastern Africa, Sinai Peninsula, and the Negev Desert of Southern Israel and Southern Jordan (Figure 1). These areas are part of the major Saharan–Arabian Desert belt. In these regions, precipitation sharply decreases south and east of the Mediterranean Sea from approximately 200 mm/y near the coast to less than 50 mm in the land interior. Therefore, these regions are lacking permanent rivers (beside the Nile River), or large-scale wetlands or shallow aquifers that were not developed throughout the Quaternary [1,6]. Most of the soils developed in these regions originate from fine particles of silt and fine sand, which are produced from the disintegration of rocks, caused mainly by salt weathering [6]. In most cases, these fine particles are transported by wind as desert dust and spread over the entire region [7,8]. After their initial deposition, most of these fine sediments were remobilized by surface flow and finally deposited along the drainage channels and valleys. Following their occasional wetting by rain and floodwater, these sediments were processed into loessic soils [9,10], supporting the local vegetation of annuals and shrubs. Although scarce, trees of various species are also present in these harsh environments, especially in places where the soil/sediment depth is 1–2 m and water availability is sufficient.

Most of the soils and fine sediments currently found in the arid Levant were deposited during the last ice age, dated to approximately 70–20 ka, as noted in numerous studies [11–14]. At the postglacial stage and during the Holocene, these soils and fine-grained sediments were gradually eroded by aggressive erosion processes, mainly by gullies [12,15]. However, throughout the Holocene, the availability of soil and runoff water created the "Desert Agriculture Geomorphic Window" described by Avni [12], forming the agricultural potential in these arid zones.

The initiation of agricultural activities in the arid zones of the Southern Levant has been largely discussed in previous studies. Some of them attributed the early farming in the Negev Desert to the Bronze and Iron Age (ca. 4th to 1st millennia BCE.; [1,16,17]), while the expansion of these activities was attributed to the Nabatean and Roman periods (ca. 1st and 2nd centuries CE.). Others, such as Shahack-Gross and Finkelstein [18,19], claimed that the early inhabitants of the Negev Highlands were mainly pastoralists who were not subsiding on the local production of agricultural crops. In the vicinity to the Petra site in Southern Jordan, Barker et al. [20,21] stated that agricultural activities were initiated during the Bronze and Iron Age. In the Marmarica region of Northwestern Egypt, Vetter et al. [22,23] reported that water management activities began as early as the 2nd millennium BCE but certainly experienced a climax in Greco-Roman times between the 2nd century BCE and the 6th century CE.

As large-scale farming activities dating back to the Bronze and Iron Age remain under debate (see [1,16,17] versus [18,19], it can be concluded that the pastoral societies of these regions could invest some efforts in low-grade runoff harvesting and terracing, aiming to intensify the natural vegetation for the benefit of herding [17]. This was probably performed in the same manner practiced by the seminomadic Bedouin population of these desert zones during the last centuries. However, the vastly distributed terrace farming that followed these early initiatives in the Southern Levant was much larger in terms of its spatial distribution, and massive construction and sophisticated methods of runoff harvesting applied by the ancient farmers together constituted well-organized agricultural areas. These large-scale agricultural enterprises are the main concern of the present study.

1.3. Previous Research on Runoff Agriculture in the Southern Levant

The ancient agriculture and terrace farming in the Southern Levant deserts have been studied intensively during the last 60 years. The focal point of this research was in the Negev Highlands of Southern Israel, where the first comprehensive study was conducted during the 1950s and 1960s by Kedar [24] and Evenari and his team [1]. These studies were accompanied by the reconstruction of several ancient farms dedicated to agricultural experiments (Figure 2). Following these pioneering studies, a similar study was conducted in the regions of Tripolitania [2], Southern Jordan [20,25–27], and Marmarica [22,23,28].

1.3.1. The Negev Highlands, Southern Israel

The Negev Highlands region encompasses an uplifted terrain, ranging in elevation between 1000–300 m a.s.l, located between the Sinai Peninsula in the west and the Dead Sea depression in the east (Figures 1 and 2). The high visibility of the ancient terrace farming systems on the desert landscape in this terrain attracted scholarly attention as early as the 19th and early 20th centuries [29–31]. With the intensification of modern archaeological research in the Negev, these systems have been the target of several comprehensive studies [16,32–34]. The Negev Emergency Survey (1979–1989) provided further data on settlement sites and related agricultural fields [35–42]. These ancient agricultural fields were also studied in terms of their hydrological, geomorphological, and botanical aspects, with specific attention being paid to the mechanisms of conveying water into fields, the processes by which arable soil accumulated, and the nature of the agricultural crops grown in the plots [1,10,34,43]. Most studies associate the major expansion of agriculture in the region with the development of large urban settlements and their agrarian hinterland during the Roman and Byzantine periods (1st–6th centuries CE; [33,34,44]).

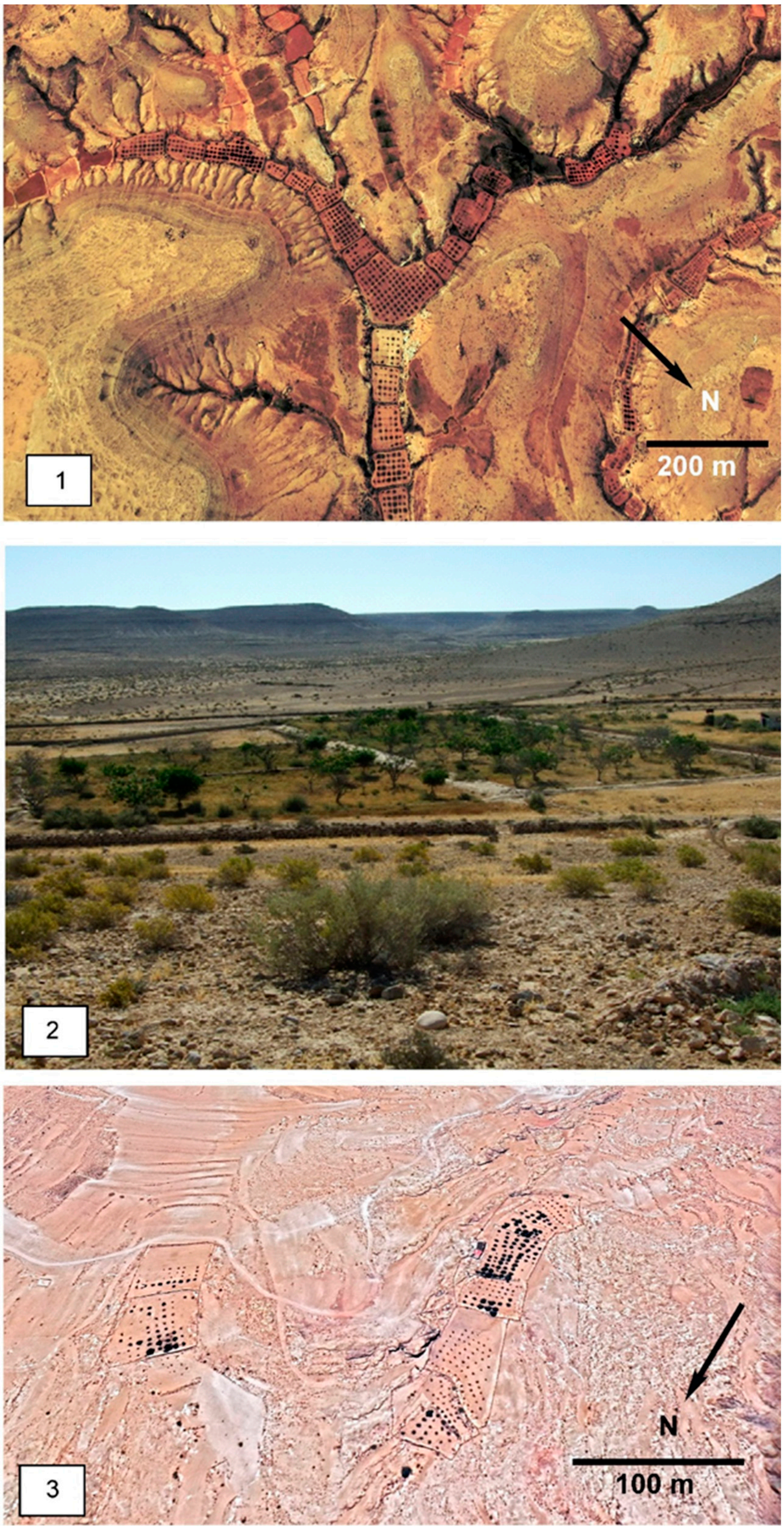

Figure 2. General view of the study regions emphasizing past and present desert agriculture and terrace farming. 1. Marmarica region, 15 km south-west of Marsa Matrouh. 2. Southern Negev Highlands. 3. Petra region, 3 km north-west of the Petra site. 1 and 3 are Google Earth imagery, while 2 is a photograph by Y. Avni.

1.3.2. Eastern Marmarica, Northwestern Egypt

Located on an elevated plateau stretching between the El-Alamein in the east and the Egyptian–Libyan border in the west and between the Mediterranean coast in the north and the Qattara Depression in the south (Figure 1), this vast area in Northwestern Egypt occupies approximately 105 km^2. This region is the eastern extension of Cyrenaica, in which large-scale ancient terrace farming agriculture installations were surveyed and reported by Barker et al. [2].

