Geospatial Landscape Permeability Modeling for Archaeology: A Case Study of Food Storage in Northern Michigan

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1. Introduction

Archaeologists have increasingly harnessed the power of geospatial technologies to model patterns of past movement and to understand the social, economic, political, and/or ideological implications of these patterns for past societies (see Bell and Lock 2000; Carballo and Pluckhahn 2007; Howey 2011; Leidwanger 2013; Llobera 2000; Llobera et al. 2011; Richards-Rissetto and Landau 2014; Wernke 2012; White and Barber 2012). While varied in approach and scale, geospatial modeling of past movement generally focuses on travel, on people in some way traversing space between discrete points. In this paper, I suggest it is important for archaeologists to focus not just on geospatial modeling of travel between places but also the potentialities created by travel. As people move, they encounter a landscape matrix composed of some mix of elements which they observe, acquire knowledge about, and engage.

Here, I explore the use of geospatial tools to analyze potentialities for past processes emergent from encounters with landscape matrix variables. To do this, I draw on the ecological concept of landscape permeability, defined as the “degree to which a given landscape is conducive to the movement of organisms and the natural flow of ecological processes” (Anderson et al. 2014: 960). Shifting this concept archaeologically, I suggest we can look at landscape permeability as the degree to which a given landscape, with its specific mix of physical and social variables, was conducive to the movement of people and the flow of social, economic, political, and/or ideological processes.

To explore permeability modeling archaeologically, I offer a specific analysis of how permeable an inland lake landscape in northern Michigan was to food storage during Late Precontact (ca. AD 1100/1200 – 1600), a cultural practice essential to community well-being in the emergent mixed hunter-gatherer and horticulturalist context of the period. I explore how people, in their intimate, day-to-day, movements across their landscape encountered the storage potential(s) of its matrix. I begin with a brief consideration of the especially significant role landscape knowledge plays in mobile societies and introduce the case study. I incorporate two landscape matrix variables critical to storage in the construction of a landscape permeability model for storage using resistant-kernel analysis (run in R; developed by Compton et al. 2007). Using the output permeability grid produced in this analysis, which represents a ‘storage-suitability scape’, I explore how communities experienced and responded to the conduciveness, or permeability, of the landscape to storage.

As Llobera (2012: 505) has elucidated, geospatial models in archaeology provide an ideal means to determine the range of possibilities associated with certain past cultural processes, these possibilities important to reference even without actual instantiation. By working through one specific permeability analysis, my goal is to present permeability modeling as an adaptable heuristic for archaeologists working elsewhere to examine interconnections between landscape matrix variables and the resulting conduciveness for the operation of various past cultural processes. Ecological permeability modeling hypothesizes species adaptive processes in response to physio-geographical constraints. For archaeology, I suggest we can use permeability modeling to hypothesize underlying processes related to knowledge of landscape suitability for various cultural activities, from subsistence practices (the focus in this paper’s specific case study), to defensive construction, to ritual engagement.

2. Movement and Landscape Matrix Knowledge in Mobile Societies

Movement plays an especially significant role in mobile hunter/gatherer/fisher (and emergent horticulturalist) societies. Movement is central to the structure and success of mobile societies. While central, movement also presents risks, requiring the crossing of what can be physically and socially dangerous landscapes (Funk 2011:30). Information, or knowledge, about the social and ecological variables composing the landscape matrix becomes essential to survival. Such knowledge has to be gathered through highly detailed observations during the course of movement through space.

Early ethnographers working on hunter-gatherers were often struck by the consummate importance placed on firsthand acquisition of reliable, detailed information on all aspects of land use in these societies (Lovis and Donahue 2011:63). The personal account Mandan warrior Crow's Heart gave to anthropologist Martha Beckwith in the 1930s provides a tangible example of this phenomenon. Recounting his time as a war scout, Crow's Heart explains "I was a good runner, hardy and enduring, and that is how I came to know the names of those hills and other landmarks in the country. I know that I am right because I have seen these places. A person who tells the stories without seeing the places, should anyone see the account will be laughed at" (Beckwith 1938:303; Zedeno et al. 2009: 106). He then proceeds to give detailed information about the natural and cultural features he learned over the course of his movements and concludes, four recorded pages later, "That is all the places I know" (Beckwith 1938:307).

