Chapter 3
Sedentary Sites

Randall Haas

Abstract Nearly every part of the world witnessed the process of human sedentarization during the Holocene Epoch. Agriculture, circumscription, and ecological structure are among the major drivers previously proposed to account for this transition from residentially mobile to sedentary lifeways. This analysis explores an alternative mechanism, which considers the appearance of continuously occupied sites among residentially mobile (i.e., non-sedentary) individuals to be a key component in the trajectory to sedentism. Drawing insights from Archaic Period settlement patterns in the high Andes and a simple computer simulation, such "sedentary sites" are shown to be an emergent property of the interaction of two basic human behaviors—population growth and *recursive mobility*. Recursive mobility refers to the preferential occupation of certain places on landscapes as a result of human restructuring of environments and consequent recycling of cultural materials. The simulations reveal gradual emergence of continuously occupied sites by residentially mobile individuals, which accounts for the protracted nature sedentarization observed archaeologically. The model further offers a socioecological context for emergent residential sedentism among individuals themselves and a mechanism for plant domestication that does not require individual sedentism.

Keywords Mobility · Sedentism · Foragers · Emergent agriculture · Andean archaic · Lake Titicaca Basin · Simulation

Nearly all of the world's contemporary human populations are what anthropologists would consider residentially sedentary. Individuals tend to inhabit sites year-round for many sequential years and even multiple generations in some instances. Anthropology long-ago showed that this wasn't always the case. Throughout the Pleistocene, the vast majority of humans were residentially mobile, moving at least once a year, often more frequently. During the Holocene, residentially mobile

---

R. Haas (✉)
Department of Anthropology, University of California, Davis, CA, USA
e-mail: wrhaas@ucdavis.edu

M. Bonomo, S. Archila (eds.), *South American Contributions to World Archaeology*, One World Archaeology,
https://doi.org/10.1007/978-3-030-73998-0_3

lifeways gradually gave way to increasingly sedentary ones independently in different parts of the world. This sedentarization process was part and parcel to a host of socioeconomic transformations related to subsistence, hierarchy, private property, inequality, disease, and innovation to name a few. Robert Kelly (2013, p. 78) suggests that "…the transition from a nomadic to a sedentary existence was the crucible of significant, pervasive, and permanent changes in the social and political lives of hunter-gatherers…." How residential sedentism evolved is therefore a perennial topic of anthropological inquiry.

Several models currently exist and collectively consider the roles of food production, competition, and territoriality in compelling mobile individuals to take up permanent residence. Early models were tightly coupled with the transition from foraging to farming economies given the intrinsic connection between farming and place. Land preparation, planting, tending, harvesting, and storage serially tether farmers to agricultural places, or farms. Early scholars who subscribed to progressivist paradigms of human social change saw residential sedentism as an obvious cultural advance that naturally followed from the "discovery" of agriculture (Bettinger et al., 2015). Subsequent scholarship, fueled largely by ethnographic hunter-gatherer observations, revealed that the transition was not so obvious. To ethnographic foragers, farming was laborious and only taken up under extreme circumstances such as forcible coercion by colonial powers. Ethnographic and experimental studies of subsistence economics show that, in fact, many foraging pursuits generate considerably higher energetic returns on labor investment than farming (Barlowe, 2006). Although agricultural surplus and storage promises a degree of economic resilience to environmental perturbation, reliance on a narrow agricultural food base simultaneously creates new insecurities that can lead to catastrophic collapse.

Even more problematic for the agricultural model was the simple fact that domestication is a process that requires time—if not incredible foresight—to transform wild plant species to their domesticated forms (Smith, 2001). Wild types tend to pale in productivity relative to their domesticated counterparts. The seed stalks of teosinte, for example, produce no more than a dozen thick-skinned seeds while the stalks of its modern domesticated form, maize, produces roughly 800 densely packed, thin-skinned kernels (Smith, 1995). It would therefore seem that food production was more likely to have been a consequence of sedentism rather than a cause. However, there are at least some empirical cases of agriculture preceding sedentism, leading Kelly (1992, 2013) to conclude that the relationship between sedentism and agriculture is unclear.

A series of ancillary challenges would have further complicated the transition to food production among early hunter-gatherers (Kelly, 2013). Sedentism rendered previously mobile individuals susceptible to a host of new diseases and pathologies as people lived in increasingly sustained proximity to waste. Land tenure created new tensions that threatened social cohesion. Inter-personal conflicts could no longer be easily resolved with residential moves, potentially raising inter-personal violence rates. So while it is clear that mobile populations did ultimately transition to sedentary ones, empirical findings suggest that the process was anything but straightforward.

In his 1998 article titled “Cheating at Musical Chairs,” Michael Rosenberg (1998) suggested that sedentism emerged at the intersection of population growth and variably productive resource environments. In this view, increasing population increases resource competition and thus the benefit of territory defense. At some critical point along the continuum of population growth and increasing competition, it paid to occupy the best territories continuously rather than abandon them seasonally, which would risk ceding prime territory to other groups. Kelly similarly concluded that “…the only reason hunter-gatherers would not move is if there is no place to which to move” (Kelly, 2013, p. 106), and the most likely impediment would have been a packed landscape, at least in homogeneous environments. He advances a separate model for the emergence of sedentism in heterogenous environments. Deriving insight from ecological patch-choice models, and echoing Childe’s (1929) propinquity theory, he argues that “…sedentism is a product of local abundance in a context of regional scarcity” (Kelly, 2013, p. 107).

The trouble with population packing models is that it is hard to imagine a hunter-gatherer landscape that is not packed—i.e., at carrying capacity—when one considers the counter-intuitive reality of exponential population growth. Richerson et al. (2001) show that even under the most conservative demographic estimates such as an initial colonization of a massive continental landscape the size of Asia, exponential growth is expected to rapidly induce density dependent effects in under 200 years. Population packing is practically instantaneous. Even as humans raise capacity via social and technological innovation, exponential growth follows on the heels of carrying capacity. With exponential growth, Rosenberg’s and Kelly’s models would seem to anticipate packed populations and thus residential sedentism from the get-go. Clearly this is not the case as residential sedentism was a relatively late phenomenon in human history.