The ongoing geo-archeological research in Marmarica is based on intensive long-term research carried out by T. Vetter and his team, which was initiated in the 1990s and concentrated on the desert tableland south of Marsa Matrouh (Figures 1 and 2). As part of this comprehensive research, soil and geomorphological analyses were conducted, coupled with remote sensing mapping of land-use inventory, published in a series of papers since 1994 [45]. Geo-archaeological surveys followed, indicating several types of terrace farming installations irrigated by runoff harvesting techniques [22,23,28]. The pottery collected in the vicinity of these terrace constructions was dated mainly to Greco-Roman times, while *optically stimulated luminescence* (*OSL*) dating of the fine-grained deposits which served as agricultural soil, and fine sediments deposited in relation to the water harvesting installations, convinced Vetter et al. [22,28] that active agricultural management started as early as the 2nd millennium BCE. They also reported that terrace farming activity intensified during the Greco-Roman ages (2nd century BCE to 1st century CE; [22,23]). These studies concluded that the gradual sediment accumulation within the agricultural plots caused the constant need for maintenance by adding rows of stone courses to the farming terraces, and that these installations were operated for a considerably long time. In the nearby arid Tripolitania located to the west of Marmarica, Barker et al. [2] reported on a vast area occupied by floodwater harvesting installations that were largely surveyed and analyzed for their geoarchaeological perspective.

1.3.3. The Hinterland of Petra, Southern Jordan

The Petra region is located on the western slope of the eastern highlands of Southern Jordan, forming an intermediate step between the hyper-arid plains of the Arava Valley in the west and the desert steppes of the Jordanian high plateau in the east [27]; Figure 1. The hinterland of Petra is situated at elevations of 900–1000 m within several valleys incising the high mountain range of Gabel Ash-Sharah, whose elevation is above 1600 m. All valleys drain toward the west to the deep Arava Valley through several steep canyons and gorges.

Archaeological evidence suggests that settlements have been present in the region surrounding the Petra site and along the eastern margin of the Arava Valley since the Natufian period, approximately between 10,800 and 8300 BCE [46,47]. These settlements intensified during the Bronze and Iron Ages [20]. From the 3rd century BCE until the 1st century CE, Petra was the capital of the Nabataean Kingdom, gradually becoming a regional administrative and economic center in the Southern Levant [48]. The agricultural techniques applied in the area include runoff terrace systems that are scattered in all valleys and plateaus. Some of them are still cultivated by the local Bedouins ([25,26]; Figure 2). Most researchers attribute the initial construction of these terrace systems roughly to the Nabataean Kingdom and to the Roman occupation (313 BCE–363 CE), mainly based on surface pottery and other relative dating techniques [25,26,46]. During the Byzantine period (324–630 CE), the Petra region reverted to a rural landscape with scattered villages accompanied by seasonal seminomadic camps [25,26]. This occupation characteristic was sustained until the end of the Umayyad period (661–750 CE) while, afterwards, a decline in settlements is witnessed in the archaeological record [27].

1.4. The Aim of the Present Study

The present study aimed to evaluate the natural conditions leading to the construction of large-scale terrace farming in three large arid regions of the Southern Levant—Marmarica, Negev Highlands and the Petra region. At each region, local environmental characteristics and terrace farming installations were described, aiming to trace their function and the timing of their construction based on the evitable published literature. In each region, a combination of relative dating methods supported by OSL and radiocarbon dating has been performed during previous studies. However, no correlation between these different regions was ever made, searching for similarities versus differential outlines in their natural conditions, their building patterns, time of initial construction and the political and economic circumstances promoting the development of large-scale terrace farming in each arid zone composing the Southern Levant.

The comparison between the regions uncover the forces behind this vast phenomenon, aiming to conclude the relevance of these arid zones to past and present agricultural productivity. This evaluation is especially important while considering the future growing demand for food production in marginal lands and the challenges imposed on arid regions due to increasing aridity, as predicted for these regions due to global warming [49].

2. Methods and Data Sources

This review study integrates several data sources, as follows:

1. New observations and data collection achieved during intensive fieldwork in the Negev Highlands of southern Israel. These observations include the following:
    (1) Ongoing observations of the agricultural enterprises run by the local Bedouin population in the most arid regions of the Negev Highlands. Data assemblage was conducted during the years 1990–2022;
    (2) Observations on the long-term survival of domesticated fruit trees planted within ancient agricultural plots in the Negev Highlands. Data collection was conducted during the years 1995–2022;
    (3) Long-term monitoring of soil erosion features in designated ancient agricultural plots, collected during the years 1990–2022.
2. Field excursions carried out in the Marmarica region of Northwestern Egypt and in the Petra region of Southern Jordan during the years 2000–2022;
3. Previously published materials citied in the text. These materials included data on natural conditions, archeological surveys, and OSL sampling locations and OSL dates yield at various sites. Regarding the OSL dates, Avni et al. [50,51] published the most important data from the Negev Highlands, Vetter et al. [22,23,28] from the Marmarica Region, and Beckers et al. [27] from the Petra Region;
4. Regional topographic and geological maps were observed and analyzed, including the 1:100,000 scale British maps of the Negev south of Be'er Sheva [52], geological maps of Israel [53], geological maps of Egypt [54], and geological maps of Jordan [55,56].

All these materials were integrated together to achieve a new perspectives on the natural and anthropogenic trajectories enabling the establishment of desert terrace farming in the arid regions of the Southern Levant.

3. Results

3.1. Natural Conditions Enabling the Development of Desert Terrace Farming in the Southern Levant

The geological composition of the Southern Levant is diverse and consists of magmatic and metamorphic rocks of Precambrian age exposed in the southern sector of the region near the Red Sea and its two northern extensions, the Suez and Aqaba gulfs (Figure 1). Paleozoic and Mesozoic sandstones are exposed in the regions surrounding this Precambrian core, such as in the Petra region of Southern Jordan [55,56], while hard limestone and dolomites are exposed in the region east of Petra and in the Negev Highlands of Southern Israel [53]. The Marmarica region of Northwestern Egypt comprises hard fossiliferous limestone of Miocene age, which forms massive beds with some minor clay horizons [57]. Each geological unit has its own characteristics in terms of mineral content, morphology in terms of exposed surfaces, level of roughness, and spacing of joints or bedding plains.

These parameters have a direct influence on the raw materials extracted from this local geodiversity and used for constructing the terrace farming installations. Soils suitable for agriculture are provided mainly from the sandy component contributed from the direct disintegration of magmatic, metamorphic, and sandstone rocks or from loessic sediments originating from desert dust. Irrigation water in this desert region is generated from the interaction between local rain events and the characteristics of specific rock outcrops exposed in each location, dictating runoff generation and runoff yield collected for irrigation. Therefore, we will describe these unique conditions in each region, which are essential for the establishment of desert terrace farming at each study site.

3.1.1. Negev Highlands (Southern Israel)

The Negev Highlands region is composed of anticlinal ridges consisting mainly of limestone, dolomite, and clay of the Early Cretaceous to Eocene age, which form a hilly and rocky desert landscape (Figures 2 and 3). In this terrain, arable soil is present only in the bottom of narrow valleys, taking the form of a thick (5–8 m) accumulation of loessic sediments [12].

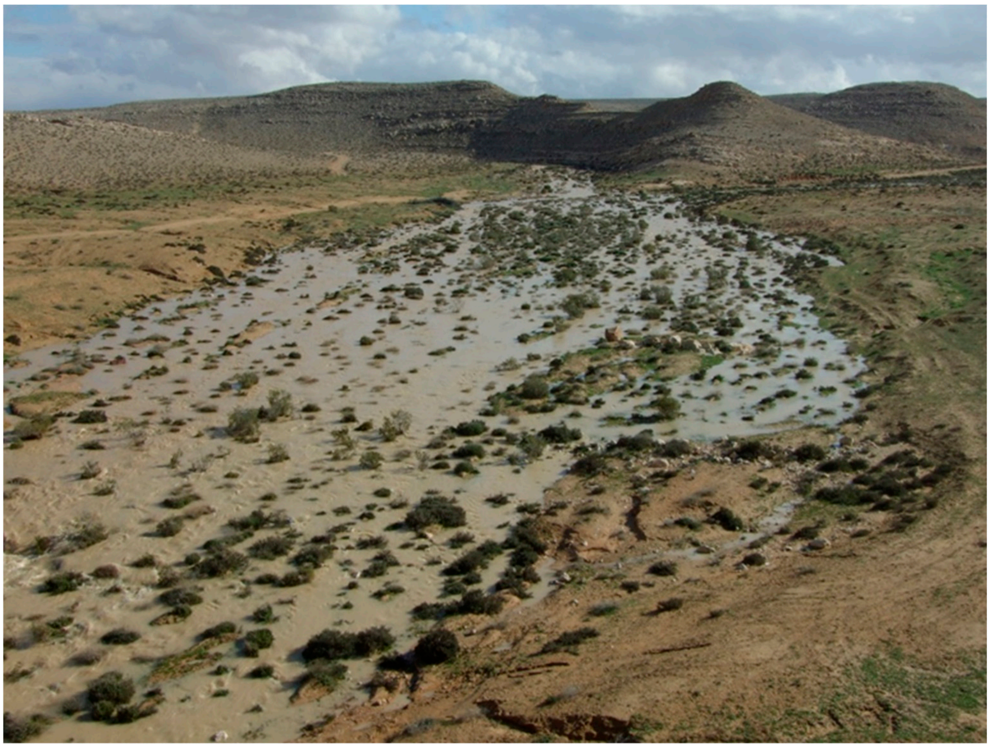

Figure 3. Negev Highlands, Southern Israel. Note the hilly topography at the background, composed of Eocene marine carbonates (limestone and chalk). Late Pleistocene loess sediments were deposited in the valley. Floodwater resulting from winter rain is the main irrigation source for local vegetation. (Photograph: Y. Avni).