To be of use in mobile societies, such socio-ecological knowledge has to circulate. In order to circulate, knowledge has to be encoded, or stored, by communities over various time scales (Whallon 2011:13). Ethnographically, we see this often entails verbal, social, and sacred systems of encoding (oral traditions, place-making, religious practices, kinship orders, gendered labor divisions) (for examples, see Basso 1996; Minc 1986; Wiessner 1982; Zedeno et al. 2009). Encoding can also be physical, spatially-embedded; things like trail markers, waypoints, rock art, and portage marks are known to be vital information markers in mobile societies (for examples, see Aporta 2009; Darling 2009; Fowler 2009; Lovis and Donahue 2011; Norder 2003). Here, I examine a suite of archaeological features -- cache, or storage, pits -- from the northern Great Lakes as such spatially-embedded features encoding landscape matrix knowledge.

3. Case Study Background: Food Storage Features in Late Precontact Northern Michigan

The northern Great Lakes saw a notable rise in the practice of food storage during the Late Precontact period (ca. AD 1100/1200 – 1600) in the form of clusters of subterranean food storage pits dispersed in various ways from residential occupation (Dunham 2000; Holman and Krist 2001) (Figure 1). Historic Anishinaabeg groups continued to construct cache pits to some degree through the early 1900s and ethnohistoric observations provide a sense of cache pits in use (Densmore 1929; Kinietz 1947; Tanner 1940 [1830]). In brief, cache pits were u-shaped features, ranging from 1 to 2 meters wide and deep, lined with birch bark, filled with foodstuff in containers with grass-type fill in between, and capped with mounded dirt. As archaeological features, cache pits are circular depressions, with diameters from 1 to 2 meters and current surface depths between .3 to .6 meters. These features almost always occur in clusters, typically with 10 to 25 pit depressions but some can have hundreds (Dunham 2000; Dustin 1966; Hambacher and Holman 1995; Schneider 1942; Schumacher 1918).

Late Precontact was marked by economic and social changes. In brief, along the coasts of northern Lake Michigan and Huron, fishing of seasonal spawns intensified and small-scale maize

cultivation became part of a mixed coastal economy (Cleland 1982; Hart and Lovis 2013; Holman and Lovis 2008; O’Gorman 2007; O’Gorman and Lovis 2006; O’Shea 2003; O’Shea and Milner 2002). With a harsh and unpredictable climate, maize cultivation was high-risk along northern coasts, made possible where lake-effect created the 120 frost-free days necessary for prehistoric maize (Yarnell 1964).

Both maize cultivation, needing lake-effect, and intensified fishing, needing Great Lake fish spawning grounds, benefited from a growing focus on coastal settlements. As spatial proximity became increasingly important, coastal forager-fisher-horticulturalists settled into larger seasonal villages on the coasts, developed corporate social identities, and demarcated more exclusive territories (O’Shea 2003:6; see also Cleland 1992; Holman and Lovis 2008; O’Shea and Milner 2002). Groups living inland found the geographic circuits for their mobile annual round reduced by the shifts on the coasts. Inland hunter-gatherer communities also intensified the use of their local (wild) resources, including foodstuffs amenable to storage such as acorns, berries, inland lake fish, and (potentially) maple syrup and wild rice (Dunham 2009; Holman 1984).

Across the region, communities found themselves engaging in their annual mobility rounds within more spatially and socially restricted territories. With the (wild and cultivated) resource base of the region being both seasonally variable and unpredictable year-to-year, the reduction in the spatial range communities could exploit to harvest food resources heightened the risk of experiencing resource failure. The need to both maximize and extend the use-life of local abundances became critical. The rise of a systematic system of food storage in the form of dispersed cache pit clusters can be understood as a strategic response to the changes of Late Precontact -- storage formed an essential buffer against starvation, an indispensable tool of survival (Holman and Lovis 2008:289).

Food storage was dependent on the construction, maintenance, and use of successful cache pits. If cache pits failed due to rot or destruction by outside forces (animals, other humans, etc.), the investment of time and labor (at the expense of other activities) that went into food storage would be wasted (Frederick 2015; Morgan 2012; Whelan et al. 2013). In an already restricted and unpredictable setting, the waste of both time and nutritional product invested in storage would place a heavy burden on those experiencing cache failure.

Cache pits were a key of community well-being during Late Precontact but to be so, they had to be properly spatially-embedded. These fixed constructions had to be in places where they would not fail, where locally available storable food stuffs could be placed in them, and where they could be reasonably accessed by communities reliant on them. Cache pits had to be built by people who had acquired essential landscape matrix knowledge for successful storage and in constructing pits, they also spatially-embedded this information in local landscapes. Can we, by comparing cache pit distribution to randomly distributed points, identify how people placed pits preferentially vis-à-vis landscape variables critical to storage? Using such variables we can show as significant to cache pit placement, can we then model more broadly how conducive, or permeable, the landscape was to food storage and how people encountered this storage suitability in their territory?

