Settlement Sizes and Agricultural Production Territories: A Remote Sensing Case Study for the Early Bronze Age in Upper Mesopotamia

Tuna KALAYCI*

Laboratory of Geophysical-Remote Sensing & Archaeoenvironment, Institute for Mediterranean Studies (I.M.S), Foundation for Research & Technology, Hellas (F.O.R.T.H), Melissinou & Nik. Fora 130, PO Box 119, Rethymnon, 74100, Crete, Greece

Abstract

Archaeological data from Upper Mesopotamia provide ample information on the extent of agricultural production territories around tell-based nucleated settlements as well as site sizes—as a proxy for ancient populations. In following, this study investigates the potential relationship between settlement sizes and food production levels during the Early Bronze Age. To start with, CORONA imagery is used to document landscape evidences of past production and settlement sizes. Second, a biological crop-growth model is built over AVHRR-NDVI data, coupled with precipitation values from the region. This model makes it possible to estimate annual production amount at sample locations. Finally, modern day production analogies are constructed in order to explore modelling data and to understand rain-fed agricultural strategies in the Early Bronze Age. CORONA-AVHRR remote sensing survey results reveal no significant relationship between archaeological sites and their production territories (r=0.40). Likewise, the relationship between site areas and estimated staples production is also a weak one (r=0.30). On the other hand, if one considers biennial fallowing as a production strategy, the relationship becomes significant (r=0.85). Furthermore, model data suggests only settlements smaller than 50 hectares were potentially practicing biennial fallowing—suggesting population pressure on production at larger settlements.

Statements of significance

The study challenges the normative assumption that there is a direct relationship between populations and local agricultural production. The analysis is possible only when the production landscapes are considered as dynamic environments, responding to changes in the environment, but also influenced by the choice of production strategies.

Data availability

Production statistics (tons/ha) are available for the years between 1982 and 2006 in shp format as a supplement to this paper.

Keywords

Early Bronze Age; Upper Mesopotamia; CORONA; NDVI; agricultural intensification; production territories

Received 18 May 2015; accepted 7 October 2016

*Email: tuna@ims.forth.gr

© 2016 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

STAR201620548923.2016.1247512
1. Introduction

Scholars have traditionally accepted that larger archaeological settlements must have been occupied by larger populations, and thus, more food must have been procured to sustain everyday life. On the other hand, this relationship between consuming populations and food production is usually investigated “under ideal circumstances” and “highlights the problem of … linear constructions” (Wilkinson 2005, 128). Furthermore, theories borrowed from early economic geography, such as Central Place Theory (Christaller 1933) or von Thünen’s Land Use Model (1966) remain static in explaining the extents of ancient production zones —as a proxy for total food amounts (Wilkinson 2005). A deeper understanding for the conditions of population-production relations remains harder to achieve for ancient times.

Even though an increase in total population indeed requires more food consumption, assuming a direct association between local production and population pressure is often problematic. First, a high population may not have necessitated local production, but instead food might have been imported from other regions, including neighboring hinterlands (Curvers and Schwartz 1990). Extracting foodstuffs through political relationships or exchanging locally produced crafts for food were other possibilities for feeding populations (Feinman, Nicholas, and Middleton 2001). Also, work animals, such as horses and donkeys as well as sheep, goats, and pigs must have required significant amounts of agricultural surplus (Halstead 1989). Therefore, it is not immediately possible to claim that more agricultural production implies higher human populations. Overall, this is also to say a large archaeological settlement may not have required a large sustaining production territory, due to its potentially multifaceted socio-economic and cultural background.

Despite such inherent complexities, models based on Site Catchment Theory (Vita Finzi and Higgs 1970) provide a commendable starting point for the investigation. The main premise behind these models is that as travel time from a settlement increases, land-use intensity around that settlement drops. Furthermore, if traveling is equally possible in all directions (i.e. isotropic movement) and if settlement is located on a flat terrain then a site’s catchment is circular in shape and that settlement is located at the center of its territory. On the other hand, ideal conditions of this kind are hardly visible in the archaeological record and criticisms call for drastic modifications in models (e.g. Smith 2003). Remarkably, however, Upper Mesopotamian site territories during the second half of the Third Millennium BCE may be represented with an idealized model; mid-to-late Early Bronze Age (EBA) tell-settlements were noticeably located on flat terrains and their site-catchments were almost circular (Wilkinson 1994).

In order to exploit this unique archaeological landscape and to advance beyond static investigations of archaeological sites and their production territories this study aims to assess agricultural...
production levels EBA habitants might have achieved. To accomplish this, modern production levels are considered as a proxy for ancient food production. The modern agricultural landscape is constructed through the use of Normalized Distance Vegetation Index (NDVI) values, precipitation levels, and precipitation-evapotranspiration relations in this semi-arid region. EBA settlement sizes and their production areas are documented on CORONA images. As for the conclusion, production variations across Upper Mesopotamia are highlighted. More importantly, the results of this study challenge the normative assumption which states that there is an immediate relationship between ancient population and foodstuffs to feed that population. Finally, the model is successful in capturing possible deviations in production strategies.

2. Study Area

Upper Mesopotamia is the vast semi-arid zone between the Tigris and Euphrates Rivers. To the north, the area is bounded by high altitude Anatolian Mountains. Other than large ancient settlement mounds and two major anticlines, called the Jebel Sinjar (920 meters) and the Jebel Abd al-Aziz (1480 meters) (Brew, Litak, and Barazangi 1999), there are no significantly obtrusive features in the physical landscape. Basaltic plateaus in the area (Ur and Wilkinson 2008) are slight modifications in the gentle topography of the region (Figure 1).