The current climatic conditions in the Negev Highlands are influenced mainly by the Eastern Mediterranean, which is located 80–100 km to the northwest (Figure 1). The mean annual temperature ranges from 17–19 °C, depending on the elevation [58]. The average annual precipitation ranges from 120 mm in the northwest to less than 80 mm in the southeast. Most of the rain events originate in the eastern Mediterranean and occasionally from the Red Sea trough, penetrating the region from the south. The rainy season is between November and March [58].

The origin of the soil in the Negev Highlands is a mixture of fragments of local rocks and fine-grained sediments, mostly silt and clay, which were brought to the region by dust storms from the Sahara and Sinai deserts [7,8]. Most of the aeolian sediments date to the last glaciation phase (ca. 73–18 ka); [12,14]. At the initial stage, these sediments were deposited on the entire landscape, creating an almost continuous alluvial cover. However, a short time after deposition, these sediments were eroded and remobilized into the valleys, where they were redeposited and exposed to several phases of soil formation [8,14]. During the transition to the current interglacial period (ca. 18–12 ka), these fine-grained sediments gradually eroded and were transported to the downstream reaches of the drainage systems. Soil erosion intensified during the Holocene, taking the form of gullies, undermining the alluvial section by creating vertical headcuts 2–4 m in height that gradually migrated upstream [15,59].

The irrigation of these fine-grained sediments by runoff (Figure 3) enables deep percolation of water, leading to soil development and stabilization, which in turn subsidizes the rich assemblage of shrubs and annuals. These soils, if irrigated properly, have agricultural potential (Figures 2 and 4). Runoff generation in this region is formed by the interaction between heavy rain events of local distribution and the exposed rocky surfaces. Wieler et al. [60] reported that different rock types exposed in the region generated different amounts of runoff yield. Brouins and Or [61] reported that the generation of runoff is also possible by exploiting compact loess sediment composing relatively continuous and smooth surfaces. Avni [15] and Avni et al. [12] pointed to positive feedback relations between rock exposure, runoff generation, and soil erosion causing inherent natural desertification during the postglacial and Holocene times.

Figure 4. Ancient agricultural plots used for cereal cultivation in the Negev Highlands, expressing the agricultural potential of the region. Note the exposed bedrock that generated the runoff harvested for irrigation. (Photograph: Y. Avni).

Avni et al. [51] discussed the long debate regarding the stability of the climate in the Southern Levant during the last three millennia. He concluded that the environmental conditions in the Negev Highlands, including the climate, were almost stable, and that the design of the runoff harvesting installations was robust enough to cope with any minor climatic fluctuations imposed on the region during the Late Holocene. This conclusion is supported by the results of a study on the stable isotopic composition of the vegetative cover in the region during the Roman and Byzantine periods, indicating the stability of the environment and climate [62]. In fact, the success of the current desert terrace farming practiced by the local seminomadic population of the region (Figure 4) is another proof of the continuation of the environmental conditions since ancient times.

3.1.2. Marmarica (North-Western Egypt)

The Marmarica Plateau consists of limestone, dolomite, and marls of the Marmarica Formation of Middle Miocene age [57]. These beds form a large plateau (500 by 150 km^2), ranging in elevation between 100–250 m a.s.l. The general landscape dictated by these beds is very flat and slightly inclined toward the north (Figure 4). The Pliocene Marmarican Cliff transvers this plateau parallel to the Mediterranean coast at a distance of approximately 30–40 km inland [23,28]. The transition to the Mediterranean coast is sharp, causing a slope of approximately 100 m over a distance of approximately 20 km, dissected by numerous valleys [23,28].

The region is influenced by its proximity to the Eastern Mediterranean coast (Figure 1). Annual mean temperatures range from 19–21 °C, while precipitation ranges from less than 50 mm in the south to 150 mm in the north near the coast [28]. The hydrological year starts in September, and December and January are the most humid months. A wide range of annual variations in precipitation occurred. Most of the region, particularly the inland area, is arid to hyper-arid [28].

The soil developed in the region originates from sand and silt that form occasional aeolian deposits accumulated along valley bottoms and on shallow depressions developed on the plateau (Figure 5). However, currently, most of the valley slopes are mostly free of aeolian deposits and covered by stone-paved bedrock outcrops [28].

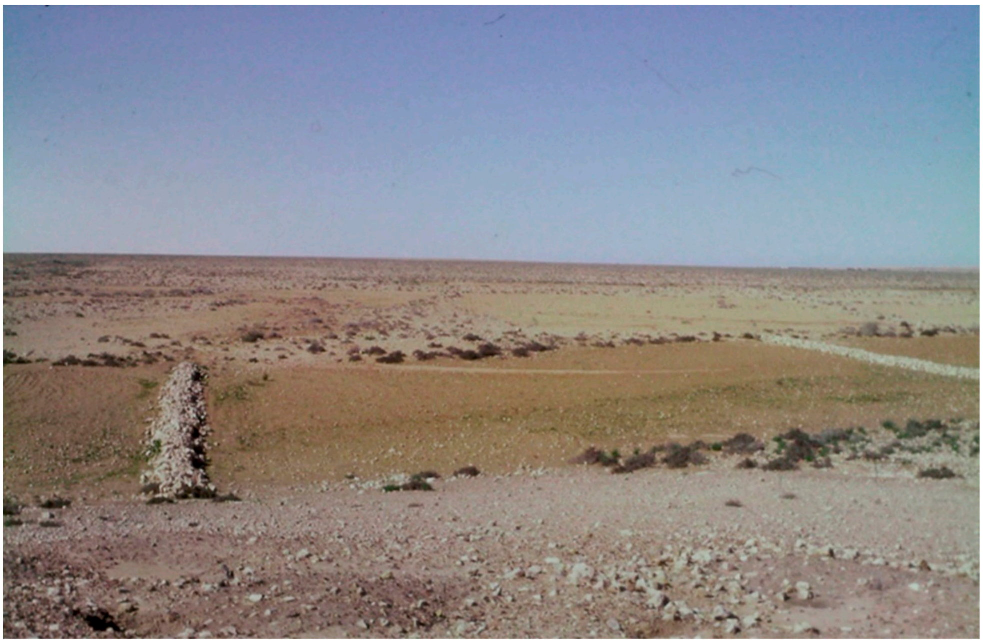

Figure 5. Soil accumulation and agricultural cultivation in the Marmarica Plateau, south of Marsa Matrouh. Note the gentle northward slope of the plateau (from left to right), the fine-grained sediments in the background, and the arable soil accumulated in the shallow valley, cultivated by terrace farming. (Photograph: Y. Avni).

Runoff generation is very much dependent on the interaction between the occasional rain events and the exposed rocks, which are gently inclined toward the north, forming good conditions for runoff harvesting. After proximity to the coast, topography is the main control of overland flow redistribution [28]. In general, barley–livestock systems with additional fruit tree cultivation dominate in the coastal fringes (Figure 2), while cereals are mainly cultivated inland. In this region, the water storage capacity of soils is mainly a function of soil depth. Today, the area is sparsely populated by a rural Bedouin population, with some minor villages scattered within a zone of approximately 20 km width south of the coast. Farther south, settlements cease as arid conditions become more pronounced [23,28].

3.1.3. Petra Region (Southern Jordan)

The Petra region is located at an elevation of 900–1000 m in a rugged desert terrain composed of Precambrian granites and volcanoclastics covered by a thick sandstone section of Paleozoic to Mesozoic age and a thick sequence of marine carbonates of late Cretaceous age ([55]; Figure 5). The main sandstone units composing the region are the Cambrian Umm Ishrin Formation and the Ordovician Disi Formation [56]. Sandstone cliffs, buttes, and mesas together form a rugged terrain, incised by deep valleys and canyons ([55]; Figure 6). The moderately inclined slopes are covered with a thin layer of the weathering residues of marl and limestone blocks, originating from the mountain front located 5–10 km to the east that are composed of Cretaceous marine sediments of the upper Kurnob and Judean (named Ajlun in Jordan) groups [56].

Figure 6. General view of the Petra region from the south. Note that the sandstone units exposed in the slopes of the high mountain range of Gabel Ash-Sharah consist of Late Cretaceous marine carbonates that reach an elevation of 1600 (in the background). Terrace farming is practiced along the slopes and valleys, utilizing the fine sediments deposited on the slopes. (Photograph: Y. Avni).

The Petra region is located in the semiarid to arid transition zone. The predominant sources of moisture are the Eastern Mediterranean cyclones tracking east. The region has a winter rain regime, but torrential rainfall events, contributed mainly from the Red Sea Trough, are common in the spring and fall seasons [63]. In the lowlands of the Arava depression to the west, erratic rainfall averages approximately 50 mm per year, and the mean annual temperature is 25 °C. At the Petra site and its hinterland, the annual rainfall increases to 180–200 mm, and the mean annual temperature decreases to approximately 15 °C due to elevation [63]. In the mountains above the Petra intermediate step, where the elevation reaches above 1600 m, the annual rainfall increases to 300 mm, forming the southernmost extension of the Mediterranean climatic zone in the entire Southern Levant. Farther east, in the rain shadow of the highlands, the annual rainfall again drops below 100 mm.

Remnants of alluvial terraces from the Pleistocene age are found along the major wadis in the Petra region, consisting of poorly sorted gravels and sands [55,56]. Ongoing incision of gullies occurred during the postglacial period and intensified during the Holocene [64]. The sediments and soils containing agricultural potential are composed of unconsolidated fluvial silts and sands that are occasionally embedded with gravel layers (Figure 6). The dominant source rock of the unconsolidated sediments is the sandstone bedrock [64].