In what follows, I present an alternative model for the evolution of sedentism that is independent of agriculture, population packing, or environmental structure. The model instead considers that incipient forms of sedentism may arise at the intersection of population growth and recursive mobility, which I define shortly. It envisions that the early stages of sedentism were less about people and more about sites becoming permanent fixtures of socioeconomic landscapes. Incipient sedentism is seen a quantitative increase in the average duration of site occupancy and concomitant reduction in the duration of occupational hiatuses resulting in eventual year-round habitation of prominent sites in the settlement systems of residentially mobile people. The model therefore makes a distinction between sedentary people and sedentary sites with the latter likely preceding the former. I further speculate that the shift to more continuously occupied sites would have simultaneously increased social interaction at few prominent sites in the settlement system creating new socioeconomic tensions and opportunities that could have catalyzed residential sedentism. The inspiration for this argument ultimately derives from archaeological observations on Andean settlement patterns. I therefore begin with a summary of those observations to provide empirical grounding before elaborating on the model, which ought to generalize beyond the Andean case.

3.1 Settlement Patterns in the South-Central Andes

Settlement pattern analysis is among the major contributions of South American Archaeology to world archaeology. Gordon Willey's (1953) examination of prehistoric settlement patterns in the Viru Valley, Peru in the 1940s was seminal. Prior to this, archaeological research tended to be site-centric, emphasizing excavation of particular sites with analysis of site structure and material contents. Willey's regional focus showed how placing individual sites into broader social landscapes could generate novel insights into the broader socioeconomic landscapes of past societies. Today, settlement survey and analysis is standard archaeological practice around the world.

The South-Central Andes is one part of the world where settlement pattern analysis has figured prominently in modelling human social change. The Lake Titicaca Basin of highland Peru and Bolivia serves as the primary empirical case under consideration here. It is particularly suited to settlement pattern analysis because previous archaeological fieldwork has generated robust baseline data with good geographic and chronological control spanning periods of major socioeconomic transformation including the transition to residential sedentism.

The Lake Titicaca Basin lies at over 3800 meters above sea level and is dominated by expansive rolling hills grasslands dissected by streams and flanked by mountains. The region is one of few in the world to witness the endogenous emergence of residential sedentism, food production, and socioeconomic complexity (Smith, 1995; Feinman & Marcus, 1998). The state of Tiwanaku thrived between 1.5 and 1.0 ka. It was characterized by intensive agriculture, monumental architecture, long-distance exchange, and complex craft economies that included textile, metal, and ceramic production (Janusek, 2004; Kolata, 1996; Moseley, 1992; Stanish, 2003). Many of these economically complex behaviors can be traced to the preceding Formative periods, 3.5–1.5 ka (Bandy, 2004, 2005, 2006; Browman, 1981; Capriles et al., 2008; Hastorf, 2008; Janusek, 2004; Kolata, 1996; Plourde & Stanish, 2006; Schultze et al., 2009; Stanish, 2003; Stanish et al., 1997, 2005; Hastorf, 1999).

Given the socioeconomic complexity evident in the Tiwanaku and Formative periods, it is not surprising that the associated settlement patterns have been characterized as hierarchical in structure. Hierarchical settlement patterns are those in which extremely large settlements—often termed *primate centers*—are circumscribed by second tier settlements, each of which is in turn circumscribed by third tier settlements, and so on (Christaller, 1966; Flannery, 1998). Following central-place economic models and local ethnographic analogs, McAndrews et al. (1997) attribute the observed hierarchical structure in the Tiwanaku valley to economic integration in a nested hierarchy of political units (see also Albarracin-Jordan

(1996)). More recently, Griffin and Stanish (Griffin, 2011; Griffin & Stanish, 2007) have shown through computer simulations that hierarchical settlement structure indeed emerges from complex interactions of ecological structure, economic complementarity, and peer-polity competition. However, Haas and Tagliabue (2012) showed that some of the structural properties of Tiwanaku and Formative Period settlement patterns could also be emergent properties of basic mobility dynamics.

Surprisingly few sites dating to the preceding Archaic Periods (11–3.5 ka) have been found near Lake Titicaca where Tiwanaku and Formative period sites are most abundant (Bandy, 2006). Rather, a series of archaeological surveys away from Lake Titicaca's margins have revealed a robust picture of Archaic Period settlement patterns. In 1994 and 1995, Mark Aldenderfer directed an intensive, systematic pedestrian survey of a 41-km^2 area in the Ilave region on the western side of Lake Titicaca Basin with the goal of locating and examining pre-Formative Period sites (Craig, 2011). Survey crews documented 468 archaeological sites and recovered 100-percent of stone tools visible on the surface of each site. In 1997, Cynthia Klink (2005) conducted settlement surveys in the adjacent Rio Huenque valley documenting 151 Archaic Period sites. The surveys documented hundreds of temporally diagnostic projectile points dating to the Early (11–9.0 ka), Middle (9.0–7.0 ka), Late (7.0–5.0 ka), and Terminal Archaic (5.0–3.5 ka) periods allowing a degree of temporal control toward settlement pattern analysis (Klink & Aldenderfer, 2005). Subsequent surveys in other regions of the Titicaca Basin have documented many additional Archaic sites and have permitted a clear picture of Archaic land-use patterns and demography (Aldenderfer & Flores Blanco, 2011; Capriles et al., 2018; Cipolla, 2005; Flores Blanco, 2017; Osorio et al., 2017).

While Early—Late Archaic period (11–5.0 ka) settlement patterns were biased away from the Lake margins and the Formative and Tiwnaku Periods (3.5–1.0 ka) toward them, Terminal Archaic Period (5.0–3.5 ka) patterns straddled the divide. The demographic center of gravity appears to have shifted from the peripheries of the Altiplano to the margins of Lake Titicaca during the Terminal Archaic—a transition that coincides with a rise in Lake Titicaca to its modern level (Cipolla, 2005; Klink, 2005; Rigsby et al., 2003). Early ceramic traditions and subterranean house structures appeared during the Terminal Archaic suggesting incipient forms of residential sedentism (Craig, 2011). Incipient food production, including the domestication of quinoa (*Chenopodium quinoa*) and potatoes (*Solanum tuberosum*), is also thought to have emerged at this time, but empirical evidence remains equivocal (Bruno, 2006; Rumold & Aldenderfer, 2016). Regardless, agricultural production and pastoralism were fully underway by the Formative Period.

Prior to the Terminal Archaic Period, populations experienced a local peak during the Late Archaic Period as indicated by high site densities and diagnostic projectile point counts (Cipolla, 2005; Craig, 2011; Klink, 2005; Marsh, 2016). Middle and Late Archaic periods are marked by a residentially mobile hunting and foraging economies as indicated by an absence of archaeologically detectable houses, communal architecture, and ceramic technology (Haas et al., 2017; Haas & Viviano Llave, 2015; Watson & Haas, 2017). Little is currently known about the socioeconomics of the Titicaca Basin's first inhabitants of the Early Archaic Period (11–9.0 ka).