3.1 Cache Pits on Douglas and Burt Lake, Northern Michigan

I explore these questions in one local inland lake landscape, Douglas and Burt Lakes located in the northern tip of the Lower Peninsula of Michigan, roughly 25 km south of the Mackinac Straits, where Lake Michigan and Lake Huron meet (Figure 1). Douglas Lake drains into the

topographically lower and larger Burt Lake three kilometers south (Figure 2). Burt Lake is within the Inland Waterway, a series of inland lakes, rivers, and streams that creates an inland route between Lakes Michigan and Huron (Figure 1; Lovis 1976:366).

Inland lakes in northern Michigan have experienced intensive development due to their high recreational draw. Over 35 years ago the threat such development posed for the archaeological record was highlighted (Lovis 1978a) but development has proceeded unchecked. A rare exception lies along Douglas and Burt Lake where the University of Michigan Biological Station (UMBS), a world-class environmental research/education station operating for the last 100 years, preserves 10,000 acres, including several kilometers of shoreline (Figure 2). While important for all archaeological sites, this protection is especially important for cache pits. As archaeological features, cache pits are subtle and have extremely low artifact densities. Contemporary development has very likely destroyed numerous pit clusters without notice of any kind (living sites, while they may be developed anyways, are likely to have been recorded, even if just by landowners, as they produce artifacts). So, while Douglas and Burt Lake are only two inland lakes, the cache pits found around them provide insight into how pits were likely similarly distributed around other inland lakes.

Cache pits were first documented on UMBS property during a short reconnaissance along Burt Lake (Albert and Minc 1987). Our team's follow-up research began in 2007. Prime time to find cache pits is late spring as snow laying in surface depressions melts slower than on the ground, making cache pits much more obvious. UMBS Resident Biologist Robert VandeKopple has led a team of citizen scientists in spring survey (results confirmed during summer). Survey methodology involves walking with GPS units in 50 meter transects two kilometers out from shore (standing water/steep gradients excluded). To date, 69 clusters of cache pits have been found (all UMBS land surveyed, survey ongoing on private property dependent on land-owner permission) (Figure 2 and Figure 3). Pit clusters were defined as a cluster when no pits were found for at least 75 meters (overlaps in Figure 2 are from map scale). Most clusters have 10 to 25 pits but one has 60+ pits and another 220+ (Figure 2). Across the Great Lakes, if not from the Historic period, cache pits almost always date to ca. AD 1000 - 1600 (Dunham 2000: 229) and that appears to be the case here based on associated ceramics, shovel-test survey, and radiocarbon dating (as well as lack of any historic evidence; see Howey and Parker 2008).

4. Analysis of Landscape Matrix Variables and Cache Pits on Douglas and Burt Lake

Recognizing that cache pits only bear benefit if they are both accessed by people situated in local landscapes and actually preserve foodstuffs, I focused on two physical and measurable landscape matrix variables related to these facts, distance to inland lake and drainage, for use in building a storage landscape permeability model. While it may seem obvious that distance to lake and drainage were significant to cache pit placement, it would nevertheless be imprudent to simply proceed to building a permeability model based on this assumption. To produce a more robust and secure model, then, I first conducted systematic statistical analyses to determine if cache pit clusters indeed pattern non-randomly in relation to these storage-relevant physical landscape variables.

To conduct this analysis, I first delineated spatially the cache pit survey area around Douglas and Burt Lake to Colonial Point working from collected GPS data and an inland lake polygon file (Figure 3; all GIS work done in ArcGIS 10.2; landscape variable data from GIS Open Data Portal State of Michigan: <http://gis.michigan.opendata.arcgis.com/>). I used a 30-meter resolution

for grid-based analyses through the study, a resolution that avoids multiple cache pit clusters in any one cell and provides robust processing ability. I clipped a 30-meter Digital Elevation Model (DEM) raster to get a total survey area grid cell count of 73,344 cells. I then created a 1% random point distribution in this study area of 733 points (Figure 3).

For cache pits and these generated random points, I extracted cell values for both variables (from ArcGIS 10.2 to Excel). Using a standard Kolmogorov-Smirnov test, I assessed the distribution of cache pit and random point distribution as related to the two matrix variables and found for both, cache pits and random points were non-normally distributed (in SPSS). I examined the continuous fit over the cache pit and random point distributions and among 10 possibilities, identified the Johnson SU best fit cache pit distribution and Normal 3 Mixture best fits random point distribution (in JMP). With both distribution curves being non-normal, I used the nonparametric two-sample Kolmogorov-Smirnov which allows for testing of differences in distributions of two samples of continuous observations (Palace et al. 2008:145; here, two samples are cache pits and random points, continuous observation values are distance to lake and CTI, as discussed below).