Abundant bedrock exposures and steep slopes constitute the quick response of small drainage basins to rain events, with a high runoff coefficient and a short runoff concentration time [64]. However, runoff generation ranges according to the local geodiversity. Granitic batholiths provide large runoff and improved water availability, while sandstone of the Kurnob Group provides low runoff. This is in contrast to the Disi Formation, which generates substantial runoff, even after short rain events, due to its massive bedding creating long and smooth surfaces, as well as its kaolinite cementation [65]. Therefore, flash floods, either channeled in the wadis and gullies or laminar as sheet flows, are a common phenomenon in this area, occurring during and shortly after heavy rainfall events [63].

3.2. Design Patterns and Raw Materials of Agricultural Terraces

All terrace farming installations, such as retaining terraces, dams, spillways, and diverting channels, constructed during antiquity in the rocky arid regions of the Southern Levant consist of local materials, such as rock fragments, extracted from the locally exposed geodiversity at each site. The great geodiversity of the Southern Levant, which exposes rock units from magmatic, metamorphic, and sedimentary origins [53,55,57], provided a large variety of collected or quarried building stones that were utilized by the ancient farmers. However, in cases where rock outcrops were not available in direct proximity to the agricultural fields, the local builders used earth embankments instead of solid stone terraces.

Although great similarities appear between arid terrace farming installations at all sites, the specific environmental conditions and the agricultural demands in each arid zone resulted in slightly different design patterns of terrace farming structures across the Southern Levant.

3.2.1. Negev Highlands

In this hilly and elevated terrain composed mainly of marine carbonates, the good exposure of rock units on the surface (Figures 3 and 4) promoted the usage of solid rock fragments, such as limestone, dolomite, chert, and chalk, as the main building stones for terrace-farming installations. Massive stone terraces were constructed perpendicular to the relatively narrow valleys, retaining walls supporting agricultural plots behind them (Figure 4). In this region, the agricultural plots, stone terraces, and dams occupy approximately 30,000 ha, constructed in conjunction with additional large areas where extensive diverting channels were built, designed for collecting runoff water from hilltops, hillslopes, and wadis. Ashkenazi et al. [66] recognized up to 10 design patterns of agricultural installations in this region. However, according to their hydrological function, they are grouped together into two major types, as follows:

Type A (Figure 7)—low elevated terraces constructed of 1–3 rows of building stones that were placed perpendicular to the valley gradient, aiming to slow and spread the runoff over the entire width of the valley. As no water ponding was aimed at by these installations, this type was especially designed for attaining irrigation suitable for cereal crop production, such as barley and wheat, or for the amplification of the natural biomass for improving the pasture for grazing [51]. Regarding their simple and robust structure, they were able to stand against the flow energy for long periods after their construction, preventing structural damage and soil erosion in the agricultural plots behind them;

Figure 7. Shallow agricultural Type A terraces of in the Negev Highlands designated for the cultivation of cereals. (Photograph: Y. Avni).

Type B (Figures 8 and 9)—highly elevated terraces composed of 6–12 rows of building stones, aiming to trap and pond larger quantities of runoff water to gain deep irrigation. This structure aimed to reach sufficient saturation of deep soils stored in the plot to meet the requirements of domesticated Mediterranean fruit trees, such as olive and grapes [51]. The deep percolation of the trapped water was crucial for achieving long-term preservation of humidity and was capable of overcoming the high seasonal and annual fluctuation in precipitation and flow events, characterizing the arid zone. Wieler et al. [60] showed that most of the Type B terraces and agricultural plots associated with them were designed and constructed in the vicinity of geological units that produced exclusively high runoff yields.

These two primary design patterns have a large effect on the structure of terrace farming installations, such as their height above the natural surface, the amount of soil accumulated within them, and their rule in soil conservation. In addition, the long-term survival of the ancient agriculture installations in this region is very much dependent on the nature of these types. The Type A terrace was only slightly affected by the flow energy during floods and, therefore, survived well over long historical periods. However, the Type B terrace was designed for ponding water and, therefore, interacted with larger quantities of water and drifted soil and sediments, causing frequent siltation of the plots. This inherent problem resulted in the gradual uplift of terrace farming installations above the natural surface, causing gradual physical instability and leading to frequent collapse. Therefore, this type required constant maintenance and even rebuilding of some complete sections of the terrace. The impact of collapse segments resulted in several generations of rebuilt phases, which are clearly seen on the terrace walls at present (Figure 9).

Figure 8. A reconstructed Type B agricultural terrace in the Negev Highlands designated for the cultivation of perennial plants, such as olive trees and vineyards. (Photograph: Y. Avni).

Figure 9. Type B agricultural terrace in the Negev Highlands. Note the collection of building stones used for the construction, composed of limestone and chert collected and quarried slabs. The uneven collection of stones in the middle can hint at occasional collapse and restoration during the cultivation time. (Photograph: Y. Avni).

3.2.2. Marmarica

In this region located in Northwestern Egypt, most of the farming installations were constructed from fragments of the Marmarica limestone collected or quarried in the nearby rock outcrops (Figure 5). Most of the farming terraces occupied one of the two following geomorphic locations: (1) within the relatively narrow streams and valleys dissecting the uplifted plateau gently inclined toward the Mediterranean Sea (Figures 1 and 2), and (2) on the flat plateau that it slightly inclined northward (Figure 5; [23,28]). A sophisticated system of earth and stone channels led the flow water from the inclined plateau to the terraced plots, supplying them with runoff water during rain events. At least four design patterns of terrace farming installations were characterized and described by Vetter et al. [28]. Three of them were constructed in the valleys, forming stone terraces that were placed perpendicular or parallel to the main flow direction (Figure 2), while one (Kurum) was built on the plateau, designed to collect runoff water directly from the tableland. The soil depth accumulated within the valley structures reaches 1–3 m, corresponding to terraces of Type B from the Negev Highlands, while the soil depth on the tableland is limited to 0.5–0.3 m, which is suitable for the cultivation of annuals and, therefore, is attributed to the shallow terraces of Type A from the Negev Highlands.

Although significant on the ground, the exact area that was transformed to arable land due to ancient terrace farming installations was never calculated at the regional scale. Vetter et al. [28] reported that, at present, from the total area of 4200 km^2 that stretched between the vicinity of Fuka and Ras el Gargoub to Marsa Matrouh (Figure 1), 10% is cultivated (42,000 hectares). More than 90% of this arable land is used for barley cultivation, while less than 10% is used for the cultivation of fruit trees (mainly olives and figs; Figure 2). The arable land decreases dramatically southward into the arid–hyper-arid boundary located on the central part of the Marmarica Plateau.

3.2.3. Petra Region

The farming terraces surrounding the Petra site were constructed in valleys curved in the Paleozoic sandstone units, mainly the Um-Issrin and Disi Formations. Among these, valleys containing a high sand fraction and loess remnants, serving as a major source of agricultural soil, were selected for constructing terraced farming installations. Most of the farming terraces consist of large slabs of massive and solid sandstone, locally quarried, occupying mean dimensions of 70-60-50 cm [27]. In addition, some limestone and chert blocks were also used (Figure 10). These were collected from colluvium relicts and abandonment Pleistocene fluvial terraces that are scattered in the region, originating from the high mountain slope to the east of the site (Figure 6).

The ancient terraces formed well-designed agricultural plots organized as staircases, 20–40 m apart, down the wadies, aligned perpendicular to the dominant flow direction (Figure 2; [25,27]). They are up to 5 m high and show signs of gradual uplift or maintenance work after their partial collapse [26,27]. Therefore, these terraces are equivalents of the Type B terraces described from the Negev Highlands (Figure 10). Considering this, no calculation of the total area transformed to arable land by terrace farming was performed in the entire Petra region. However, one must keep in mind that the Petra site is located only 5–10 km west of the high mountain range of Gabel Ash-Sharah, which receives up to 300 mm of rain and is suitable for the production of all Mediterranean crops, cereals, and fruit trees. Therefore, this relatively fertile area could easily supply much of the needs of the Petra population, with no need to invest large effort in terracing in the vicinity of the Petra site itself, especially in places where the construction of agricultural plots would demand a high level of labor.

Figure 10. Ancient Type B agricultural terrace in the Petra region, constructed from massive limestone and chert slabs. Note the uneven collection, probably indicating several events of collapse and reconstruction. (Photograph: Y. Avni).

In all sites in the Southern Levant mentioned above, the Type B farming terraces, aiming to pond large quantities of irrigation water, are accompanied by the constant siltation of the original farming installations by fine-grained sediment which drifted with the runoff. The high siltation rate is caused by the high erosion rates of fine sediments stored in all Southern Levant drainage basins since the Late Pleistocene. The common solution in all regions under discussion was to uplift the Type B terrace structures, row by row, to preserve irrigation capacity in the agricultural plots. This is the constant result of the long-term usage of the farming systems, contributing to their physical instability and to their inherent risk of collapse, expressed by the commonly found indication of maintenance and repair (Figures 9 and 10). However, Type B is the one that accumulated datable sediments, especially by the implementation of the OSL method, which are required for any discussion concerning the historical context of their construction and their operation intervals at different sites.

3.3. Radiometric Dating of Terraces: The OSL Dating Method

The gradual accumulation of fine-grained sediments within the Type B terraced plots appears to be a direct proxy for dating the construction of agricultural terraces. Dating soils that contain quartz grains, such as most soils of the Southern Levant originating from desert dust, has become possible by the OSL dating method, continually developed during the last 30 years [67,68]. The relatively easy process of soil erosion and transportation of the quartz-bearing fine-grained desert dust in the Southern Levant, coupled with the relatively short time required for complete bleaching of quartz grains, made the OSL method the preferred dating technique of terrace farming installations. This dating method was heavily used in the Negev Highlands [12,50,59,69], leading to the establishment of a solid dataset, which was widely accepted for dating the operation of the ancient agriculture initiatives in this region [51].