In an effort to evaluate the extent to which hierarchical settlement patterns were cause or consequence to economic complexity, Haas and colleagues (Haas et al., 2015; Haas & Kuhn, 2019) evaluated Archaic Period settlement structure under the initial expectation that the hierarchical settlement patterns observed during the Formative and Tiwanaku periods should have been attenuated during the Archaic Periods. Whereas Formative and Tiwanaku period sites were expected to be highly variable in size including small and extremely large sites, Archaic Period sites were expected to exhibit a much narrower range of size variation. Surprisingly, however, the mathematical properties of settlement hierarchy were found to be virtually constant across all time periods (Haas et al., 2015). Settlement systems from the Early to Terminal Archaic periods are hierarchical in structure with each time period exhibiting a large "primate center" sequentially nested among smaller sites in hierarchical fashion. Followup analyses showed that such hierarchical patterns do not reflect residential sedentism or hierarchcial social organization but are rather emergent properties of recursive residential mobility strategies in which foragers preferentially occupy previously occupied places on landscapes. Such recursive mobility practices would have served to leverage economic benefits that come with recycling cultural infrastructure and materials (Haas & Kuhn, 2019; Haas et al., 2019). Though I gloss over the mechanics of this model at the moment, they are critical to the model of sedentary sites to be presented below. I will therefore elaborate on the mechanics in the next section.

Settlement pattern research in the Titicaca Basin has revealed a consistent pattern of nested hierarchical structure. While it has been argued that these structural properties reflect incipient forms of ayllu social organization or hierarchical social organization associated with socioeconomic complexity (Albarracin-Jordan & Mathews, 1990; Griffin & Stanish, 2007; McAndrews et al., 1997; Stanish, 2003), more recent studies have found comparable structural properties among even the earliest residentially mobile hunter-gatherer settlement patterns in the region and outside the Andes (Haas et al., 2015), thus challenging hypotheses that see settlement hierarchies as indexes of social hierarchy or any other form of complex social order. It may simply be that micro-scale mobility patterns are sufficient to drive the emergence of macro-scale hierarchical patterns from the bottom up rather than from the top down via hierarchical social organization. I have argued elsewhere that the empirical pattern can be understood as the result of recursive mobility in constructed landscapes and may have provided a context for the emergence of complex social behaviors such as sedentism, agricultural, and hierarchy (Haas & Kuhn, 2019; Haas et al., 2019). My goal here is to explore how the dynamics of recursive mobility interact with other fundamental hunter-gatherer behaviors to affect emergent complexity in human societies.

3.2 The Model

I propose a simple model for the evolution of sedentism that operates at the intersection of two basic human behaviors—population growth and recursive mobility. The model considers that these two behaviors naturally and gradually give rise to permanent occupation of sites. To be clear, it is does not anticipate permanent occupation by individuals. Rather, the model anticipates the gradual emergence of continuous occupation of sites by residentially mobile people. To show how it works, I begin by discussing the two independent variables first before presenting an analysis of their interaction.

Population Growth The first behavior of the model is rather uncontroversial and requires little explanation. All biological populations necessarily reproduce and undergo periods of population growth. Humans are no exception. Although human populations certainly experience periods of population stability and decline, it is undeniable that human populations have experienced net growth over the species' existence, and recent archaeological research shows that such growth was likely sustained throughout the Holocene even if punctuated by geographically and temporally localized peaks and troughs (Peros et al., 2010; Shennan et al., 2013). In one particular case study, forager populations appear to have sustained a net growth rate 0.04% over approximately 6000 years (Zahid et al., 2015). Such rates are low in absolute terms but are nonetheless comparable to growth rates experienced by early agricultural populations. So it seems clear that early, residentially mobile populations generally sustained growth at approximately 0.04% throughout the Holocene. I therefore assume this value in the working model.

Recursive Mobility The second behavior of interest requires more explanation. Recursive mobility is defined here as the propensity to habitually re-occupy locations on landscapes. For mobile populations, residential mobility serves to secure spatially and temporally incongruous resources such as fall nut masts, spring tubers, or summer fish runs (Binford, 1980; Kelly, 2013). Thus, exogenous factors play an important role in dictating when and where to move. However, endogenous factors may also play an important role in conditioning mobility decisions. One such factor might include social interaction. Certainly mobility allowed periodic social interaction and aggregation (Turnbull, 1968; Wiessner, 1982). Humans are also habitual users of tools and infrastructure, and we might expect their material lives to influence movement patterns (Binford, 1982). One patent example is caching behavior. Foragers can be expected to store tools in anticipation of future returns to a given foraging location (Kuhn, 1995).

In a series of recent studies, I have suggested that even without intention, the manipulation of environments also affects the calculus of human mobility (Haas et al., 2015, 2019; Haas & Kuhn, 2019). Humans are habitual tool users. We engage with some form of material culture for the vast majority of subsistence pursuits. We also habitually construct houses and clothing to maintain homeostasis not to mention the various social purposes of such behaviors. It is often unnecessary, impractical, or even impossible to move such tools and infrastructure among various residential locations and so cultural materials are routinely left behind. Regardless of whether such cultural materials are intentionally left behind in anticipation of future return (i.e., caching), those materials become potential resources for future occupants of that space. Whether the same or different individuals, they can realize cost savings in the acquisition, production, and transport of material necessities simply by recycling previously used materials. Unoccupied sites thus become defacto resource patches that preferentially attract human use.

The constructed dimensions of human environments are not only relevant to understanding human mobility, they also entail surprising, archaeologically observable structural properties when iterated many times. Preferential attachment to places naturally generates extreme variation in site occupation intensity such that a few locations in mobile settlement systems are reoccupied with great frequency and most locations experience very little occupation. Mathematically, the structure of variation appears hierarchical.

To understand why this is so, imagine a forager has exhausted resources at their current location and intends to move to another location where resources are more abundant. Two candidate resource patches are equidistant from the forager's current location. But one of the patches contains an unoccupied camp with flaked stone, house-construction poles, and seed-grinding stones. Clearly the forager would prefer the patch with the unoccupied camp because its occupation would entail savings in the cost of house production and stone tool acquisition and transport. Once the location is re-occupied, further improvements are made by adding infrastructure or making repairs and depositing additional materials. Thus the site gains even more material prominence relative to other places on the landscape. Thus develops a feedback loop in the attractiveness of certain locations. Of course that attractiveness is tempered by finite resources. So while a centripetal force draws foragers in, a simultaneous centrifugal force pushes them out to other locations. What emerges is something of a randomized central-place mobility pattern in which foragers tack back and forth between natural and culturally constructed environments. Importantly, this model does not require environmental heterogeneity to derive variation in the use-intensity of sites. Rather, environmental heterogeneity emerges endogenously from the differential use and deposition of cultural materials among places on the landscape.