Modern-day Upper Mesopotamia has a semi-arid climate. Average rainfall ranges from 100 mm to 600 mm per year; precipitation increases towards the northern mountain ranges. To the south, precipitation levels critically drop under 200–300 mm/year—a threshold for dry-farming (Wilkinson 1994). Rainfall also decreases from west to east due to mountains running along the Mediterranean coast which create rain shadows for the inner sections of Upper Mesopotamia. Low rainfall in one part of the region indicates low rainfall in another area and vice versa (Wilkinson 1994, 501).

2.1. Archaeological Background

The later Early Bronze Age in Upper Mesopotamia had at least two major cultural developments; rapid urbanization and agricultural intensification based on dry-
farming strategies. These developments drastically changed the Upper Mesopotamian cultural landscape and left physical marks which are still visible today.

In the second half of the Third Millennium BCE some EBA sites grew significantly, forming a distinctly urban pattern and new settlements were formed around larger central places, creating a settlement hierarchy. Tell Leilan with the initial size of 15 hectares reached to 90–100 hectares (Weiss 1983). At the peak of urban period Tell Brak was as big as 65 hectares (Emberling et al. 1999). Hamoukar, a prominent tell site in eastern Upper Mesopotamia extended as much as 105 hectares (Ur 2002). In the Iraqi Jazira, Tell al-Hawa may have been as large as ca. 60 hectares (Wilkinson 1994). Due to their immense sizes, these nucleated tell-settlements are easily distinguishable in the landscape and almost invariably discernible on CORONA images (Figure 2).

In regards to agricultural production, two landscape signatures provide clear evidence; sherd scatters and hollow ways. Archaeological surveys around Tell es-Sweyhat (Wilkinson 2004, 1:55–81), Tell Beydar (Wilkinson 2002), Hamoukar (Ur 2008) and Tell al-Hawa (Wilkinson and Tucker 1995) revealed dense sherd scatters, surrounding these settlement mounds. Wilkinson (1994) strongly argues that these scatters form the evidence of ancient manuring during the mid-to-late Early Bronze Age. According to his model, ancient producers applied manure to agricultural fields in order to intensify production. The manure was most probably composed of night soils and domestic wastes which must have also included broken sherds. This centuries-long manuring process resulted in increased pottery densities around settlements and is detectable through archaeological surveys.

The other landscape feature in Upper Mesopotamia which is related to agricultural production is the so-called the hollow way (Ur 2003; Casana 2013). Hollow ways are recessed linear features, cross-cutting the landscape at different lengths and angles. In some cases, they radiate from settlements and bifurcate after a distance, averaging 2.5 to 3 kilometers (Figure 3). In other cases, they extend further in the landscape and connect settlements to one another. Wilkinson (1994) suggests that hollow ways radiating from ancient settlements were used for the transportation of flocks from settlements to open pasture land. While moving, livestock was kept in large groups to minimize crop damage and when the agricultural production boundary was passed flocks were dispersed in open pasture land. As a result of this continuous use by animals (as well as humans), linear depressions around settlements were formed, and thus, the terminal points of these hollow ways indicate the extents of agricultural production.

Even though sherd scatters provide clear evidence for the intensification of agriculture, detection of these off-site features via remote sensing is a challenging task (Kalayci 2010). Among these two landscape signatures, only hollow ways are clearly visible on aerial/satellite imagery (van Liere and Lauffray 1954; Ur 2003). Therefore, in this study only the remnants of ancient road systems are used in order to model agricultural catchments of Early Bronze Age settlements.

Figure 3 Tell Brak is one of the most important centers in Upper Mesopotamia during Early Bronze Age. Hollow ways, radiating from this settlement are visible on CORONA imagery (DS1102-1025DA013, December 11th, 1967).
2.2. Problematiques

Two politico-economic issues of the mid-to-late Early Bronze Age require further attention for the investigation of population-production relations; agro-pastoralism and the tributary system. The staples economy and its relation to other production domains (e.g. pastoralism) and the flow of agricultural surplus between EBA sites (mainly from peripheral sites to central settlements) must have impacted local production decisions both in the upper and lower tiers of settlement hierarchies.

The connection between plant and animal economies is a complex one. This relationship is inherently linked to the ecologies of risk and the ways in which the risk was absorbed by local communities (Wilkinson et al. 2014). First, it is highly plausible that animal products contributed to total food availability. Integration of livestock into farming in order to buffer crop failures are well attested (Halstead 1990; Morton 2007). This might have been especially true for the complex EBA economies in which elites and royal households were able to mitigate crop failure (Wilkinson et al. 2014, 57). Second, the transition from flax to wool based textile production must have affected labor organizations and gender relations (McCrorston 1997), but also the structure of agricultural land use (Lawrence and Wilkinson 2015, 337). Zoarchaeological evidence further suggests a more specialized mid-to-late Early Bronze Age economy based on sheep and goats in contrast with the earlier more diversified herding practices (Stein 2004). In sum, the agricultural surplus consumed by animals and the amount of pastoralist products contributing to the diet (but also the contribution of other garden vegetables) complicates the investigation of population-production relations.

In regards to the tributary system of the mid-to-late Early Bronze Age, Wilkinson (1994) reveals the structure of dry farming states in Upper Mesopotamia. According to the model, growing centers were recipients of agricultural surplus to feed their populations. The secure flow of foodstuffs must have been especially necessary in drought years. This must have contributed to the creation of a dense network of interactions between settlements not only for subsistence reasons (Kalayci 2013), but also for the sustainment of socio-political relations in the form of royal visits (Sallaberger and Ur 2004; Ristvet 2011).

Dynamic population-production relations require elaborate investigations. For the sake of simplicity and operationality of the proposed model in this study, agro-pastoralism and the tributary structure of hierarchical settlement pattern are omitted from the analyses. This is also to say that animal products are not factored in the staples economy and settlements are considered to be in isolation and no external movement of foodstuffs is considered in the analysis.