This is also the case in the Marmarica and Petra regions. In these regions, the OSL method was implemented as a complementary method to large-scale archaeological surveys, aiming to relate the farming installations to the nearby archaeological inventory [25–27,70]. In Marmarica, the OSL-dated samples taken from anthropogenically induced sediments confirm the previous archaeological data but also provide evidence of the accumulation of much earlier alluvial sediments deposited during the Pleistocene–middle Holocene [22]. However, in the Petra region, Beckers et al. [27] reported incomplete bleaching, which is present in almost all samples taken to date the construction and the operation time of the terrace farming installations. Additionally, Beckers et al. [27] noted that some samples showed a weak OSL signal, probably owing to the dominant nearby sandstone outcrops providing quartz grains, coupled with the limited cycles of bleaching, resulting from the torrential nature of floods and a very short distance and time of transportation. However, an overall agreement between OSL ages, radiocarbon ages, and the archaeological record supports the acceptance of the OSL dating method as a reliable method in all regions of the Southern Levant, although some disorders between the stratigraphic order and the OSL ages were reported from all regions (Table 1).

3.4. Time of Construction and Abandonment of Terrace Farming across the Southern Levant

3.4.1. Negev Highlands

Although initiated earlier, the main phase of agricultural terrace construction in this region was in the Late Roman–Early Byzantine period (3–4 century CE; [50]), while in some sites within this region, such as in the Shivta site [69], it started earlier, around the 1st century CE (Table 1). The vast construction of farming terraces in the arid zone of the Negev Highland is attributed to the long period of economic and political relative stability under the Roman and Byzantine rule that enabled the expansion of the cultivated land into the Negev Highlands desert zone [50,51,69]. This expansion period was performed while the environmental markers indicated that the climate during that period was very much in accordance with the present climate [51,62]. All indications from previous research [12,50,51,59] indicated that the abandonment of most of the agricultural plots was dated to the 10–11th century CE (Table 1), and that their decline was the outcome of political and economic changes imposed on the region, with almost no sign of environmental degradation (see below). However, the utilization of part of the best-preserved agricultural plots probably continued during the historical ages to the present time, without adding additional rows of building stones and without the accumulation of additional datable soil within the plots. After their total siltation, most of the Type B terraces were used only for cereal cultivation, in the same way as practiced by the present Bedouin population of the Negev Highlands [71].

3.4.2. Marmarica

Vetter et al. [28], based on Rieger and Möller [70], noted that ceramics collected in agricultural fields during the geo-archeological survey range from the 2nd century BCE to the 6th century CE, and related this finding to the Greco-Roman period of extended land use and settlement expansion in Eastern Marmarica. This age is supported by the direct dating by OSL of the sediments stored behind an agricultural terrace in Wadi Umm el-Ashtan, located 20 km west of Marsa Matrouh, to 2.06 $\pm$ 0.17 ka, which corresponds to the Ptolemaic and the early Roman imperial period ([22,28], Table 1). Vetter et al. [22,28] reported that the colluvial base of the tableland agriculture plot in Wadi Umm el-Ashtan yielded an OSL date of 4.04 +/− 0.43 ka. In addition, the lateral alluvial terrace in Wadi Magid located 15 km southwest of Marsa Matrouh was dated to 3.2 +/− 0.18 ka [22]. These middle Holocene fine-grained alluvial sediments are probably attributed to the pre-anthropogenic stage of alluvial deposition within the valleys, similar to the deposition of pre-anthropogenic units in the Negev Highlands described by Avni et al. [12,59], and, therefore, cannot serve as reliable indications for early agricultural activities. In addition, the main wadi fill of Wadi Umm el-Ashtan was deposited in the late Pleistocene (12–23 ka, [22]). It is important to note that Faersthein et al. [14] presented similar ages of natural loess accumulation in the Negev Highlands. All these are natural accumulations of loess-type sediments deposited during the Late Pleistocene LGM and the postglacial periods over the entire Southern Levant [7,8].

Table 1. Study sites and their geographical, geological, and archaeological significance.

Site Name	Geographic Position	Distance from the Mediterranean Sea	Elevation	Geological Composition	Precipitation	Main Archaeological Periods of Terrace Farming	OSL Age of Agricultural Soil	Present Operation of Terrace Farming
Marmarica	Northwestern Egypt	0–30 km	0–200	Fossiliferous limestone of Miocene age	150–100 mm	Greco-Roman 2nd century BCE–6th century CE	0–500 CE	Yes
Negev Highlands	Southern Israel	80–100 km	300–1000	Limestone, chalk, and chert, Late Cretaceous and Eocene	150–80 mm	1st–10th century CE	200–1000 CE	Yes
Petra	Southern Jordan	160 km	900–1200	Sandstone and limestone Paleozoic–Mesozoic	200–180 mm	2nd century BCE–8th century CE	100 BCE–800 CE	Yes

The abandonment of the agricultural plots in the Marmarica region is dated to the 5th century CE [28]. After their abandonment, the terrace farming installations located within the valleys underwent intensive soil erosion and gulling, leading to their partial collapse, as reported by Vetter et al. [23,28].

3.4.3. Petra Region

The majority of the investigated sections reported by Beckers et al. [27] from Wadi al Ghurab, approximately 4 km north of the Petra site, have a similar stratigraphic sequence, namely a sudden shift from the underlying pebble layers, indicating high-energy fluvial environments, to fine sediments, reflecting low-energy fluvial deposition regimes. This sedimentological shift is usually associated with the construction of agricultural terraces, which caused retention of surface runoff in the upslope areas and forced infiltration and storage of the water in the terrace fills.

The OSL ages indicate that the construction of these terraces and the accumulation of fine sediments started around the beginning of the Common Era (1st century BCE to the 1st century CE; Table 1) and that terrace agriculture was practiced until at least 800 CE [27]. These dates confirm radiocarbon ages and the assumptions made by Kouki [25], based on the archaeological record, that agriculture in the Petra region was rapidly expanding in the first century CE and that agriculture was an important part of the regional economy, even after the decline of Petra as an urban center. The utilization of part of the best-preserved agricultural plots by the seminomadic population probably continued during the historical ages to the present time (Figure 2), in the same way as practiced by the local Bedouin population currently living near the Petra site [25,26]. At this stage, most of the Type B agricultural terraces were used for cereal production without the need to add additional rows of stones and, therefore, were not accumulating additional soil behind them. Therefore, this farming stage was probably not recorded by the OSL signal. In addition, as mentioned earlier, the high mountain range of the Ash-Sahara Mountains, only 5–10 km to the east of the Petra site, was probably a preferable zone for agricultural production to the inhabitance of the Petra region. Therefore, the construction and maintenance of the agricultural terraces in the much degraded and arid terrain surrounding the Petra (Figures 6 and 10) was carried out only during times of enormous population growth, when the demand for arable land reached its zenith.

3.5. Present Practice of Terrace Farming

Patches of ancient agricultural terraces and other farming installations are still in use in all desert zones of the Southern Levant. Therefore, we can track their present function under the present environmental conditions, as well as their role and contribution to agricultural production in these arid zones.

3.5.1. Terrace Farming in the Negev Highlands

The seminomadic Bedouin population of the Negev Highlands utilized the best-preserved ancient plots for agricultural production during the last 250 years ([30,71]; Figures 4 and 11). Most of these plots were used for cereal cultivation while, in small, designated plots with improved runoff irrigation, they cultivated small orchards (mainly olives and figs, but also carob, almonds, and dates; [72]). In the 1:100,000 scale British maps of the Negev south of Be'er Sheva that were published in 1942–1946 [52], approximately 8–10% of the land was characterized as "cultivation in patches". Most of these plots were cultivated for the production of cereals by the local Bedouin population of the Negev Highlands, estimated at several thousand people (Figure 11).

Figure 11. Present barley cultivation in the Negev Highlands, utilizing ancient Type A terraces. (Photograph: Y. Avni).

Since 1950, field surveys and agriculture experiments in the Negev Highlands have highlighted the role of ancient terrace farming as one of the successful methods for small-scale agricultural production [1].

Between 1959 and 1970, Evenari and his team constructed experimental plots within reconstructed ancient agriculture farms in Avedat and Shivta, while a larger area was constructed for mass production in the Shekher farm [1]. The experimental farms were equipped with long-term monitoring devices for climate proxies and runoff yields. In addition, methods for calculating agricultural production were implemented. These long-term studies, and the present vitality of the fruit trees planted in the agricultural plots, clearly show that the multiannual conservation of humidity in the deep loessic soil preserved within the ancient Type B agricultural plots was high enough to support perennial fruit trees, such as apricot, peach, olive, figs, carob, almond, grape wines, and others. As the current climate in the Negev Highlands is arid, receiving approximately 100–90 mm/y of rainfall, it is clear that the utilization of ancient terrace farming is productive, even under the present harsh arid conditions. Therefore, no climatic improvements are required to achieve significant agricultural crops. However, although successful and vital, in terms of modern economic value and quantities, the production of terrace farming is limited to designated plots placed within the valleys, while vast arable land is left fallow as no runoff irrigation could reach these lands.

Currently, most of the agricultural production is of cereals (ca. 98%), while the production of fruit trees is extremely marginal (Figures 3 and 10). However, in terms of soil conservation, the terrace farming plots are considered to be a great success, as no soil erosion processes were active within them. This conclusion refers to any preserved plot that was not breached since its abandonment during the last millennia, while severe soil degradation processes are active in the natural lands and within agricultural plots that were breached, taking the form of riles and gullies, forming extensive badlands (Figures 12 and 13).