4.1 Landscape Matrix Variable 1: Distance to Inland Lake

Inland lakes provided a key residential base for communities during Late Precontact. A major survey of the Inland Waterway conducted in 1974/5 identified the majority of Woodland occupation sites along shorelines (Holman 1978; Lovis 1976, 1978a, 1978b). Our work on Douglas and Burt has found occupation evidence only on shores. Additionally, inland lakes were key to storage accessibility, as transport avenues that allowed people to move across territory, to and from living sites, to resources, and to storage features (Blackbird 1887). Inland lakes were also themselves an important source of storable food resources including fish but also water tubers and (potentially) wild rice (and fresh water for the necessary leaching of acorns).

I created a 30-meter raster with every grid cell assigned a value of calculated distance to inland lake (Figure 4). Comparing extracted distance to inland lake values for cache pits and random points, I found the difference between these distributions is significant (Kolmogorov-Smirnov two-sample test; $p < 0.01$) and also that the medians of these distributions are significantly different (Kolmogorov-Smirnov two-sample median test; $p < 0.01$). Cache pits (median distance, 244.6 meters) are significantly closer to inland lakes than randomly distributed points (median distance, 933.4 meters).

4.2 Landscape Matrix Variable 2: Compound Topographic Index

One of the surest ways to rot food in a Great Lakes subterranean storage pit is saturation by water. We see indeed, in the narratives of John Tanner (a captive who ended up living with the Ojibwe), he laments having to construct a ‘sunjegwun’ (cache) above ground from logs because the ground was too swampy to create the cache pit in the “usual manner of burying,” which he identifies as preferable for keeping items both fresh and safe (Tanner 1940[1830]:35). To assess drainage, I used a comprehensive index called the Compound Topographic Index (CTI) that provides a way of looking at topography as well as soil drainage (Beven and Kirkby 1979; Moore et al. 1991):

CTI = $\ln(a/\tan B)$

*where a is upstream contributing area and B is slope

CTI, by providing a way to index water accumulation in soils and topography provides a more salient landscape variable for successful food storage in subterranean cache pits than looking at topography alone. Using a 30 meter DEM, I calculated CTI using flow direction (upslope contributing area to the point under consideration per unit contour length) and slope (Figure 5). Lower CTI values are produced when there is (medium to) high slope and small contributing area and so, lower scores indicate improved drainage. Higher CTI values indicate broader, flatter, wetter areas, often occurring at the end of drainage features (Luo et al. 2010: 100). Just as with distance to lake, I compared extracted CTI values for cache pits and random points. I found the difference between these distributions is significant (Kolmogorov-Smirnov two-sample test; $p < 0.01$) and also that the medians of these distributions are significantly different (Kolmogorov-Smirnov two-sample median test; $p < 0.01$). Cache pits (median CTI, 7.66) are significantly located on better drained areas than randomly distributed points (median CTI, 9.03).

There is more to this patterning that, while qualitatively assessed, deserves mention. Looking at cache pit clusters cell-by-cell on the CTI raster, it is striking that even at the same topographic elevation, pits are located, it seems, selectively, on better drained locations (avoiding cells at the same elevation with even slightly higher CTI values). We can appreciate this in the context discussed above about the immense value people in mobile societies place on detailed and accurate landscape knowledge. People moving through this inland lake landscape didn't, obviously, have soil drainage testing equipment, but they had the ability to make detailed observations about things like how plants grew differently, or different plants grew, even slightly so, on the land and to translate this into knowledge about better drainage for their cache pits. Cache pits being located where they would not become saturated was a critical factor for storage success and this knowledge was acquired and encoded in the spatial-embedding of pits purposefully in this landscape.

5. Landscape Permeability Model of Storage on Douglas and Burt Lake

Having confirmed the placement of storage pits patterned non-randomly to distance to lake and drainage, I turned to using these landscape matrix variables in the construction of a model of the permeability of the broader landscape to storage. My aim was to create a continuous surface that reveals the implications of the physical landscape matrix with respect to amenability to storage. With this, it becomes possible to conceptualize the distribution of storage potential and to look at how communities organized their use of the landscape in response to this distribution.