3. Methodology

3.1. Mapping Early Bronze Age Settlements and Hollow Ways

A National Endowment for Humanities (NEH) funded project, the “CORONA Atlas of the Middle East”, developed efficient means of photogrammetric correction and now provides an extensive image database for orthorectified CORONA images (corona.cast.uark.edu). The project offers a unique opportunity to explore landscapes in a comprehensive manner at multiple spatial and temporal scales (Casana, Cothren, and Kalayci 2012). Using this digital atlas, one can now perform a remote sensing based archaeological survey of Upper Mesopotamia and identify Early Bronze Age sites, due to their unique morphology (Figure 2). In such an effort, more than 1000 nucleated tell-settlements were visually documented, most of which possibly dated to Early Bronze Age (Kalayci 2013).

CORONA was deployed before the state sponsored constructions, industrial-scale agriculture, and urban expansion in the Middle East. The impact of these modern developments on the preservation of ancient material culture is significant (Casana, Cothren, and Kalayci 2012). Considering the problems in obtaining historic aerial photographs in the Middle East (Philip et al. 2002), the value of CORONA imagery as a snapshot of the area before the drastic landscape transformation is beyond doubt (Philip et al. 2005).

CORONA imagery is used to document and analyze hollow ways (Ur 2003). Roads radiating from mounded settlements appear on CORONA imagery in distinctive forms mostly due to their differential water retention capabilities (Figure 3). A structural comparison of hollow ways is also given by Casana (2012, 13). Briefly, soils filling recessed hollow ways are less reflective in comparison to hollow way edges, and thus, they appear darker on greyscale images. Likewise, water drainage at the edge of hollow ways is more due to the morphology of these features. Also, inward sloping sides reveal the calcium carbonate rich soil horizon after erosion (Wilkinson et al. 2010, 748). This unique structure makes hollow way boundaries to appear in bright colors attributable to high reflectivity (Ur 2003, 106). Previous mapping projects based on visual assessment (Ur 2002) or semi-automated approaches (Menze and Ur 2012) already provide comprehensive information on settlement systems and movement dynamics in Upper Mesopotamia. In this respect, the archaeological dataset used in this study replicates only a small portion of previous work. On the other hand, the model differs from other research in the ways in which data are further exploited. Specifically, an automated curve fitting methodology is applied so that a systematic, but more importantly a standardized determination of production boundaries is achieved.
3.1.1. The Dating Problem

In order to proceed with a remote-sensing based archaeological survey one has to tackle the dating problem of off-site archaeological features. This problem is further pronounced when there is little or no fieldwork data available. Considering the extent of Upper Mesopotamia such ground-work is simply not feasible. Therefore, some inferences are made based on the results of previous archaeological surveys in the area and EBA settlement morphologies.

Surveys from the area report there are very few non-mounded settlements with Early Bronze Age occupation. For instance, Ristvet (2005) shows only seven of 60 settlements were non-mounded in Tell Leilan region. Similarly, Wilkinson (2002) reveals at least 20 Early Bronze Age sites, with only one of them appearing as a flat site around Tell Beydar. Finally, for Hamoukar region Ur (2008) reports high mounded sites were usually occupied during the Third Millennium BCE. Thus, it can be tentatively stated that a nucleated tell-site was the signature settlement type during the Early Bronze Age. Yet, one should further investigate if there were tell-sites which were not occupied during Early Bronze Age. Aforementioned archaeological surveys as well as other studies by Wilkinson and Tucker (1995) and Sallaberger and Ur (2004) suggest that Early Bronze Age mounds were usually larger in size and higher than other earlier prehistoric or Iron Age mounds. Specifically, sites occupied earlier than Early Bronze Age were typically not-obtrusive in the landscape and Iron Age settlements were morphologically dispersed complex low mounds. Habitation during proceeding Roman and Islamic Periods was mainly at flat settlements. Under this morphological frame, it is possible to pinpoint large and tall tell-sites (i.e. Early Bronze Age settlements) on satellite/aerial imagery with high accuracy.

While archaeological surveys and corresponding morphological classification provide relatively secure dates for settlements, assigning temporal information to off-site archaeological features is a challenge. Nevertheless, a plausible dating effort can be provided. Wilkinson et al. (2010) suggest these features might have been in use as early as the Late Chalcolithic 4th millennium BCE). Furthermore, there is evidence for the later use of road systems in Roman and Islamic times. Nevertheless, radial hollow ways appears to be mainly in use during the later Early Bronze Age.

First, Early Bronze Age settlements must have had the capacity to generate a volume of traffic, resulting in the formation of hollow ways (Casana 2013). In earlier and later cultural phases, low and dispersed settlements were less likely to be responsible for the formation of wide hollow ways. Considering the importance of agro-pastoral economy, controlled movement of large number of animals must have also contributed to the formation of hollow ways of both large and small settlements. Such large flock sizes are well attested in the archaeological record for the Early Bronze Age (Archi 1993; Porter 2012). Finally, structural differences between wider Early Bronze Age hollow ways and narrower routes of later cultural periods provide further evidence for secure dating of radial hollow ways during the Early Bronze Age (Ur 2003).

Based on the discussion above, it is considerably safe to assume that any prominent mound with wide hollow ways radiating from it can be dated to Early Bronze Age. Furthermore, these hollow ways were mainly in use during the same period. This simple inference makes it possible to conduct a remote sensing based archaeological survey over the relatively flat Upper Mesopotamian terrain in order to map Early Bronze Age settlement and road system in its entirety (Ur 2003; Kalayci 2013).