To operationalize this conceptual model, we can imagine a forager who must decide where to reside on some periodic basis—say weekly, monthly, or seasonally. With some probability, m, the forager decides to move to the location of a previously deposited unit of material culture—say a house frame or stone tool. Then, with some opposite probability, $1-m$, the forager's movement decision is independent of previously deposited material culture and instead is entirely based on some exogenous factor such as a resource opportunity in a place without material culture. Thus the forager moves to a novel place on the landscape. Previous simulations show that when the value of m is high—on the order of 90%—simulated settlement patterns are remarkably similar to empirical settlement patterns (Haas & Kuhn, 2019).

The rather uncontroversial suppositions of habitual tool use, human mobility, and economic rationality along with empirical support from archaeology and ethnography would seem to justify the model of recursive mobility with strong attachment to previously occupied places. The question examined now is how such recursive mobility behavior interacts with population growth and to what effect.

Growth and Recursive Mobility In the introduction, I argued that population packing does not necessarily entail sedentism because human populations are nearly always at carrying capacity. The recursive mobility model also does not entail sedentism. Like a body in motion that stays in motion in the absence of an external force (Newton, 1803), a mobile individual recursively occupying places on landscapes ought to continue to do so unless compelled by some other interest to stay in place. Might residential sedentism emerge when the populations of recursively mobile populations grow? I will cut to the chase: the answer is no. There still is nothing intrinsic to the combination of population growth and recursive mobility that should compel a mobile individual to cease being mobile. Nonetheless, an interesting and relevant dynamic does emerge. At some point in the trajectory of population growth, the most prominent site in the system—the one that experiences the highest frequency of re-occupation by mobile foragers—ceases to experience an occupational hiatus. In other words, with enough people moving through constructed landscapes, there will eventually emerge a site that always has at least one occupant and often more. With the addition of more individuals still, we should expect a second site to similarly become permanently occupied and so on. In this way, sedentism does not emerge at the intersection of growth and mobility, but continuously occupied places do naturally emerge.

Here is how it happens. Consider a single forager, or a forager family if you prefer, occupying some place on the landscape. As in the recursive mobility model, that forager uses material culture to interface with their environment whether to procure nutrients, construct shelter, or care for family. In doing so, they modify their location by aggregating materials, building shelter, digging storage pits, depositing lithic materials, etc. In doing so, they create an archaeological site. We'll imagine that they deposit one unit of material culture per unit of time. At time two, the forager decides where to reside next—either the location of a previously deposited unit of material culture to take advantage of its utility or to a novel location on the landscape independent of cultural materials on the landscape. The forager iterates this process, which results in preferential attachment to a few prominent sites and continuous creation of new sites.

Meanwhile, the forager and subsequent foragers reproduce with a probability of 0.04% resulting in population growth at that rate. Any new foragers also restructure the landscape, are recursively mobile, and reproduce at a rate of 0.04%. The virtual foragers do not prefer their own materials. All materials have utility to all foragers and thus are fair game. These behaviors are allowed to repeat for some specified amount of time, generating a virtual settlement system that we can monitor for changes in the tempo of occupation at sites.

3.3 Results: Sedentary Sites

Figure 3.1 shows the results of a sample simulation allowed to run for 12,000 time units, or ticks. We could imagine that a tick is a day, week, month, or season. The particular temporal unit is not so important as long as it is assumed to be sub-annual, and the particular values should not be taken to be meaningful, but I use them here to illustrate the broad, relative trends in settlement dynamics. Panel A of Fig. 3.1 shows population growth in the simulation beginning at one forager and ending with 400 foragers. Panel B shows site-size variation in the settlement system. Each dot represents a simulated site. The x axis shows the size rank of the site, and the y axis shows site size measured as number of deposited artifacts. Both axes are log scale. The resultant pattern is clearly linear and thus log-linear given the log-log scale of the graph. This log-linear structure is consistent with site-size variation observed in human settlement patterns including hunter-gatherer, agricultural, and state settlement patterns (Drennan & Peterson, 2004; Haas et al., 2015; Krugman, 1996; McAndrews et al., 1997; Newman, 2005; Stanish, 2003) and thus provides a useful check on the model.

Panel C of Fig. 3.1 monitors the continuity of occupation of the largest site in the system at each time step. This provides a way to track the highest degree of occupational continuity in the system. For each site in the system, if it is occupied by one or more foragers at a given tick, the site's occupational continuity value is incremented by one. If the site is unoccupied at a given tick, the continuity is set to zero. The greatest occupational continuity value is recorded at each tick. Panel C shows an overall increase in maximum occupation continuity throughout the simulation. However, from zero to approximately 5000 ticks, maximum occupational continuity stays relatively low, below about 500 ticks and typically far fewer. In other words, none of the sites early in the simulation exhibit long-term continuity of occupation—they all experience occupational hiatuses at some point. Beyond 5000 ticks, site occupation history begins to change. The largest site in the system begins to experience exponentially longer occupational continuity. Beyond approximately 8000 ticks, the largest site in the system ceases to experience occupational hiatuses. Panel D shows the same data as panel C but with the y-axis log transformed to show more subtle variation in the relationship. The graphic reveals that after 4000 ticks, there is always at least one site in the system with an occupational continuity of two or more ticks. Prior to that, the most intensively occupied site in the system at any given time was just one tick.

Thus the model reveals that under conditions of population growth and recursive mobility, continuous occupation of few prominent sites in a given settlement system should emerge following a protracted period of low occupational continuity.