To develop such a continuous surface, I drew on ecological modeling of permeability (see Anderson et al. 2014; Belisle 2005; Compton et al. 2007; Theobald et al. 2012; Van Buskirk 2012; Zeller et al. 2012). While specific methods vary, such modeling asks the question to what extent are flows outward from every cell in a continuous surface impeded or facilitated by the surrounding landscape matrix. Methodologically, permeability modeling starts with a focal cell and looks at the resistance to flows outward in all directions through the cell's local neighborhood using one of various calculation approaches (Zeller et al. 2012). The permeability of two adjacent cells increases with the similarity of those cells and decreases with their contrast, this contrast interpreted as indicating where an ecological process is likely to be disrupted

(Anderson et al. 2014). Translating this to the archaeological case study at hand, contrasts reflect where people would have encountered land less amenable to storage in the given neighborhood of a focal cell.

5.1 Resistant-Kernel Analysis

Specifically, I conducted permeability modeling using a resistant-kernel analysis developed by Dr. Compton and the University of Massachusetts Conservation Assessment and Prioritization System (CAPS) (program run in R; <http://www.umasscaps.org/about/team.html>; Compton et al. 2007). A kernel distance is set by the user and then a least-cost “kernel” is calculated that is a surface scaled to represent the probability of an individual dispersing or a process spreading from the focal cell to any other point in the landscape based on input landscape resistances (Compton et al. 2007:791). This provides a means of tracing the theoretical spread of a process outward from a focal cell as a function of the resistance values of the neighboring cells and their distance from the focal cell out to the maximum distance (set for the kernel) (Anderson et al. 2014). To create a continuous resistant-kernel permeability surface, a least-cost kernel is calculated for each focal cell, the kernel sum is assigned to the focal cell, and this is repeated for the entire grid (Compton et al. 2007:791).

5.1.1 Procedure Step 1: I re-classified distance to inland lake and CTI grids into 20 resistance weight values that were scored 1 to 20 based on quantile breaks. This re-classification created two input grids with comparable value scales, wherein lower resistance weight values are, respectively, closer to lake and lower CTI.

5.1.2 Procedure Step 2: I created a final resistance grid for input into the kernel modeling that combined both variables. I computed three scenarios to determine optimal weightings of the input variable grids into the final resistance grid: 20% distance to water and 80% CTI; 50% distance to water and 50% CTI; 80% distance to water and 20% CTI. In both the first and second scenario, distance to water overwhelmed CTI. Distance to water occurs in more regular, continuous bands around the lakes (Figure 4) whereas CTI is a more nuanced variable across the landscape (Figure 5), and so distance to water has a strong effect on permeability modeling. To mitigate against a disproportionate effect, I used the third weighting scenario in the final input resistance grid.

5.1.3 Procedure Step 3: I set the resistant-kernel size at one kilometer to examine the spread of processes within a distance people could have readily moved in their day-to-day occupation around these lakes. I set the program to run from all cells treating each cell as the focal cell at one point in the analysis, moving around its one kilometer kernel neighborhood, and then summing across all kernels for a final surface. The resulting grid shown in Figure 6 is a continuous surface that reflects how permeable (conductive, amenable) the area around these lakes was to storage. In resistant-kernel analysis, the results are relative and lower scores reflect resistance to the flow of processes and higher scores reflect process flow across a landscape without encounter of landscape matrix variability. Higher scores reflect increased permeability and lower scores reflect reduced permeability.

5.2 Analyzing Late Precontact Encounter of Storage Permeability

Given the specific inputs of this model, the final relative permeability grid cell scores range from 0.004 to 0.153. Known pit locales have a higher mean permeability value (.084) than the overall permeability surface cell value mean (.039) (with overall mean value standard deviation of 0.028, pit mean permeability is over one standard deviation above average). We should not be surprised to find cache pit clusters falling in above average permeable locations on the landscape given I used their distribution to inform the permeability model, but their distinctly high permeability values do further emphasize how thoughtfully they were placed.

The real strength of permeability modeling is, however, that it provides a way of not just looking at processes in relation to discrete points (like known cache pits), but of representing the flow of processes across a whole landscape. The permeability grid produced here, then, represents what I suggest can be productively characterized as a 'storage-suitability scape' (Figure 6). As people moved through the landscape, this surface models the way they may have encountered places of varying suitability for storage (Figure 6).