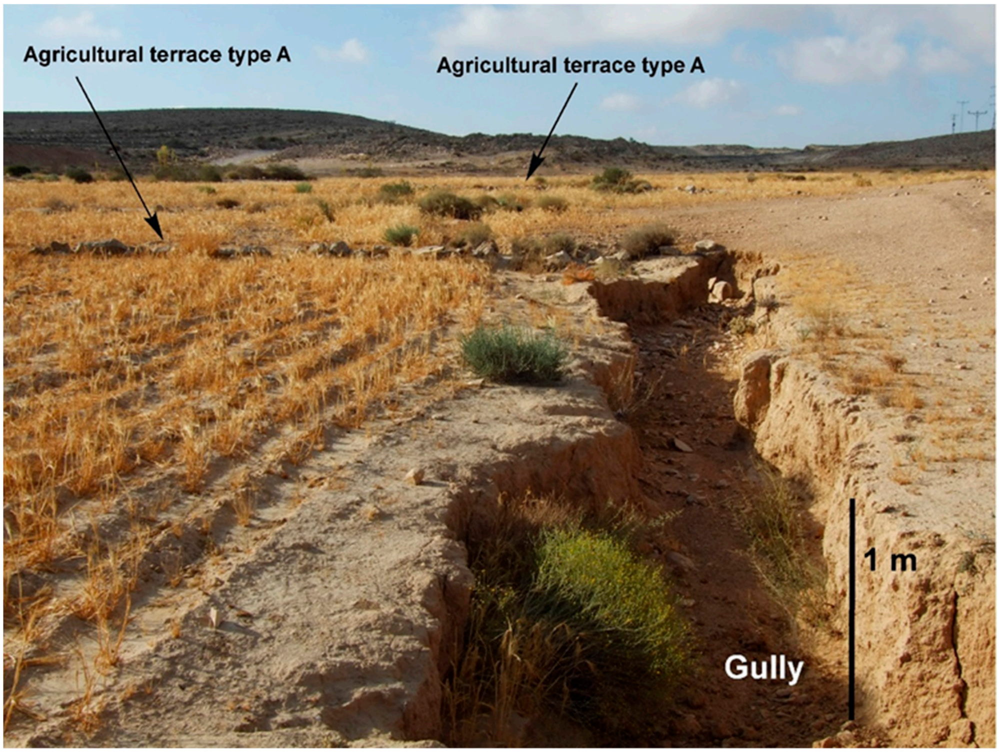

Figure 12. Gully developed within an agricultural plot, dissecting Type A terraces. Negev Highlands. (Photograph: Y. Avni).

Figure 13. Badlands developed within the Type 2 agricultural plot, Negev Highlands. (Photograph: Y. Avni).

The Southern Boundary of Terrace Farming in the Negev Highlands—The Experimental Site near Mizpe Ramon

The southern part of the Negev Highlands is a high-altitude plateau reaching an elevation of 900–1000 m a.s.l. This region is situated on the fringe of the hyper-arid climate zone, defining the southern border of the ancient terrace farming zone. This region, receiving at present an annual precipitation of only 80–70 mm, expresses high annual variability; for example, in 2020, this region received 170 mm, more than 240% of the multiannual rainfall, while in the successive year (2021), it received 28 mm, which encompasses only 40% of the multiannual rainfall.

In a small tributary of the large drainage basin of Nahal Zin located approximately 3 km west of Mizpe Ramon, an experimental agricultural plot was established in 1995 (Figure 14). The plot, occupying 64 m^2, was composed of a retaining terrace consisting of limestone slabs locally collected and placed at the bottom of a small drainage basin, occupying 2000 m^2. Therefore, the agriculture area versus the contribution area ratio was approximately 1:30, in the same range reported by Evenari et al. (1982 [1]) as characterizing the ancient agriculture plots constructed in the same region during the Byzantine period. The rocks exposed in the drainage basin are of the Zafit Formation, composed of well-bedded dolomite (90% of the basin), and the Avnon Formation, composed of massive limestone (10% of the basin; Figure 13). The agricultural soil within the plot, only 1–0.5 m deep, originated from a local relic of loessic apron deposited during the last glacial period, dated to 60–20 ka [12,59]. No fertilizers or organic matters were added to this natural soil since the construction of the plot.

Figure 14. An experimental Type B agricultural terrace plot constructed at the southern fringe of the ancient agricultural zone in the Negev Highlands. (Photograph: Y. Avni).

The plot is solely irrigated by runoff, which appears one to four times a year, mainly during the winter. Regarding the specific rock units exposed in the drainage basin and the hydraulic characteristics of the basin, the minimum rain event required for generating soil saturation and runoff is from 6–8 mm/day [60]. At each runoff event, 20–32 m^3 of runoff water was trapped within the plot (Figure 14). Spillways, made of locally collected stones, control the water level within the plot, and the extra water is released from the plot to the downstream catchment during heavy runoff events.

Five fruit trees were planted within the plot, namely olive, fig, almond, pomegranate, and pear. Since they were first planted in 1995, the Mediterranean fruit trees (olive, fig, almond, and pomegranate) have grown well and are prosperous; however, the pear, which is not a Mediterranean crop and require continues irrigation throughout the summer, is on the edge of survival. This experimental plot is similar to small Bedouin gardens and orchards, which are widespread in the Negev Highland, as reported by Ashkenazi et al. [72]. In most cases, these small orchards utilize ancient Type B agriculture plots, left almost intact from ancient times.

Present irrigation in these orchards is based on the traditional methods of runoff harvesting, mostly by reconstructing the original diverting channels from the nearby slopes. It is important to note that all present orchards were constructed and maintained by the seminomadic population of the region, which has very limited agricultural knowledge. Therefore, although successful, the agricultural production from these plots at present is marginal. However, their presence and prosperity indicate the present agricultural potential of the region, which is maintained until the southern edge of the ancient terrace farming zone of the Negev Highlands.

3.5.2. Marmarica

Currently, the local inhabitants of the Marmarica region are practicing terrace farming by utilizing the same methods as the ancient farmers (Figures 2, 5 and 15). Based on a land-use survey supported by accurate satellite imageries, Vetter et al. [22,28] reported that in the northern tableland close to the Mediterranean coast, the current barley cultivation amounts to 18.5% of the total area, while fruit tree cultivation amounts to 1.2%. When migrating southward, the total arable land shrinks to less than 10% and totally disappears at a distance of 30–40 km south of the coast (Figures 5 and 15).

Figure 15. Recent cultivation in the Marmarica Plateau south of Marsa Matrouh. (Photograph: Y. Avni).

However, Vetter et al. [23] noted that "this land-use structure is not in a sustainable agreement with the ecological potential, since barley cultivation is heavily subsidized by the government, resulting in mechanized plowing of large areas regardless of their pedological and hydrological suitability for cultivation". In addition, he noted that the fruit tree cultivation is quite low because much of the formerly arable areas located along the narrow valleys dissecting the Marmarica plateau have been gullied severely or removed irreversibly by erosion [22,28]. Currently, the agricultural production of the region is concentrated mainly along the coastal plain, and only marginal production is possible on the Marmarica Plateau (Figure 15).

3.5.3. Petra Region

The Petra region is scattered with remains of runoff terrace systems, which are present in almost all sandy valleys in the region, at a distance of 5–10 km north and south of the Petra site. Some of these terrace installations are preserved and still cultivated by the local Bedouins, mainly for cereal production, but most of the Type B terraces are abandoned, and the terrace walls and terrace fills are severely dissected by gullies [27]. In addition, some small-scale orchards are also present in designated locations in this region, cultivating Mediterranean fruit trees, mainly olive, grape, and figs (Figures 2, 6 and 16).

Figure 16. Bedouin orchard near Petra, containing Mediterranean fruit trees. (Photograph: Y. Avni).

The vitality of all these ancient agriculture installations indicates that the method of arid zone terrace farming is still implemented and productive across the Southern Levant, while the current population of the region—mainly seminomadic—is using the same traditional methods of farming and irrigation as the ancient farmers. However, currently, their total agricultural production is low. As indicated by previous research [51,72], the ancient farmers in this region were well-experienced farmers and, therefore, their agricultural production was expected to be much greater under the same environmental conditions.

4. Discussion

4.1. Local Environmental Conditions Enabling Terrace Farming in the Arid Southern Levant

In almost all arid regions of the Southern Levant, the two basic components enabling the establishment of agriculture, namely arable soil and water for irrigation, although scarce, were provided by local desert environments during the entire Holocene. These two vital components are very much dependent on the interaction between the geological and geomorphological characteristics and the local patterns of the arid climatic conditions in each specific region [12].

In most of the Southern Levant, fine-grained sediments originating from desert dust were used as the foundation for agricultural soil. These sediments were originally deposited on the fringes of the desert zone, mainly during the late Pleistocene glacial phase [7,8,14]. Soon after their initial deposition, these sediments were transformed to loess soils, characterized by high water-holding capacity that enables deep percolation of water and preservation of humidity. In the Negev Desert of Southern Israel, these loessic soils are the prime component supporting natural biomass and holding agricultural potential, as the majority of the land is composed of rocks and lacks any local source for generating soil ([15,51]; Figures 3, 4 and 11).