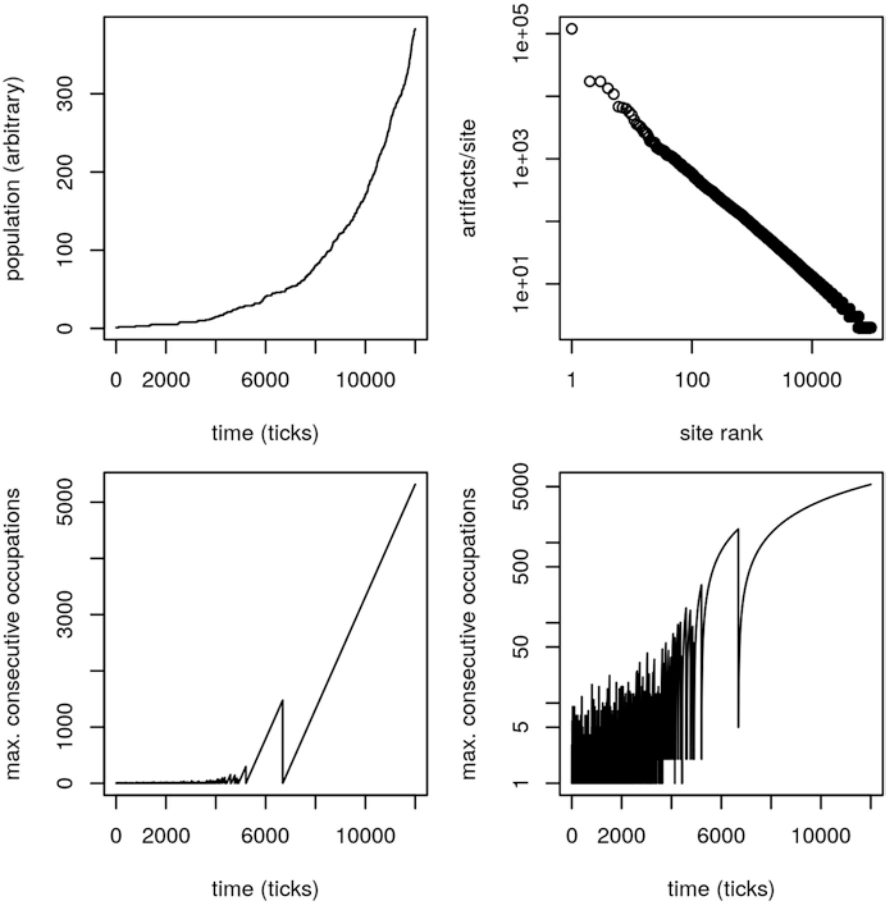

Fig. 3.1 Example output from a single simulation run after 12,000 time units (ticks). (**a**) Population change. Exponential population growth at 0.04% after 12,000 arbitrary time units. (**b**) Site-size. The resultant site-size distribution shown as a rank-size plot and revealing the log-linear structure of settlement hierarchy. (**c**) Maximum occupation continuity. Continuous occupation duration of the most continuously occupied site showing that after 6000 ticks, the most continuously occupied site becomes permanently occupied. (**d**) Maximum occupation continuity, log-scaled y axis. The plot shows the same data as (**c**) with the y-axis log-transformed to show that after approximately 3000 ticks, there is always at least one site with consecutive occupancy

3.4 Summary and Discussion

The appearance of residential sedentism was a watershed moment in the evolution of human societies. While great opportunities for population growth and innovation came with sedentism, great challenges in terms of disease and conflict were also part and parcel. Such tensions have made it difficult for scholars to identify the mechanism of emergent sedentism. Early thinking saw sedentism as a natural and logical outcome of the discovery of agriculture, but there are empirical and theoretical reasons to doubt such a causal relationship. Other hypotheses have suggested that population packing was the key, but a potential problem with such explanations is that human populations are virtually always packed given Malthusian population dynamics leading to the untenable prediction that virtually all human societies in all times ought to have been sedentary.

The analysis presented here does not answer the question of how people became sedentary per se. At best, it suggests a key component in the pathway to human sedentism. It may, however, suggest a pathway to sedentism if we are willing to consider that sedentism can reside in places in addition to people. At the intersection of two relatively basic human behaviors—population growth and recursive mobility—continuous site occupancy emerges following a protracted period of discontinuous site occupancy. In this scenario, people do not become sedentary. Sites become sedentary. Thus it may be that sedentism—at least early sedentism—may reside in sites, not people.

The proposed pattern fits the empirical record qualitatively. Holocene human populations all began as residentially mobile ones. Sedentism emerged over thousands of years with sedentism appearing earlier or later in different places. The model also aligns with the Andean case study that inspired the model. Settlement-size variation seen in the model dynamics is consistent with the hierarchical structure observed empirically in the Titicaca Basin. Most sites associated with any given archaeological period are relatively small, and extremely large sites are rare but invariably present. The first 7000 years of human occupation in the Titicaca Basin were marked by residential mobility as indicated by a clear lack of evidence for substantial architecture and ceramics. Between 5.0 and 3.5 ka, the first sedentary or semi-sedentary villages such as Jiskairumoko and Kaillachurro appeared. From the early Formative Period onward, it seems apparent that numerous villages are occupied on a permanent basis. This trajectory in settlement patterns seems to align well with the dynamics observed in the model presented here.

The conclusions reached here furthermore resonate with observations made on Batak mobility patterns. The Batak are a residentially mobile population in the Phillipines. Based on long-term ethnographic observations, Eder (1984: 838) "argue[d] that sedentariness [can be] seen as a threshold property of social groups, while mobility is best seen as a continuous variable and an attribute of individuals (albeit in their social organizational contexts)…" and that "…'the rise of sedentism' in a particular group does not necessarily entail a decline in mobility." The working model thus offers a way to understand Batak situation in which "…some individuals are present in the [primary] settlement throughout the year" while remaining residentially mobile.

While it may be useful to reconceptualize early sedentism as a quantitative change in site occupancy dynamics as opposed to individual mobility, it is clear that average residential mobility of individuals did decline over time. The current model does not offer an explanation for that process. However, it may offer some clues to how residential sedentism may of emerged, and I speculate here. We could imagine that as residentially mobile populations grew and the occupation frequency of sites increased, human interaction rates necessarily increased especially at prominent sites in the settlement system. Such heightened interaction frequency entails several new dynamics that could trigger individual sedentism. First, increased inter-personal interaction at certain sites would have created opportunities for economic coordination. Consider a scenario where a forager currently resides at a prominent site in a settlement system. The next day, the forager decides it's time to leave to pursue some resource elsewhere. But another forager shows up with the intent to forage in the vicinity. Because the first forager's knowledge of local resources is likely greater than the second forager's, the first forager is likely a more efficient forager at the location, so perhaps the two strike a deal where the first takes the place of the second by continuing to forage the current locale while the second exploiting resources at another site, and there is agreement to share in the spoils. In this mutually beneficial way, a sedentary site could translate into sedentary individuals.

Alternatively, and at the other extreme, the posited dynamics would likely have created conflicts that could have motivated individual sedentism. By increasingly using the same site at the same time, competition for resources intensifies. If so, an earlier occupant might stake despotic claim on the site (Winterhalder et al., 2010), and others might concede, whether willingly or not. Here we see a context for "cheating at musical chairs" even in the absence of population packing in the sense envisioned by Rosenberg (1998) and Kelly (2013: 107).