I used this modeled surface to conduct further analysis to better understand how Late Precontact communities encountered and responded to storage permeability. Through intensive 10-meter transect shovel-test survey of low shoreline terraces associated with cache pit clusters, we have identified, to date, four living sites on UMBS property on Douglas and Burt Lake. Expanded excavations showed three of these have a notable Late Precontact component (post ca. AD 1100/1200) (Figure 7). These sites hosted seasonal residential activity during Late Precontact and the communities at these sites would have been engaging in storage locally as well as depending on stored provisions across this landscape as they performed their annual rounds in increasingly restricted geographic circuits (Holman and Krist 2001; Howey and Parker 2008). Given the importance of storage to community well-being, were loci of residential activity organized in locations where people could easily encounter and capitalize on storage permeability?

I created a nested series of 1 kilometer buffers around living sites (Figure 7). For each kilometer-increase neighborhood buffer, I calculated its mean permeability score. I continued buffers until the mean equalized with the mean for the whole grid (at 8 kilometers; 0.039). As shown in Figure 8, I found a strong negative correlation between distance from living site and permeability score (Pearson's $r = -0.977$; statistically significant at the .01 level, two-tailed). The further out from a living site, the lower the average permeability score -- the proximate neighborhoods of living sites incorporate areas of above average permeability.

Looking at the pattern of decrease more closely, permeability values are nearly the same from 1 to 2 kilometers, they drop at 3 kilometers, and then fall thereafter (Figure 8). This indicates local communities positioned living sites where daily accessible neighborhood held above average storage permeability. Taking a 4 km/hour walking rate, a one kilometer round trip (from living site to storage) would be 50 minutes while a two kilometer round trip would be 100 minutes (timing could be particularized using Tobler's function but this general figure provides a quick and useful means of furthering the appreciation of buffer results). At both of these distances, then, people could have reasonably encountered areas with above average suitability for food storage within daily routines.

Using known cache pit clusters, I analyzed how many cache pits were incorporated in each increasing buffer around living sites (Figure 9). Indeed, the biggest gains occur in the first three kilometers and drop precipitously thereafter (note, the few incorporated clusters at further

distances may potentially fall in the first few kilometers of a currently unknown living site's vicinity). Living sites were not just anywhere around these lakes, they were oriented around neighborhoods permeable to storage.

6. Discussion and Conclusions

6.1 Case Study Considerations

Cache pits were a strategic response to the changing socioeconomic world of Late Precontact across the northern Great Lakes. As Late Precontact communities moved around Douglas and Burt Lake, they were observing, recognizing, and learning the intricate details of the landscape matrix as related to storage. In the above analyses, I showed they used such landscape matrix knowledge to construct their cache pit clusters in locales more suitable for food storage and they oriented themselves to capitalize on storage permeability. As Crow's Heart passionately declared he was right about the features of his countryside because he had "seen these places", so too people moving through Douglas and Burt Lake had seen the places where food storage worked and where it failed. To not "see these places" was quite literally, a matter of life and death. During Late Precontact, people knew where pits had to be built to feed their families and to sustain their broader community and they spatially-embedded this knowledge purposefully across the landscape.

In future work, model improvements could be made, including incorporating additional landscape variables and conducting more detailed sensitivity analyses of the resistance grid. That said, the model as presented still succeeds in furthering our understanding of food storage and social geographies during Late Precontact. In future work, it would also be productive to expand to other inland lakes. Such an expansion could be used as a predictive model for cache pits that could inform a targeted survey of non-developed land with high storage permeability scores.

6.2 Broader Reflections

My larger aim in presenting this research is to highlight the applicability of permeability modeling for archaeology. In every case of past movement, people were brought into encounter with a landscape matrix composed of some set of variables that both impacted and created potentialities for the flow of cultural processes across a landscape. The procedures I have presented here are not specific to my case study or to only the cultural process of food storage, but are readily adaptable to other cases. In any given case of interest, researchers can identify the pertinent mix of landscape matrix variables that would impact the flow of cultural processes of importance to their case. Just as I used permeability modeling (specifically by using resistant-kernel analysis) to produce a continuous surface that represents a 'storage-suitability scape', other researchers could create permeability surfaces that represent, say, a 'defensive-suitability scape' or a 'sacred-suitability scape'.

Again, the strength of permeability modeling is that it provides a way of not just looking at processes in relation to discrete points, but of representing the flow of processes across a whole landscape. As archaeologists continue to be interested in understanding how people encountered and engaged with past landscapes, layering them with social knowledge and geographies, developing and refining geospatial techniques that provide just such the representation permeability modeling does will be ever important.