Figure 4 The distribution of 33 documented production zones across the landscape and the results of the shape fitting process (a sample is given in the inner box).
3.2. Modeling Early Bronze Age Agricultural Production Territories

Terminal points of radial hollow ways designate boundaries of Early Bronze Age agricultural fields. Thus, it is possible to define the geometric shape of agricultural boundaries in a statistical sense. The process involves fitting a shape to terminal points while minimizing the error between the modeled shape and terminal points. High accuracy is achieved only when hollow ways fully span the space. Among documented >1000 nucleated tell-sites only 33 settlements provide the necessary full spatial configuration for accurately modeling production extents so that only these settlements are considered for further analysis.

A quick exploration of these 33 sets of hollow ways indicates that production territories were roughly circular. Therefore, the difficulty is reduced to fitting a circular shape to the terminal points of hollow ways. In solving this mathematical problem, the methodology developed by Taubin (1991) and implemented by Chernov (2009) is used which minimizes the algebraic distance from a point (i.e. the terminal point of an hollow way) to the circle (Figure 4).

3.3. Precipitation

The deployment of modern precipitation data within the context of the Early Bronze Age settlement sizes and agricultural production territories provides a test ground for investigating theories about production strategies. Modern climatic data remain as the only source in the absence of paleoclimatic reconstructions or simulated datasets. Ethnographic analogies are also of immense use (e.g. Frachetti 2008), but the level of detail needed in this study cannot be achieved through this approach.

For the reconstruction of modern precipitation in Upper Mesopotamia, the dataset provided by the Global Precipitation Climatology Center (GPCC) at the Deutscher Wetterdienst is used. GPCC products include monthly precipitation data with 0.5, 1.0 and 2.5 degree grid-sizes. In Upper Mesopotamia, the finest available resolution (0.5°) is chosen in order to fully capture spatial variations of rainfall for the years between 1982 and 2005. This specific temporal range matches with the Normalized Difference Vegetation Index (NDVI) time series data, as discussed later.

Creating continuous precipitation surfaces from station data has been of interest to many researchers (e.g. Eischeid et al. 2000; Lloyd 2005; Ruelland et al. 2008; Zhang and Srinivasan 2009). In this study, inverse-distance weighting (IDW) is employed since raw data is already in gridded format and IDW performs efficiently due to the regularity of data. To define IDW:

$$Z(u) = \frac{1}{\sum_{i=1}^{N} w_i(x)} \sum_{i=1}^{N} w_i(x). Z(x), \text{ where } w_i(x) = \frac{1}{d(x, x_i)^p}$$ (1)
The weight “w” determines predictor contribution to interpolation. Weight is based on the power (p) of the Euclidean distance between data and estimation point. According to the formula, as distance increases, the weight of data on estimation decreases. For the interpolation, ArcGIS 10.0 is used in batch processing mode, resulting in 288 monthly precipitation surfaces for the years between 1982 and 2005. The power p is selected as 0.5 to retain original values at grid locations (Figure 5).

3.3.1. Evaluation of Dry-Farming in the Area
A reliable understanding of the relationship between precipitation and dry-farming practice depends on to what extent other supplemental systems (e.g. irrigation) are excluded from the production schema. To explore this, Normalized Difference Vegetation Index (NDVI) values may be employed. NDVI can also reveal information on vegetation health, growing conditions, and the amount of biomass production.

Specifically, NDVI data obtained from the Advanced Very High Resolution Radiometer (AVHRR) is selected for investigating the role of irrigation in the production schema. AVHRR sensor series are mounted on National Oceanic and Atmospheric Administration (NOAA) polar orbiting platforms (POES). AVHRR has four or five channels, collecting data in the visible, near-infrared, and thermal infrared portions of the spectrum with the aim of environmental monitoring (James and Kalluri 1994). Spectral data from these sensors also provide a historic NDVI dataset from 1981 onwards. The data set is already processed for radiometric calibration, atmospheric correction, cloud screening, and solar zenith angle correction and served to the public with 8 km spatial resolution (Tucker et al. 2005) (Figure 6).

If investigated in time-series form, NDVI data provide further information on production strategies. Simply put, a dominant peak in NDVI time series is a characteristic of single production cycle and usually associated with rain-fed agriculture. Irrigation agriculture, on the other hand, makes it possible to acquire multiple yields, resulting in multiple peaks in the NDVI series (Kamthonkiat et al. 2005).

Eight sample points are explored falling in the production boundaries of Early Bronze Age settlements (Figure 4). Samples 1, 2, and 3 indicate a relatively complex production schema where irrigation has some contribution; observed in a secondary yet usually a smaller peak in each cycle (Figure 7). For the samples, 4–8 irrigation has little contribution as NDVI time-series has dominant single peak character. In all samples, the impact of low precipitation in 1989 is clearly visible (see arrows in Figure 7). This observation further confirms the importance of rainfall even in the modern-day agricultural production in Upper Mesopotamia.

Irrigation practice becomes clear on NDVI data for the areas which are known to be supplemented. The visual comparison of modern satellite images (dated to 2010) with Landsat data (dated to 1990) reveal additional irrigation infrastructure (Figure 8). NDVI time-series data suggests this infrastructure might have been continuously improved since 1996 as the pattern in time-series drastically changes after this year towards double production schema (Figure 8a). Second sample shows a complex irrigation schema from the early days of 1982 (Figure 8b). Such
complex patterns are easy to detect and are withheld from the analysis in order to mimic dry-farming conditions of the Early Bronze Age.

Regional agricultural statistics can also be used to investigate the role irrigation plays in modern day agriculture. In this respect, the Syrian Agriculture Database hosted by the National Agricultural Policy Center (NAPC-MAAR) provides substantial data for understanding the part of precipitation in agricultural production (NAPC 2006). Statistics from this database suggest that irrigation indeed plays a minor role in most of the areas despite an increase in the coverage of irrigated fields. This discussion relies on data, obtained from modern day Al-Hassakeh which falls to the center of the study area, and thus, represents modern production practices. Agricultural data from this region reveal that rain-fed agriculture is the dominant production strategy (Figure 9). When translated into actual (barley) production levels, the share of rain-fed strategy in agricultural production becomes even more visible (Figure 10). Only after 2005 irrigation starts to make an impact on total barley production. 2005 is also the last year in which the remote sensing model is built, and thus, it can be assumed that the role of irrigation on agricultural production is minimized in the model for the temporal domain under investigation.