A somewhat similar situation is observed in the Marmarica region of Northwestern Egypt, as the thin cover of fine-grained sediments was brought to this region, composed mainly of hard limestone rocks, by wind ([23,28]; Figures 5 and 15). However, in the Petra region of Southern Jordan, the sediments used in most of the terraced plots were composed of coarse sand grains originating mainly from local sandstone units of Paleozoic and Mesozoic age. This local component was mixed with a finer fraction originating from desert dust, which possibly represents long-range dust transport during the entire Holocene ([27,73]; Figures 6 and 16). In these arid regions, runoff is generated during rare events of heavy rains penetrating the desert zone (Figure 2). Most of the rain affecting the Marmarica region and the Negev Highlands originates in the eastern Mediterranean Sea during the winter season. However, part of the rain in the Negev Highlands and the Petra region originates from the Red Sea Trough, which is a monsoon type of rain cell characterized by much heavier, although shorter and localized, rain spells, generating powerful flash floods [63,74].

In all regions, rainfall forming high-intensity showers is transformed to surface runoff, especially when the rainfall interacts with rocky surfaces exposed during postglacial erosion processes [10,12]. However, during heavy rains, dense loessic sediments composing smooth surfaces also contribute to runoff generation [61]. The runoff-contributing surfaces show great variation in the Southern Levant, as a reflection of its wide-range geodiversity. Massive fossiliferous limestone beds crop out in the Marmarica region, composing relatively long and smooth impermeable surfaces, with high hydraulic conductivity, slightly inclined toward the north [22,28]. These conditions make these rocks excellent for runoff generation, as the rock bedding and surface inclination are in accordance with the general direction of the rain fronts originating in the Mediterranean Sea.

In contrast, well-bedded limestone and dolomite interbedded with clays, chalk, and flint are exposed in the Negev Highlands of Southern Israel (Figures 2–4). This wider geodiversity dictates very different rock-climate interactions in each location. In the majority of this region, the hillslopes are not uniform and relatively short, as dictated by the geological structure of the Negev Highlands, which is composed of synclines and anticlines of Cretaceous age [53]. Therefore, runoff generation is very much dependent on the specific conditions at the site, influenced by the type and hydraulic characteristics of the local rock formation exposed on the surface and its inclination, length, and aspect relative to the main direction of the rain fronts coming mainly from the Mediterranean Sea. As a result of these complex relations, ancient farmers must have carefully selected the location of their agriculture plots by analyzing all cardinal components vital for achieving improved and reliable runoff ([60]; Figure 4).

A third case of runoff generation is demonstrated in the Petra region, where runoff is produced from the sandstones of the Umm Ishrin and Disi Formations [55]. Of special importance is the Disi Formation, which forms relatively flat and long slopes, generating a high runoff coefficient relative to other rock units exposed in the region. Therefore, most of the terrace farming agricultural enterprises were placed in valleys and streams that were fed by runoff originating in this formation. Another usage of the Disi Formation is for the construction of large water cisterns and water reservoirs, utilizing its impermeability due to its hard kaolinite cementation [65].

It is important to note that in all the different regions of the Southern Levant, the specific locations selected by the local builders for the construction of the terrace farming installations demonstrate a deep understanding of the local geodiversity and the arid environment conditions, as indicated by Wieler et al. [60].

4.2. The Establishment of Terrace Farming in the Arid Southern Levant

In all regions of the Southern Levant, the coexistence of three components—soil, rocks, and climatic conditions—provided the basic components for the establishment of desert agriculture based on runoff harvesting throughout the Holocene. Although still under debate, it is widely accepted that in the Mediterranean climatic zone of the Levant, the basic components of terrace farming installations, such as retaining walls, leveled agricultural plots, and diverting channels for irrigation, were already well known and implemented in the Bronze Age, at least since 4000–2500 BCE [75–77]. For example, the agricultural plots near Tel Yarmouth in central Israel were dated to the Early Bronze age (4000–3500 BCE, [76]). Finkelstein [78] proposed that the introduction of large-scale terracing into the Canaan Highlands occurred during the first half of the 2nd millennium BCE, and possibly even earlier [79]. At this time, early occupation of the arid zone of the Southern Levant by pastoral societies is well documented in the archeological record [16,17,22]. In the arid zone of Wadi Feinan on the eastern margin of the hyper-arid Arava Valley, Barker et al. [20,48] described a succession of agricultural plots irrigated by floodwater that were developed during the Bronze Age, Iron Age, Nabataean, Roman/Byzantine, and Early Islamic periods. Some of these early structures were described by Barker [21] as representing “agropastoralism”.

It is important to note that the brink of the Mediterranean agricultural zone is located relatively short from the arid zone (5–10 km to the east of the Petra region; 40–80 km to the north of the Negev Highlands) (Figure 1). Therefore, it is reasonable to assume that the relatively simple method of terrace farming, widely distributed across the entire Mediterranean zone [80], was well known to the inhabitants of the arid zone of the Southern Levant that were in constant contact with the sedentary zones. Another issue of wide agreement is that these early inhabitants had the qualifications for establishing basic farming installations. This is proven by the construction of their own settlements made of stone, spread over the entire arid zone of the Southern Levant [81]. However, for pastoral societies, the application of this method was probably directed at the enrichment of natural vegetation for herding by leveling small-scale designated plots [18,19], in the same way as has been carried out by the local population of the Bedouin in the last centuries in the Negev Highlands [71].

Therefore, the timing for the establishment of agricultural terrace farming in vast regions of the arid Southern Levant was not a question of a new technology, gradually penetrating into the arid regions, but rather the emergence of a critical need to implement the well-known technique of terrace farming in the inconvenient harsh arid environment.

In all regions, the establishment of terrace farming in the arid Southern Levant was based mainly on the cultivation of Mediterranean crops, such as serials (barley and wheat), while fruit trees, such as olive, grapes, figs, carob, pomegranate, and others, were only slightly cultivated. These perennial crops required sufficient soil moisture during the whole year to be productive. However, all Mediterranean fruit trees are highly tolerant to long periods of water shortage, as characterizes the long and dry summer conditions in the Mediterranean climate zone and, therefore, were adopted in arid terrace farming [1]. Experiments and observations performed in all regions indicated that deep loessic soils are capable of the long-term preservation of humidity needed for the survival and productivity of these crops, including during repeated droughts. However, cereals need only three to four months of sufficient soil moisture to achieve an appropriate yield, which is totally dependent on the duration of the runoff events. These crops are the most important for the ancient inhabitants of the arid zone of the Southern Levant, as they are for the seminomadic population inhabiting these regions at present [22,28,71].

4.3. Political and Economic Circumstances Promoting the Establishment of Arid Terrace Farming across the Southern Levant

As indicated in Table 1, the exact timing for the establishment of the main phase of desert agriculture varies between the arid regions under discussion (Figure 17).

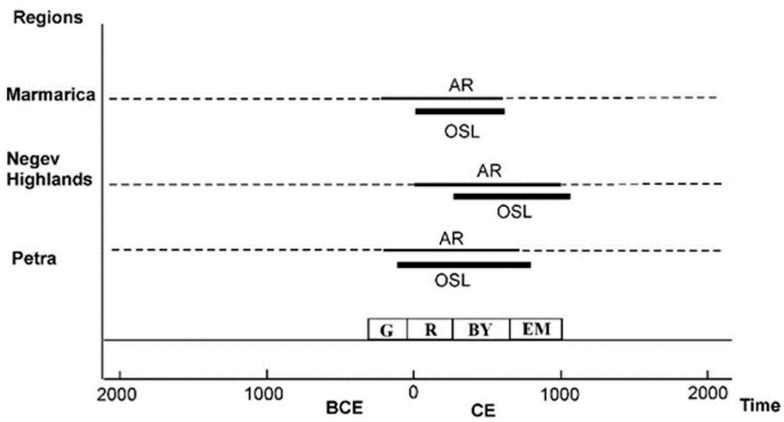

Figure 17. Operation time of large-scale terrace farming in different locations in the arid Southern Levant. Solid line—timing according to Archeological Surveys (AR). Thick solid line—timing according to OSL dating. Dashed lines—minor construction and utilization of arid terrace farming. Here, G is Greek era, R is Roman era, BY is Byzantine era, and EM is the early Muslim era.

The main construction phase of terrace farming in the arid zone of the arid Negev Highlands was in the 1st–2nd century CE and lasted until the 10th–11th centuries CE [50,69]. During this long period, a high demand for agricultural production was reported in the entire Levant, following the establishment of the Roman–Byzantine Empire. This was followed by a peak in population and agricultural production in the regions bordering the arid zone, along with the development of a large economic value for agricultural goods, such as olive oil and wines [50,69]. It seems that the expansion of terrace farming was part of the natural growth and development of Byzantine settlements in the Negev and not the outcome of a planned imperial enterprise [50].

The methods of runoff harvesting previously implemented in all regions of the Southern Levant were locally improved and adapted to the local environmental conditions, resulting in more than 10 design patterns of terrace farming installations [66]. This indicates that the constructions were built by local farmers and not by imperial design or organized labor by an external force. This conclusion is supported by the high correlation between the location of the agricultural plots and the highly productive runoff generation units, as indicated by Wieler et al. [60], attesting to the high environmental knowledge expressed by the local farmers, likely achieved by their long experience in this desert zone. However, as the agriculture installations seen today on the ground were constantly built until the 9th–10th century [50], there was sufficient time to achieve this local adaptation as seen today.

As indicated by archeological surveys [35–40,42], a large number of vine presses and even olive oil presses found in the Negev Highlands signposted the large-scale production of agricultural goods from this region, while surpluses were probably shipped to other commercial centers further north of the arid zone. This evidence is a clear indication that this marginal region on the fringe of the major desert belt was integrated into the global economy of the Roman–Byzantine world.