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References

- Albert, D. A. and L. Minc, 1987. *The Natural Ecology and Cultural History of the Colonial Point Red Oak Stands*. A Report to the University of Michigan Biological Station (on file at UMBS).
- Anderson, M., Clark, M., and A. O. Sheldon, 2014. Estimating Climate Resilience for Conservation across Geophysical Settings. *Conservation Biology* 28: 959-970.
- Aporta, C., 2009. The Trail as Home: Inuit and their Pan-Arctic Network of routes. *Human Ecology* 37: 131-146.
- Basso, K. H., 1996. *Wisdom Sits in Places: Landscape and Language Among the Western Apache*. University of New Mexico Press, Albuquerque.
- Beckwith, M., 1938. *Mandan-Hidatsa Myths and Ceremonies*. Memoirs of the American Folk-Lore Society, Volume 32, New York.
- (http://www.minotstateu.edu/library/pdf/ecoll_mandanindians.pdf)
- Belisle, M. 2005. Measuring Landscape Connectivity: The Challenge of Behavioral Landscape Ecology. *Ecology* 86: 1988-1995.
- Bell, T. and Lock, G.R., 2000. Topographic and Cultural Influences on Walking the Ridgeway in Later Prehistoric Times. In: Lock, G.R. (ed.), *Beyond the Map: Archaeology and Spatial Technologies*. IOS Press, Amsterdam, pp. 85-100.
- Beven, K.J., and M.J. Kirkby, 1979. A Physically Based, Variable Contributing Area Model of Basin Hydrology. *Hydrological Sciences Bulletin* 24: 43-69.
- Blackbird, A. J., 1887. *History of the Ottawa and Chippewa Indians of Michigan*. The Ypsilantian job printing house, Ypsilanti, Mich.
- Carballo, D. M., and Pluckhahn, T., 2007. Transportation Corridors and Political Evolution in Highland Mesoamerica: Settlement Analyses incorporating GIS for Northern Tlaxcala, Mexico. *Journal of Anthropological Archaeology* 26: 607-629.
- Cleland, C. E. 1982. The Inland Shore Fishery of the Northern Great Lakes: Its Development and Importance in Prehistory. *American Antiquity* 47(4):761-784.
1992. *Rites of Conquest: The History and Culture of Michigan's Native Americans*. University of Michigan Press, Ann Arbor.
- Compton, B.W., McGarigal, K., Cushman, S.A., and L.R. Gamble, 2007. A Resistant-Kernel Model of Connectivity of Amphibians that Breed in Vernal Pools. *Conservation Biology* 21: 788 -799.

- Darling, J.A., 2009. O'odham Trails and the Archaeology of Space. In: J. Snead, C. Erickson, and J.A. Darling (eds.), *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective*. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, pp. 61-83.
- Densmore, F., 1929. *Chippewa Customs*. Smithsonian Institution Bureau of American Ethnology Bulletin 86. U.S. Govt., Washington, DC.
- Dunham, S. B.
2000. Cache Pits: Ethnohistory, Archaeology, and the Continuity of Tradition. In: M. Nassaney and E. S. Johnson (eds.), *Interpretations of Native North American Life: Material Contributions to Ethnohistory*. University of Florida Press, Gainesville, pp. 225-260.
2009. Nuts about Acorns: A Pilot Study on Acorn Use in Woodland Period Subsistence in the Eastern Upper Peninsula of Michigan. *Wisconsin Archeologist* 90:113-130.
- Dustin, F., 1966. Prehistoric storage pits in Saginaw County, Michigan. *Michigan Archaeologist* 14(1,2):48-52.
- Frederick, K., 2015. The Beginners Guide to Food Caching. Paper Presented at the Society for American Archaeology Annual Conference, San Fransisco.
- Fowler, C., 2009. Reconstructing Southern Paiute-Chemehuevi Trails in the Mojave Desert of Southern Nevada and California: Ethnographic Perspectives from the 1930s. In: J. Snead, C. Erickson, and J.A. Darling (eds.), *Landscapes of Movement: Trails, Paths, and Roads in Anthropological Perspective*. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, pp. 84-105.
- Funk, C., 2011. Yup'ik Eskimo Gendered Information Storage Patterns. In: R. Whallon, W. A. Lovis and R. K. Hitchcock (eds.), *Information and Its Role in Hunter-Gatherer Bands*. Ideas, Debates, and Perspectives 5. Cotsen Institute of Archaeology Press, University of California Los Angeles, Los Angeles, pp. 29-58.
- Hambacher, M.J. and M. B. Holman (with contributions from K. C. Egan and B. A. Smith), 1995. Camp, Cache and Carry: The Porter Creek South Site (20MN100) and Cache Pits at 20MN31 in the Manistee National Forest. *Michigan Archaeologist* 41:47-94.
- Hart, J. P. and W. A. Lovis, 2013. Reevaluating What We Know About the Histories of Maize in Northeastern North America: A Review of Current Evidence. *Journal of Archaeological Research* 21(2):175-216.
- Holman, M. B.,
1978. *The Settlement System of the Mackinac Phase*. Unpublished PhD Dissertation, Michigan State University, East Lansing.