The production model fuses a growth model (Wang et al. 2008) with a remote sensor model (Moriondo, Maselli, and Bindi 2007) for parameterization and to estimate production levels at sample locations. To start with, precipitation-evapotranspiration of

---

**Figure 7** NDVI time-series data from eight sample locations (Sample locations are given in Figure 4). Red arrows highlight the year 1989 with low precipitation records.
agricultural production is given by:

$$\text{Yield} = H \cdot (Ec - Es) \cdot \frac{k}{\Delta e}$$  \hspace{1cm} (2)$$

where $H$ is the crop harvest index, $Ec$ is the crop evapotranspiration, and $Es$ is the evaporation from the soil surface (Wang et al. 2008). For the arid and semi-arid regions of the world evaporation constitutes 30% of evapotranspiration (Liu, Zhang, and Zhang 2002; Kang et al. 2003). Also, considering weed crops can only grow above the 110 mm/year rainfall limit, the equation can be constricted to and re-written as:

$$\text{Yield} = 0.7H.Ec \cdot \frac{k}{\Delta e} \text{ for } Ec \geq 110 \text{ mm}$$ \hspace{1cm} (3)$$

Figure 8 Two samples indicate the effect of irrigation in the production schema. Red arrow in (a) indicates the onset of change towards irrigation. Following 1996, double peaks start to dominate the NDVI time series data.
with harvest index (H), crop evapotranspiration (Ec), crop specific index (k), and vapor pressure deficit (Δe). k is usually set between 45 and 60 kilopascal (kPa); smaller k implies less yield and vice versa (Ehlers and Goss 2003). Under rain-fed conditions, Ec can be replaced by total precipitation amount (Wang et al. 2008, 1962).

Vapor pressure deficit (Δe), the drying power of air is determined by the temperature and relative humidity of the environment at the time of measurement. Vapor pressure deficit can be calculated in the field (Bassow and Bazzaz 1998) or a satellite remote sensing approach can be used to estimate Δe values (Hashimoto et al. 2008). Estimation of this value is beyond the scope of this study. But, since the yield formula is a linear combination of Δe, it can be fixed to a single value for comparative purposes. In this study, Δe is set as 15 since this value signifies high temperature with low relative humidity conditions, and thus, imitates semi-arid conditions. With this methodology, the only unknown variable remains the harvest index (H). H usually requires ground observations to estimate its value. On the other hand, considering the size of the study area such an option is not feasible. But, estimation of the harvest index is also possible by using Normalized Difference Vegetation Index (NDVI) values.

### 3.5. Determination of Harvest Index using AVHRR

The basic assumption in using NDVI values to calculate Harvest Index (H) is that water and temperature stress affect the optimal final harvest index (H_{MAX}) and are related to the drop in NDVI from pre-anthesis to post-anthesis stages in the crop cycle (Moriondo, Maselli, and Bindi 2007). This can be formulated as:

\[
H_{NDVI} = H_{MAX} - H_{RANGE} \left(1 - \frac{NDVI_{post}}{NDVI_{pre}}\right)
\]  

where \(H_{NDVI}\) is the final harvest index. Optimal values for \(H_{RANGE}\) and \(H_{MAX}\) are dynamically calculated for each growing season. NDVI_{pre} is the mean NDVI value from emergence to anthesis and NDVI_{post} is the average value from anthesis to maturity date. The ratio for post and pre-values usually ranges between 0 and 1 (Figure 11).
Figure 11  Monthly average NDVІ\textsubscript{pre} (above) and NDVІ\textsubscript{post} (below) values of the study area for the years between 1982 and 2005.

Figure 12  Sample results from the production model for years (a) 1982, (b) 1992, and (c) 2002. Spatial time-series data is available for all years when precipitation and NDVІ values exist.
Merging Equation 3 with the NDVI estimation of harvest index produces a new yield formula:

\[ \text{Yield} = 0.7 \left( H_{\text{MAX}} - H_{\text{RANGE}} \left( 1 - \frac{\text{NDVI}_{\text{post}}}{\text{NDVI}_{\text{pre}}} \right) \right) Ec \frac{k}{\Delta e} \]  

(5)

3.6. The Production Model

In order to construct a relationship between precipitation and agricultural production one should not use annual precipitation, but the amount of rainfall during growing season since the growing season rain precipitation is the main hydrological determinant on crop growth. In and around Upper Mesopotamia, barley and wheat sowing is practiced around November 15, and average harvest dates are June 23 for barley and July 13 for wheat (Mauget and De Pauw 2004). Following these dates, the growing season is set for between December and May and growing season precipitation values are extracted from the GPCC dataset. After plugging the NDVI harvest index into equation 5, fixing \( \Delta e \) to 15, and setting \( k \) to the minimum number, 45kPa (in order to obtain a conservative estimate), yield calculation can be simplified into:

\[ Y = 10.5 \cdot (\text{Growing Season Precipitation}) \left( H_{\text{MAX}} - H_{\text{RANGE}} \left( 1 - \frac{\text{NDVI}_{\text{post}}}{\text{NDVI}_{\text{pre}}} \right) \right) \]  

(6)

Based on the Equation 6, it is possible to calculate total grain yield (in tons per hectare) when growing season precipitation values and NDVI are available at a specific location (Figure 12). With this approach, one can gain information on local productivity rather than relying on regional databases (e.g. NAPC 2006). Therefore, the proposed model is more powerful in capturing minute variations in the production landscapes and more accurately represents agro-ecological zones. The proposed production model is also more realistic when compared with production estimations with fixed productivity values across large landscapes. The methodology generates a series of agricultural production levels for the years between 1982 and 2005. As the final step, these production levels are

Figure 13 Mean agricultural production statistics for the years between 1982 and 2005 at EBA production zones.