It is also worth noting that sedentary sites offer a potential solution to a major theoretical challenge associated with plant domestication. Residential mobility is often thought to be at odds with the evolution of agriculture because cultigens left unattended for long periods of time are vulnerable to predation by non-human consumers. Pathways to domestication are thus easily disrupted. In the current scenario, as occupation frequency increases, human introduced plants at prominent sites in the settlement system receive defacto protection via serial occupation of the site. Such protection could have allowed directional selection trajectories to persist without perennial tending by singular individuals or families.

Scholars have emphasized the complexity of mobility, critiquing simple models as simplistic. Eder, for example, argued that archaeological notions of mobility such as Binford's collector-forager dichotomy belie considerable diversity in multi-level mobility repertoires of individuals and groups. Kelly (1992) reached a similar conclusion in his review of sedentism (see also Kelly (2013). The current treatment implicitly acknowledges that complexity but reduces it to randomness in order to isolate the interactive effects of two simple behaviors—population growth and recursive mobility. The working model does not explicitly account for resource patchiness, seasonality, kin structure, social relations, economy, or the variety of other behaviors that could conceivably condition an individual's or group's mobility decisions. Although it is certain that such factors contributed to emergent sedentism, it also seems likely that the interactive effects of population growth and recursive mobility cannot be excluded as principal drivers of sedentary sites in human settlement systems.

Acknowledgments Gregory Wada (UC Davis) offered helpful conversation and insights.

Appendix I: Simulation Code

```
###Model parameters###
###R Statistical Computing Language version 3.6.1 (R Core Team 2019)###
###Code is bold. Comments preceded by pound sign.###
iter<-12000 #number of iterations
m<-.9 #probability of occupying location of previously deposited material (Haas and Kuhn 2019)
g<-.0004 #population growth rate set to 0.04% (Zahid et al. 2016)
f<-data.frame(forager=1,site=1) #forager list initiated with forager 1 at site 1.
s<-data.frame(site=1,materials=1,consec=1) #site table with cultural material counts and consecutive occupations initialized with site 1 a material count of 1, and consecutive occupations count of 1.
pop<-c(1) # vector to store population beginning with 1 at time 1.
sedentism<-c(1) #vector to store the maximum of consecutive occupations without occupational hiatus from all sites beginning with time 1.
#######Start simulation
for (i in 2:iter){ #initiate simulation loop.
 print(i) #show simulation progress.
 #population growth
 for(j in 1:nrow(f)){ #for each forager…
  if (runif(1)<g){#reproduce if random value between 0 and 1 < growth rate, g.
   f[nrow(f)+1,]<-c(max(f$forager)+1,f$site[j])#add new forager to list.
 }
 #end growth
 #move forager
 if (runif(1)>m){ #if random number > than m…
  site<-max(unique(s$site))+1 #select random new site location, i.e., create new site
 s[nrow(s)+1,]<-c(site,1,1) #add new site to site table
 }
 else { #otherwise
 site<-sample(s$site,1,prob=s$materials) #select a random material (artifact) location at an existing site. This is simulated by sampling sites weighted by prob of material count.
 }
 #end move forager
 #deposit material
```

(continued)

```
 f[j,2]<-site #update foragers home sites.
  s[which(s$site==site),2]<-s[which(s$site==site),2]+1 #increment material count at occupied site
  }
 pop[i]<-nrow(f)#update the population growth list
 os<-unique(f$site) #occupied sites
 s$consec[which(s$site%in%os==FALSE)]<-0 #if site is unoccupied, reset consecutive occupations to zero.
 s$consec[which(s$site%in%os==TRUE)]<-s$consec[which(s$site%in%os==TRUE)]+1 #if site is occupied, increase consecutive occupations by one.
 sedentism[i]<-max(s$consec) #find the site with the highest frequency of consecutive occupation and add to the list.
}
```

References

Albarracin-Jordan, J. (1996). Tiwanaku settlement system: The integration of nested hierarchies in the lower Tiwanaku Valley. *Latin American Antiquity, 7*(03), 183–210. https://doi.org/10.2307/971574

Albarracin-Jordan, J., & Mathews, J. E. (1990). *Asentamientos prehispánicos del Valle de Tiwanaku* (Vol. 1). Producciones Cima.

Aldenderfer, M. S., & Flores Blanco, L. A. (2011). Reflexiones para avanzar en los estudios del Periodo Arcaico en los Andes Centro-Sur. *Chungara: Revista de Antropología Chilena, 43*(1), 531–550.

Bandy, M. S. (2004). Fissioning, scalar stress, and social evolution in early village societies. *American Anthropologist, 106*(2), 322–333. https://doi.org/10.1525/aa.2004.106.2.322

Bandy, M. S. (2005). New World settlement evidence for a two-stage Neolithic demographic transition. *Current Anthropology, 46*(S5), S109–S115. https://doi.org/10.1086/497665

Bandy, M. S. (2006). Early village society in the Formative Period in the southern Lake Titicaca Basin. In W. H. Isbell & H. Silverman (Eds.), *Early village society in the Formative Period in the southern Lake Titicaca Basin* (Vol. III). Springer.

Barlowe, K. R. (2006). A formal model for predicting agriculture among the Fremont. In D. J. Kennett & B. Winterhalder (Eds.), *Behavioral ecology and the transition to agriculture* (pp. 87–102). University of California Press.

Bettinger, R. L., Garvey, R., & Tushingham, S. (2015). *Hunter-gatherers: Archaeological and evolutionary theory* (2nd ed.). Springer.

Binford, L. R. (1980). Willow smoke and dogs' tails: Hunter-gatherer settlement systems and archaeological site formation. *American Antiquity, 45*(1), 4–20.

Binford, L. R. (1982). The archaeology of place. *Journal of Anthropological Archaeology, 1*(1), 5–31. https://doi.org/10.1016/0278-4165(82)90006-x

Browman, D. L. (1981). New light on Andean Tiwanaku: A detailed reconstruction of Tiwanaku's early commercial and religious empire illuminates the processes by which states evolve. *American Scientist, 69*(4), 408–419.

Bruno, M. C. (2006). A morphological approach to documenting the domestication of chenopodium in the Andes. In M. A. Zeder, D. G. Bradley, E. Emshwiller, & B. D. Smith (Eds.), *Documenting domestication: New genetic and archaeological paradigms* (1st ed., pp. 32–45). University of California Press.