In contrast, the vast construction of desert terrace farming in the Marmarica region, as indicated by the indirect and direct dating of the farming installations, was already in place by the Greco-Roman period (332 BCE–395 CE; Figure 17), while the region experienced a general population growth indicated by a peak in the number of settlements [22,28]. The archaeological investigations provide plenty of evidence, particularly pottery production and archaeo-botanical and zoological remains [70,82], demonstrating that the Marmarica region produced a surplus of agricultural goods during this period. This surplus production was reconstructed mainly from the existence of numerous pottery production sites along the coast and on the tableland, dated to between the 2nd century BCE and the 5th century CE. The workshops' production was mainly transport amphorae, indicating that, as in the Negev Highlands, vines and wines played a major role in the range of cultivated crops as the base for the regional and possibly global economic production at that time.

The construction of the terrace farming installations in the vicinity to the Petra site goes well with the expansion of the population, grounded by the Nabataean trade routes and the establishment of the Nabataea Kingdom (3nd BCE–2nd CE; [25,26]; Figure 17). However, as better environmental conditions for establishing agricultural enterprises are available a short distance (5–10 km) east of the Petra site on the slopes of the Ash-Sharah Mountains, the actual construction of terrace farming in the relatively harsh and ragged terrain surrounding the Petra site (Figure 6) was only during the period of high demand for arable soil. The direct dating of agricultural soil stored behind terraces reported by Beckers et al. [27] indicates that these agricultural terraces were constructed around the beginning of the Common Era (1st century CE). At that time, Petra was a political and economic center, and its population substantially expanded.

General Remarks

At all sites, the establishment of large-scale terrace farming agricultural enterprises was performed in accordance with the population growth and the increase in the economic value of arable land in each region. The large spreading of agricultural installations in the Marmarica region is dated approximately 400 years earlier than the main example of farming terrace construction in the Negev Highlands, while the construction of the terrace farming installations in the vicinity of Petra is dated back to 200–300 years before almost the same installations were constructed in the Negev Highland (Figure 17).

Therefore, these agricultural enterprises were constructed in each arid region of the Southern Levant diachronically, according to the local political and economic circumstances. This diachronism ruled out any attempt to connect the vast construction of terrace farming in these arid regions to the propagation of new methods into the region or to wet climatic spells imposed on the Southern Levant deserts, as previously claimed [83,84].

The different design patterns of agricultural installations in each region indicated that local farmers constructed their own terrace farming installations in each desert zone. This conclusion opposes previous suggestions on imperial forces being responsible for the vast construction of these agricultural enterprises (see discussion in Avni et al. [50,51] and Shahack-Gross and Finkelstein [19]). However, all farmers used the same variety of runoff-harvesting techniques, and they all invested large efforts to erect retaining walls and farming terraces, solid enough to stand against the powerful floods that characterize these arid regions. Therefore, there are large similarities in their general construction and function across the Southern Levant.

It is important to note that general similarities are also found when comparing the terrace farming installations of the arid Levant region to terrace farming installations constructed in other arid regions of the world, such as in the northern Atacama Desert in Peru [85,86] and in the arid regions of North America [87]. Although constructed by totally separated societies that were not distributing any kind of agricultural knowledge between them, the outcomes are very much similar.

4.4. Long-Term Function of Farming Installations: Terrace Farming as an Indication of Near-Stable Climate Conditions in the Levant during the Last Two Millennia

One of the characteristics of terrace farming in the arid regions of the Southern Levant is its long-term function over the last two millennia. It is clear that the continuation of terrace farming was achieved due to their relatively simple design, and good adaptation to local geodiversity and climatic patterns in each arid region. Therefore, we can conclude that these structures are robust enough to overcome all environmental changes imposed on these diverse arid regions during the last 2000 years (Figure 17). In this way, the continuous practice of desert farming is contributing to the long debate concerning the general stability of the Holocene climate in the Southern Levant and its influence on human civilization [84] versus [51,62]. Regarding this debate, Avni et al. [50] concluded that "a direct link between the rise and fall of desert runoff agriculture and the claimed climatic changes in the Southern Levant seems unlikely".

During the last century, the local seminomadic population of the Southern Levant continued to practice terrace-based farming methods, resulting in small-scale agricultural enterprises, which hinted at the agricultural potential of these arid regions. However, it is important to remember that the agricultural cultivation as seen at present is only a portion of the true agricultural potential of these arid regions. The Bedouin population in all regions is practicing agriculture as a secondary occupation relative to herding, which is their primary economic profession. Therefore, due to their marginal economic value, the Bedouin population only partly uses old terraces and mainly uses them for low-grade cereal cultivation [22,28,71]. Another important factor limiting Bedouin investment in desert terrace farming is the limited labor resources allocated for the construction and maintenance of agricultural constructions, especially of the Type B installations. This is in contrast to ancient times, when farmers probably organized together to establish communal enterprises of terrace farming and runoff harvesting installations. These results suggest that the social and economic structure is the chief factor in increasing agricultural production in the arid regions of the Southern Levant, and not the climatic or environmental conditions, which remain nearly constant [51,62].

However, it is important to bear in mind that agricultural cultivation in all arid zones will always remain a marginal production, highly influenced by annual fluctuation, relative to the more humid agricultural zones. In addition, modern mass agricultural production in much fertile regions located relatively short distances from the Southern Levant deserts and improvements in transportation means during the 20th century decrease the present need for large investments in agricultural production in these less profitable regions. Additionally, as a result of the implementation of heavy machinery in modern agriculture practices, terrace farming has become marginal in all global locations [4,5].

4.5. Future Implications of Arid Zone Terrace Farming in a Warming World

In arid regions worldwide, arable soils are under cardinal risk because of aggressive soil erosion processes ([15,23,28,59]; Figures 11 and 12). This ongoing erosion is expected to increase in the future as the impact of extreme climatic conditions, inducing powerful floods and droughts, is expected to grow under the increasingly warming climate [86]. Considering the expected growing demand for arable land and agricultural production in future times, these warning signs are alarming.

However, regarding the gradual change in our understanding of the critical importance of these terraced arable lands, which were very productive in the past, a new chapter of terrace farming in arid lands is expected to be attained. One of the clear benefits of terrace farming in a warmer world is its role in the preservation of humidity in deep levels of soils, which is vital for maintaining the productivity of most agricultural crops, especially perennial plants. In addition, terrace farming, if maintained properly, provides excellent conditions for soil preservation, protecting them from soil erosion and gullying [4,5]. Therefore, over the last two millennia, terrace farming in arid regions has been demonstrated to be one of the best strategies for increasing agricultural productivity while combating accelerated soil erosion and its related desertification [12,51].

The past and present state of desert terrace agriculture, multiplied by the potential of developing more arable land by providing means for additional irrigation from sophisticated methods of runoff harvesting, can increase the capability of these presently marginal lands to become more productive in the future. Another improvement for increasing agricultural production can be achieved by adding supplementary water supply from other resources, such as subsurface water reservoirs, to achieve constant and improved agricultural production in terrace farming. In this way, additional potential arable lands, located at present in places that are beyond the capacity for irrigation by runoff harvesting methods, will become irrigated and productive. This will amplify the general agricultural productivity of terrace farming in arid zones.

5. Conclusions

In the arid Southern Levant and Northern Africa, natural conditions prevailed during the Holocene and promoted the emergence of local-scale agricultural production based on the availability of arable soil and runoff. The emergence of low-grade terrace farming was probably carried out in synchronism with pastoralism, aiming to improve natural vegetation (especially grasses and cereals; Figure 17). However, the move from the limited actions of improving natural vegetation toward large-scale terrace farming, aiming to amplify agricultural production, demands vast investments in labor and improved methods for irrigation. Therefore, large-scale terrace farming in arid lands was only constructed as a result of high population growth in the fertile regions bordering the arid zone, imposing economic pressure and economic opportunities on these marginal arid lands (Figure 17).

The ability of the arid zone to join this economic prosperity by increasing its agricultural production was very much a combined effect of the capability of the arid zone to provide arable lands and to irrigate these lands by local water resources, such as runoff water. Under these conditions, the best agricultural method that was practiced in vast areas throughout the Southern Levant was terrace farming in its arid version, taking the form of runoff harvesting installations designed for the irrigation of designated terraced plots.

The results of this study showed that the environmental conditions in the Southern Levant provided the natural components of soil and water throughout the entire Holocene, and that terrace farming, although practiced only on a minor scale, was a well-known method to the early inhabitants of the region. However, the actual implementation of the vast phase of terrace farming was diachronic across the region, according to the political and economic circumstances at each location. These conditions were first achieved in the Marmarica region of Northwestern Egypt (2nd century BCE) and then in the Petra region of Southern Jordan (1st century BCE–1st century CE) and only later in the Negev Highland desert (2nd–3rd century CE; Figure 17). The large variety of design patterns recognized over the Southern Levant indicates that the builders of the agricultural installations achieved good adaptation to the variable local environmental conditions and to their farming needs. Another important conclusion was that these constructions were built by local farmers and not by governmental organized labor arranged by external forces, such as army units or imperial engineers. As such, the outcome of this operation was probably a relatively uniform design accompanied by much massive construction.

Since terrace farming constructions were built and the environmental conditions were kept almost constant during the late Holocene, the opportunity to use them was maintained through all historical ages. This is proven by the continued usage of a portion of the agricultural installations by the seminomadic population of the region and by the agricultural experiment plots that were reconstructed and reused in the same regions during the last decades. However, it is important to note that very similar terrace farming installations are widespread over other arid zones worldwide, constructed by nonconnected societies, such as in the Far East and across the American continents [4,5]. This indicates that the terrace farming method is a product of human adaptation to the basic and simple demands of agriculture, namely soil protection and irrigation that promote agricultural productivity.

The adaptation of terrace farming to almost all topographical and climatic conditions on a global scale is vital in the present and will be even more important in the future, as climate changes caused by global warming are expected to negatively affect agricultural productivity globally.

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