Figure 14 The scatter plot for (unitless) normalized values of settlement areas and production areas of settlements. The plot suggests there is no immediate relationship between the size of settlements and their sustaining areas.
averaged to obtain a single map and Early Bronze Age agricultural production territories are overlaid with this dataset in order to calculate how much foodstuffs might have been —on the average— procured by the inhabitants of these settlements (Figure 13)

4. Results

The wide range in potential EBA production levels is due to the variation in the sizes of production areas as well as the locations of settlements within diverse agro-ecological zones. Statistics suggests that even if the Early Bronze Age settlement was located at a low productivity agro-ecological zone, inhabitants of the site might have had the chance to compensate production deficit by extending production areas — when there was enough space to expand and labor to spare. Nevertheless, the threshold for dry-farming (∼300 mm/year) was also the hard limit for settlements to expand into low productivity zones (Wilkinson 1994;
Such an expansion might only have been episodic, and therefore hollow ways would be unlikely to form over relatively short time spans.

In contrast with the normative assumption which states that larger archaeological settlements must have been surrounded by larger catchments, results of this study suggest there was no immediate relationship between these two variables (Figure 14). The Pearson product-moment correlation coefficient ($r$) for the relationship between EBA settlement sizes and their corresponding agricultural production zones (after standard normal transformation) is 0.4. Even though this number suggests some relationship, it is not high enough to assert that larger settlements (with higher populations) required larger catchment areas (for more production). These 33 EBA settlements provide empirical evidence for the problems of "traditional ways of modelling site territories" (Wilkinson 2005).

When the relationship between the size of settlements and estimated food production amounts during the Early Bronze Age is investigated, a drop in the strength of the relationship is observed from 0.4 (settlement areas vs. production areas) to 0.3 (Figure 15). This drop comes as an evidence for the necessity of modeling soil productivity rather than mere catchments of sites. The drop is also a call for integrating more complex and realistic production schemas to the model in order to "correct" for this statistic.

Wilkinson (1997) proposes four different methods of dry-farming in Upper Mesopotamia during Early Bronze Age; annual planting, planting with fallowing, annual planting with manuring, planting with manuring and fallowing. Each strategy must have provided different amounts of food at the end of each production cycle. Therefore, if the aim is to compare total amount of foodstuffs with settlement areas, different strategies of dry-farming should be considered. In this respect, only biennial fallowing is integrated into production estimations. However, the problem remains in detecting which settlements were practicing a fallowing strategy.

To answer this question with the help of biennial fallowing strategy, total production amount is halved for the smallest settlement in the dataset and correlation coefficient is recalculated for total agricultural production.
production and settlement size. To determine which settlements were possibly practicing fallowing, this process is iterated for the next smallest settlement in the dataset. Finally, correlation coefficients are plotted with respect to settlement sizes until all production zones are treated with fallowing (Figure 16). The plot of iterated correlation coefficients suggests that the relationship between settlement area and the amount of food production becomes meaningful as the coefficient reaches 0.74. This maximum is reached for the settlements smaller than ~50 hectares. The relationship starts to fall if fallowing is assumed also for settlements larger than ~50 hectares. In following, one can suggest ~50 hectares is a critical limit in the fallowing strategy.

The plot also reveals an extremely curious case for a settlement, namely Rumeylan Kabir (detected by the red circle in Figure 16). A closer look to this site on CORONA imagery reveals another mounded settlement to the north (Figure 17). This smaller daughter settlement was located within the production boundaries of Rumeylan Kabir and must have shared the agricultural territory. To reduce the complexity in agricultural land use strategies, Rumeylan Kabir is removed from the dataset and the analysis is initiated again for the remaining 32 sites.

For this updated dataset, the correlation coefficient between settlement sizes and production areas is 0.51 (in comparison to initial r=0.3). Furthermore, when biennial fallowing is introduced for the settlements smaller than 50 hectares, food production-settlement area relationship becomes even more meaningful (r=0.85) (Figure 18).

5. Conclusions and Discussion

This study explores the relationship between settlement areas and food production levels in Upper Mesopotamia during Early Bronze Age. The extents of archaeological settlements and hollow ways were documented using CORONA imagery. Settlement sizes provide proxy information for the number of people living at nucleated tell-settlements and hollow ways are used to model production territories. Next, a remote sensing methodology coupled with a biological growth model was built in order to investigate modern dry-farming landscapes—as a representation of possible Early Bronze Age production levels. Settlement areas were cross-compared with production statistics in order to explore the potential relationship between these variables.

Results of CORONA based remote sensing survey show no immediate relationship between settlement areas and their production territories. The correlation coefficient for this relationship is calculated as 0.4. In order to include local productivity variations into the equation and to provide a more dynamic land-use model, total foodstuff within the production boundaries is calculated. This model, however, also presents a poor relationship between settlement sizes and total food production. Introducing biennial fallowing to the overall model, however, significantly increases the relationship between settlement areas and their sustaining territories as well as the amount of staples produced in these territories. If one considers fallowing for sites less than 50 hectares, the correlation coefficient between settlement areas and total food production increases to a significant value.

The curious case of Rumeylan Kabir informs about complex land-use practices and the organization of agricultural production. It is most likely that labor constraints in the parent settlement limited the amount of local production, even though there was enough agricultural land around it. In similar cases, a smaller settlement must have been established to increase the amount of agricultural labor at the expense of losing some portion of the production zone for establishing the daughter settlement. These arguments, however, are only valid under the assumption that settlements were occupied contemporaneously. In cases where a peripheral settlement’s production zone is surrounded by the parent settlement it seems logical to suggest that the overlapping area belonged to the peripheral settlement.