Capriles, J. M., Domic, A. I., & Moore, K. M. (2008). Fish remains from the Formative Period (1000 Bc–Ad 400) of Lake Titicaca, Bolivia: Zooarchaeology and Taphonomy. *Quaternary International, 180*(1), 115–126. https://doi.org/10.1016/j.quaint.2007.08.022

Capriles, J. M., Albarracin-Jordan, J., Bird, D. W., Goldstein, S. T., Jarpa, G. M., Calla Maldonado, S., & Santoro, C. M. (2018). Mobility, subsistence, and technological strategies of early Holocene hunter-gatherers in the Bolivian Altiplano. *Quaternary International, 473B*, 190–205. https://doi.org/10.1016/j.quaint.2017.08.070

Childe, V. G. (1929). *The most ancient near east: The oriental prelude to European prehistory*. Alfred A. Knopf.

Christaller, W. (1966). *Central places in southern Germany*. Prentice-Hall.

Cipolla, L. M. (2005). Preceramic Period settlement patterns in the Huancané-Putina River Valley, Northern Titicaca Basin, Peru. In C. Stanish, A. B. Cohen, & M. S. Aldenderfer (Eds.), *Preceramic Period settlement patterns in the Huancané-Putina River Valley, Northern Titicaca Basin, Peru* (pp. 55–64). Cotsen Institute of Archaeology at UCLA.

Craig, N. (2011). Cultural dynamics, climate, and landscape in the south-central Andes during the mid-late Holocene: A consideration of two socio-natural perspectives. *Chungará, 43*(especial), 367–391. https://doi.org/10.4067/s0717-73562011000300004

Drennan, R. D., & Peterson, C. E. (2004). Comparing archaeological settlement systems with rank-size graphs: A measure of shape and statistical confidence. *Journal of Archaeological Science, 31*(5), 533–549. https://doi.org/10.1016/j.jas.2003.10.002

Eder, J. F. (1984). The impact of subsistence change on mobility and settlement pattern in a tropical forest foraging economy: Some implications for archeology. *American Anthropologist, 86*(4), 837–853.

Feinman, G. M., & Marcus, J. (Eds.). (1998). *Archaic states*. School of American Research Press.

Flannery, K. V. (1998). The ground plans of archaic states. In G. M. Feinman & J. Marcus (Eds.), *Archaic states* (pp. 15–57). School of American Research Press.

Flores Blanco, L. A. (2017). El periodo Arcaico en la cuenca del lago Titicaca y sus alrededores, Andes centro-sur. In R. Vega-Centeno Sara-Lafosse (Ed.), *El periodo Arcaico en la cuenca del lago Titicaca y sus alrededores, Andes centro-sur* (pp. 1–84). Instituto de Estudios Peruanos.

Griffin, A. F. (2011). Emergence of fusion/fission cycling and self-organized criticality from a simulation model of early complex polities. *Journal of Archaeological Science, 38*(4), 873–883. https://doi.org/10.1016/j.jas.2010.11.017

Griffin, A. F., & Stanish, C. (2007). An agent-based model of prehistoric settlement patterns and political consolidation in the Lake Titicaca Basin of Peru and Bolivia. *Structure and Dynamics: eJournal of Anthropological and Related Sciences, 2*(2), 1–47.

Haas, R., & Kuhn, S. L. (2019). Forager mobility in constructed environments. *Current Anthropology, 60*(4), 499–535. https://doi.org/10.1086/704710

Haas, R., & Tagliabue, J. (2012). Prediciendo la coalescencia en los Períodos Formativo y Tiwanaku en la Cuenca de Titicaca: un modelo simple basado en agentes. In L. F. Blanco & H. Tantaleán (Eds.), *Prediciendo la coalescencia en los Períodos Formativo y Tiwanaku en la Cuenca de Titicaca: un modelo simple basado en agentes* (pp. 243–260). Instituto Francés de Estudios Andinos; Cotsen Istitute of Archaeology at UCLA.

Haas, R., & Viviano Llave, C. (2015). Hunter-gatherers on the eve of agriculture: Investigations at Soro Mik'aya Patjxa, Lake Titicaca Basin, Peru, 8000–6700 BP. *Antiquity, 89*(348), 1297–1312. https://doi.org/10.15184/aqy.2015.100

Haas, R., Klink, C. J., Maggard, G. J., & Aldenderfer, M. S. (2015). Settlement-size scaling among prehistoric hunter-gatherer settlement systems in the New World. *PLoS One, 10*(11), e0140127. https://doi.org/10.1371/journal.pone.0140127

Haas, R., Stefanescu, I. C., Garcia-Putnam, A., Aldenderfer, M. S., Clementz, M. T., Murphy, M. S., Viviano Llave, C., & Watson, J. T. (2017). Humans permanently occupied the Andean highlands by at least 7 ka. *Royal Society Open Science, 4*(6), 170331. https://doi.org/10.1098/rsos.170331

Haas, R., Surovell, T. A., & O'Brien, M. J. (2019). Dukha mobility in a constructed environment: Past camp use predicts future use in the Mongolian Taiga. *American Antiquity, 84*(02), 215–233. https://doi.org/10.1017/aaq.2018.88

Hastorf, C. A. (Ed.). (1999). *Early settlement at Chiripa, Bolivia: Research of the Taraco Archaeological Project*. Archaeological Research Facility, University of California.

Hastorf, C. A. (2008). The Formative Period in the Titicaca Basin. In H. Silverman & W. H. Isbell (Eds.), *Handbook of South American achaeology* (pp. 545–561). Springer.

Janusek, J. W. (2004). Tiwanaku and its precursors: Recent research and emerging perspectives. *Journal of Archaeological Research, 12*(2), 121–183.

Kelly, R. L. (1992). Mobility/sedentism: Concepts, archaeological measures, and effects. *Annual Review of Anthropology, 21*(1), 43–66. https://doi.org/10.1146/annurev.an.21.100192.000355

Kelly, R. L. (2013). *The lifeways of hunter-gatherers: The foraging spectrum* (Second ed.). Cambridge University Press.

Klink, C. J. (2005). Archaic Period research in the Rio Huenque Valley, Peru. In C. Stanish, A. B. Cohen, & M. S. Aldenderfer (Eds.), *Archaic Period research in the Rio Huenque Valley, Peru* (pp. 13–24). Cotsen Institute of Archaeology at UCLA.

Klink, C. J., & Aldenderfer, M. S. (2005). A projectile point chronology for the South-Central Andean highlands. In C. Stanish, A. B. Cohen, & M. S. Aldenderfer (Eds.), *A projectile point chronology for the South-Central Andean highlands* (pp. 25–54). Cotsen Institute of Archaeology at UCLA.

Kolata, A. L. (1996). *Tiwanaku and its hinterland: Archaeology and paleoecology of an Andean civilization* (Vol. 1). Smithsonian Institution Press.

Krugman, P. (1996). *The self-organizing economy*. Blackwell Publishers.

Kuhn, S. L. (1995). *Mousterian lithic technology*. Princeton University Press.

Marsh, E. J. (2016). The disappearing desert and the emergence of agropastoralism: An adaptive cycle of rapid change in the mid-Holocene Lake Titicaca Basin (Peru–Bolivia). *Quaternary International, 422*, 123–134. https://doi.org/10.1016/j.quaint.2015.12.081

McAndrews, T. L., Albarracin-Jordan, J., & Bermann, M. (1997). Regional settlement patterns in the Tiwanaku Valley of Bolivia. *Journal of Field Archaeology, 24*(1), 67–83.

Moseley, M. (1992). *The Incas and their ancestors: The archaeology of Peru* (Revised ed.). Thames and Hudson.

Newman, M. E. J. (2005). Power laws, Pareto distributions and Zipf's law. *Contemporary Physics, 46*(5), 323–351. https://doi.org/10.1080/00107510500052444

Newton, I. (1803). *The mathematical principles of natural philosophy* (A new ed. / (with the life of the author and a portrait, taken from the bust in the Royal Observatory at Greenwich), carefully rev. and corr. by W. Davis.. ed.). H.D. Symond.

Osorio, D., Steele, J., Sepúlveda, M., Gayo, E. M., Capriles, J. M., Herrera, K., Ugalde, P., De Pol-Holz, R., Latorre, C., & Santoro, C. M. (2017). The Dry Puna as an ecological megapatch and the peopling of South America: Technology, mobility, and the development of a late Pleistocene/early Holocene Andean hunter-gatherer tradition in northern Chile. *Quaternary International, 461*(Suppl C), 41–53. https://doi.org/10.1016/j.quaint.2017.07.010

Peros, M. C., Munoz, S. E., Gajewski, K., & Viau, A. E. (2010). Prehistoric demography of North America inferred from radiocarbon data. *Journal of Archaeological Science, 37*(3), 656–664. https://doi.org/10.1016/j.jas.2009.10.029

Plourde, A., & Stanish, C. (2006). The emergence of complex society in the Titicaca Basin: The view from the north. *Andean Archaeology, 3*, 237–257.

Richerson, P. J., Boyd, R., & Bettinger, R. L. (2001). Was agriculture impossible during the Pleistocene but mandatory during the Holocene? A climate change hypothesis. *American Antiquity, 66*(3), 387–411. https://doi.org/10.2307/2694241

Rigsby, C. A., Baker, P. A., & Aldenderfer, M. S. (2003). Fluvial history of the Rio Ilave valley, Peru, and its relationship to climate and human history. *Palaeogeography, Palaeoclimatology, Palaeoecology, 194*(1–3), 165–185. https://doi.org/10.1016/s0031-0182(03)00276-1

Rosenberg, M. (1998). Cheating at musical chairs. *Current Anthropology, 39*(5), 653–681. https://doi.org/10.1086/204787

Rumold, C. U., & Aldenderfer, M. S. (2016). Late Archaic–Early Formative Period microbotanical evidence for potato at Jiskairumoko in the Titicaca Basin of southern Peru. *Proceedings of the National Academy of Sciences, 113*(48), 13672–13677. https://doi.org/10.1073/pnas.1604265113

Schultze, C. A., Stanish, C., Scott, D. A., Rehren, T., Kuehner, S., & Feathers, J. K. (2009). Direct evidence of 1,900 years of indigenous silver production in the Lake Titicaca Basin of Southern Peru. *Proceedings of the National Academy of Sciences, 106*(41), 17280–17283. https://doi.org/10.1073/pnas.0907733106

Shennan, S., Downey, S. S., Timpson, A., Edinborough, K., Colledge, S., Kerig, T., Manning, K., & Thomas, M. G. (2013). Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nature Communications, 4*(1). https://doi.org/10.1038/ncomms3486

Smith, B. D. (1995). *The emergence of agriculture*. Scientific American Library.

Smith, B. D. (2001). Low-level food production. *Journal of Archaeological Research, 9*(1), 1–43. https://doi.org/10.1023/a:1009436110049

Stanish, C. (2003). *Ancient Titicaca: The evolution of complex society in southern Peru and northern Bolivia*. University of California Press.

Stanish, C., De la Vega, M. E., Steadmann, L., Chávez Justo, C., Frye, K. L., Mamani, L. O., Seddon, M. T., & Chuquimia, P. C. (1997). *Archaeological survey in the Juli-Desaguadero region of Lake Titicaca Basin, southern Peru*. Field Museum of Natural History.

Stanish, C., Cohen, A. B., de la Vega, E., Arkush, E., Chávez, C., Plourde, A., & Schultz, C. (2005). Archaeological reconnaissance in the northern Titicaca Basin. In C. Stanish, A. B. Cohen, & M. S. Aldenderfer (Eds.), *Archaeological reconnaissance in the northern Titicaca Basin* (pp. 289–316). Cotsen Institute of Archaeology at UCLA.

Turnbull, C. M. (1968). The importance of flux in two hunting societies. In R. B. Lee & I. DeVore (Eds.), *Man the hunter* (pp. 132–137). Aldine Publishing Company.

Watson, J. T., & Haas, R. (2017). Dental evidence for wild tuber processing among Titicaca Basin foragers 7000 ybp. *American Journal of Physical Anthropology, 164*(1), 117–130. https://doi.org/10.1002/ajpa.23261

Wiessner, P. (1982). Beyond willow smoke and dogs' tails: A comment on Binford's analysis of hunter-gatherer settlement systems. *American Antiquity, 47*(1), 171–178. https://doi.org/10.2307/280065

Willey, G. R. (1953). *Prehistoric settlement patterns in the Virú Valley, Perú*. U.S. G.P.O.

Winterhalder, B., Kennett, D. J., Grote, M. N., & Bartruff, J. (2010). Ideal free settlement of California's Northern Channel Islands. *Journal of Anthropological Archaeology, 29*(4), 469–490. https://doi.org/10.1016/j.jaa.2010.07.001

Zahid, H. J., Robinson, E., & Kelly, R. L. (2015). Agriculture, population growth, and statistical analysis of the radiocarbon record. *Proceedings of the National Academy of Sciences, 113*(4), 931–935. https://doi.org/10.1073/pnas.1517650112