The study goes well beyond the static representations of agricultural land-use models and opens up new research opportunities since the proposed workflow provides empirical data for further testing of normative archaeological theories. With the help of this dynamic territorial model, the role of landscape archaeology is further emphasized and the deficiency in unrealistic modelling of site territories is reduced, mainly due to the intensive and innovative use of satellite remote sensing data, coupled with archaeological data.

Due to its workflow the study is open to further improvements. The problematics related to agro-pastoral strategies and the flow of agricultural surplus between settlements under the tributary paradigm can be integrated into the model. However, such integration requires the parametrization of local pastoralist economies as well as the contextualization of the secondary urbanism of the mid-third millennium BCE.

Conflict of interest statement

The author confirms there is no conflict of interest.

Acknowledgments

The study mainly relies on the products of the ‘CORONA Archaeological Atlas Project’, funded by grants from the National Endowment for the Humanities (NEH) and the American Council of Learned Societies (ACLS). Also, the study has its foundational basis in the ‘Settlement Systems and Environmental Change in the Northern Fertile Crescent’ project, supported by the NASA Space Archaeology program. I would like to thank project principle investigators, Jesse Casana (Dartmouth College) and Jackson Cothren (University of Arkansas, Fayetteville).
Notes on contributor

This study is based on the findings of the author’s dissertation work with the title “Agricultural Production and Stability of Settlement Systems in Upper Mesopotamia during the Early Bronze Age (Third Millennium BCE).” Currently, the author is a post-doctoral scholar at the Institute for Mediterranean Studies, Greece and specializing on satellite remote sensing and archaeological prospection.

References

Archis, A. 1993. “Trade and Administrative Practice: The Case of Elba.” Altorrivalien Forschungen 20 (1): 43–58.

Bassow, S. L., and F. A. Bazzaz. 1998. “How Environmental Conditions Affect Canopy Leaf-Level Photosynthesis in Four Deciduous Tree Species.” Ecology 79 (8): 2660–75.

Brew, G., R. Litak, and M. Barazangi. 1999. “Tectonic Evolution of Northeast Syria: Stratigraphic Implications and Hydrocarbon Drift.” GeoArabia 4 (3): 289–318.

Casana, J. 2013. “Radial Route Systems and Agro-Pastoral Strategies in the Fertile Crescent: New Discoveries from Western Syria and Southwestern Iran.” Journal of Anthropological Archaeology 32 (2): 257–73.

Casana, J., J. Cothren, and T. Kalayci. 2012. “Swords into Ploughshares: Archaeological Applications of CORONA Satellite Imagery in the Near East.” Internet Archaeology 32.

Christaller, W. 1933. Die Zentralen Orte in Süddeutschland.

Die Zentralen Orte in Süddeutschland.

Emberling, G., J. Cheng, T.E. Larsen, H. Pittman, T.B.B. Skuldeboel, J. Faye tteville, AR: Thesis (PhD). University of Arkansas.

Emberling, G., J. Cheng, T.E. Larsen, H. Pittman, T.B.B. Skuldeboel, J. Faye tteville, AR: Thesis (PhD). University of Arkansas.

Fischer. 2003. “A Simple Model of Regional Wheat Yield Based on NDVI Data.” European Journal of Agronomy 26 (3): 266–74.

Frey, H. 1954. Nouvelle Prospection Archéologique dans La Haute Jazeh Syrienne. Les Annales Archéologiques Arabes Syriennes 4/5: 129–48.

Lawrence, D., and T. J. Wilkinson. 2015. “Hubs and Upstarts: Pathways to Urbanism in the Northern Fertile Crescent.” Antiquity 89 (344): 328–44.

Liu, Changming, Xiying Zhang, and Yongjiang Zhang. 2002. “Determination of Daily Evaporation and Evapotranspiration of Winter Wheat and Maize by Large-Scale Weighing Lysimeter and Micro-Lysimeter.” Agricultural and Forest Meteorology 111 (2): 109–20.

Lloyd, C.D. 2005. “Assessing the Effect of Integrating Elevation Data into the Estimation of Monthly Precipitation in Great Britain.” Journal of Hydrology 308: 128–50.

Maquet, S.A., and E. De Pauw. 2004. Icarda AgroClimate Tool (version 2.0). Visual Basic 6.

McCorriston, J. 1997. “The Fiber Revolution: Textile Extensification, Alienation, and Social Stratification in Ancient Mesopotamia.” Current Anthropology 38 (4): 517–35.

Menze, B.H., and J.A. Ur. 2012. “Mapping Patterns of Long-Term Settlement in Northern Mesopotamia at a Large Scale.” Proceedings of the National Academy of Sciences.

Moriando, M., F. Maselli, and M. BINDI. 2007. “A Simple Model of Regional Wheat Yield Based on NDVI Data.” European Journal of Agronomy 26 (3): 266–74.

Morton, J.F. 2007. “The Impact of Climate Change on Smallholder and Subsistence Agriculture.” Proceedings of the National Academy of Sciences 104 (50): 19680–85.

NAPC. 2006. “Notes on the Use of the Syrian Agriculture Database for Policy Analysis.” Ministry of Agriculture and Agrarian Refrom-National Agricultural Policy Center (NAPC).

Philip, G., D. Donoghue, A. Beck, and N. Gallatstatos. 2002. “CORONA Satellite Photography: An Archaeological Application from the Middle East.” Antiquity 76 (291): 109–18.

Philip, G., D. Donoghue, A. Beck, and N. Gallatstatos. 2005. “Settlement and Landscape Development in the Horns Region, Syria Report on Work Undertaken during 2001–2003.” Levant 37: 21–42.

Porter, A. 2012. Mobile Pastoralism and the Formation of Near Eastern Civilizations: Weaving Together Society. Cambridge: Cambridge University Press.

Ristvet, L. 2005. Settlement, Economy, and Society in the Tell Leilan Region, Syria, 3000–1000 BC. Cambridge: King’s College, University of Cambridge.

Ristvet, L. 2011. “Travel and the Making of North Mesopotamian Polities.” Bulletin of the American Schools of Oriental Research 361: 1–31.

Ruelland, D., S. Ardoine-Bardin, G. Billen, and E. Servat. 2008. “Sensitivity of a Lumped and Semi-Distributed Hydrological Model to Several Methods of Rainfall Interpolation on a Large Basin in West Africa.” Journal of Hydrology 361: 96–117.

Sallaberger, W., and J.A. Ur. 2004. “Tell Beydar/Nabada in Its Regional Setting.” In Third Millennium Cuneiform Texts from Tell Beydar (Seasons 1996–2002), edited by L. Milano, W. Sallaberger, P. Talon, and K. Van Lerberghe, 51–71. Subaruti 12. Turnhout: Brepols.

Smith, A. T. 2003. The Political Landscape: Constellations of Authority in Early Complex Polities. University of California Press.

Stein, G. 2004. Ristvet, L. 2011. “Travel and the Making of North Mesopotamian Polities.” Bulletin of the American Schools of Oriental Research 361: 1–31.

Thompson, H. 1985. How Environmental Conditions Influence the Formation and Stability of Settlement Systems in Upper Mesopotamia During the Early Bronze Age (third Millennium BCE). “Fayetteville, AR: Thesis (PhD). University of Arkansas.

Thompson, H. 1985. How Environmental Conditions Influence the Formation and Stability of Settlement Systems in Upper Mesopotamia During the Early Bronze Age (third Millennium BCE). “Fayetteville, AR: Thesis (PhD). University of Arkansas.

van Liere, W.J., and J. Lauffray. 1954. Les Annales.

Weber, and H.T. Wright. 1999. “Agricultural Water Management.” Agricultural and Forest Meteorology 108. Los Angeles: Cotsen Institute of Archaeological Research.

Zimmerman, E.A. 1993. “Feast and Famine: Early Roman Midway Implications.” GeoArabia 4 (3): 289–318.

Zimmerman, E.A. 1993. “Feast and Famine: Early Roman Midway Implications.” GeoArabia 4 (3): 289–318.
Vita Finzi, C., and E.S. Higgs. 1970. “Prehistoric Economy in the Mount Carmel Area of Palestine: Site Catchment Analysis.” Proceedings of the Prehistoric Society XXXVI: 1–37.

von Thünen, J. H., and P. G. Hall. 1966. Isolated State: An English Edition of Der Isolierte Staat. Pergamon Press.

Wang, E., Q. Yu, D. Wu, and J. Xia. 2008. “Climate, Agricultural Production and Hydrological Balance in the North China Plain.” International Journal of Climatology 28 (14): 1959–70.

Weiss, H. 1963. “Excavations at Tell Leilan and the Origins of North Mesopotamian Cities in the Third Millennium B.C.” Paléorient 9 (2): 39–52.

Wilkinson, T.J. 1994. “The Structure and Dynamics of Dry-Farming States in Upper Mesopotamia.” Current Anthropology 35 (5): 483–520.

Wilkinson, T.J. 1997. “Environmental Fluctuations, Agricultural Production and Collapse: A View from Bronze Age Upper Mesopotamia.” In Third Millenium B.C. Climate Change and Old World Collapse, edited by H.N. Dalfes, G. Kukla, and H. Weiss, 67–106. New York.

Wilkinson, T.J. 2000. “Settlement and Land Use in the Zone of Uncertainty in Upper Mesopotamia.” In Rainfall and Agriculture in Northern Mesopotamia, edited by R.M. Jas, 3–35. Istanbul: Nederlands Historisch-Archaeologisch Instituut.

Wilkinson, T.J. 2002. “Archaeological Survey of the Tell Beydar Region, Syria, 1997: A Preliminary Report.” In Tell Beydar Environmental and Technical Studies, edited by K. Van Lerberghe and G. Voet, 1–37. Subartu 6. Turnhout: Brepols.

Wilkinson, T.J. 2004. On the Margins of the Euphrates: Settlement and Land Use at Tell Es-Sweyhat and in the Upper Lake Assad Area, Syria. Vol. 1. Chicago: The University of Chicago Oriental Institute Publications.

Wilkinson, T.J. 2005. “Approaches to Modelling Archaeological Site Territories in the Near East.” In Non-Linear Models for Archaeology and Anthropology, edited by C.S. Beekman and W.W. Baden, 123–38. Aldershot: Ashgate Press.

Wilkinson, T.J., C. French, J.A. Ut, and M. Semple. 2010. “The Geoaanthropology of Route Systems in Northern Syria.” Geoarchaeology: An International Journal, 25 (6): 745–71.

Wilkinson, T. J., G. Philip, J. Bradbury, R. Dunford, D. Donoghue, N. Galiatsatos, D. Lawrence, A. Ricci, and S. L. Smith. 2014. “Contextualizing Early Urbanization: Settlement Cores, Early States and Agro-Pastoral Strategies in the Fertile Crescent During the Fourth and Third Millennia BC.” Journal of World Prehistory 27 (1): 43–109.

Wilkinson, T.J., and D.J. Tucker. 1995. Settlement Development in the North Jazira, Iraq. A Study of the Archaeological Landscape. Warminster, Wiltshire: Aris & Phillips.

Zhang, X., and R. Srinivasan. 2009. “GIS-Based Spatial Precipitation Estimation: A Comparison of Geostatistical Approaches.” Journal of the American Water Resources Association 45 (4): 894–906.