1984. The Identification of Late Woodland Maple Sugaring Sites in the Upper Great Lakes. *Midcontinental Journal of Archaeology* 9:63-89.
- Holman, M. B. and F. J. Krist, 2001. Late Woodland Storage and Mobility in Western Lower Michigan. *Wisconsin Archaeologist: Papers in Honor of Carol I Mason* 2:7-32.
- Holman, M. B. and W.A. Lovis , 2008. The Social and Environmental Constraints on Mobility in the Late Prehistoric Upper Great Lakes Region. In: H. Barnard and W. Wendrich (eds.), *The Archaeology of Mobility: Old and New World Nomadism*. Cotsen Advanced Seminars 4. Cotsen Institute of Archaeology, University of California, Los Angeles, pp. 280-306.
- Howey, M. C.L. and K. Parker, 2008. Camp, Cache, Stay Awhile: Preliminary Considerations of the Social and Economic Processes of Cache Pits along Douglas Lake, MI. *Michigan Archaeologist* 54: 19-43
- Howey, M.C.L., 2011. Multiple Pathways across Past Landscapes: Circuit Theory as a Complementary Geospatial Method to Least Cost Path for Modeling Past Movement. *Journal of Archaeological Science* 38: 2523 – 2535.
- Katzenberg, M. A., H. Schwarcz, M. Knyf, and F. J. Melbye, 1995. Stable Isotope Evidence for Maize Horticulture and Paleodiet in Southern Ontario, Canada. *American Antiquity* 60(2):335-350.
- Killion, T.W., 2013. Nonagricultural Cultivation and Social Complexity: The Olmec, Their Ancestors, and Mexico's Southern Gulf Coast Lowlands. *Current Anthropology* 54:569-606.
- Kinietz, W. V., 1947. *Chippewa Village: The Story of Katikitegon*. Cranbrook Institute of Science, Bloomfield Hills, MI.
- Leidwanger, J., 2013. Modeling Distance with Time in Ancient Mediterranean Seafaring: A GIS Application for the Interpretation of Maritime Connectivity. *Journal of Archaeological Science* 40: 3302-3308.
- Llobera, M., 2000. Understanding Movement: A Pilot Model Towards the Sociology of Movement. In: Lock, G. (ed.), *Beyond the Map: Archaeology and Spatial Technologies*. IOS Press, Amsterdam, pp. 65-84.
2012. Life on a Pixel: Challenges in the Development of Digital Methods Within an "Interpretive" Landscape Archaeology Framework. *Journal of Archaeological Method and Theory* 19: 495-509.
- Llobera, M., P. Fábrega-Álvarez, and C. Parcero-Oubiña., 2011. Order in Movement: A GIS Approach to Accessibility. *Journal of Archaeological Science* 38:843–51
- Lovis, W. A.,

1976. Quarter Sections and Forests: An Example of Probability Sampling in the Northeastern Woodlands. *American Antiquity* 41(3):364-372.
- 1978a. A Case Study of Construction Impacts on Archaeological Sites in Michigan's Inland Waterway. *Journal of Field archaeology* 5:357-360.
- 1978b . A Numerical Taxonomic Analysis of Changing Woodland Site Location Strategies on an Interior Lake Chain. *The Michigan Academician* 11(1):39-48.
- Lovis, W. A. and R. E. Donahue, 2011. Space, Information and Knowledge: Ethnocartography and North American Boreal Forest Hunter-Gatherers. In: R. Whallon, W. A. Lovis and R. K. Hitchcock (eds.), *Information and Its Role in Hunter-Gatherer Bands*. Ideas, Debates, and Perspectives 5. Cotsen Institute of Archaeology Press, University of California Los Angeles, Los Angeles, pp. 59-88.
- Luo, W., Harmann, J.F., and F. Wang, 2010. Terrain Characteristics and Tai Toponyms: A GIS Analysis of Muang, Chiang, and Viang. *GeoJournal* 75: 93-104.
- Minc, L., 1986. Scarcity and Survival: The Role of Oral Tradition in Mediating Subsistence Crisis. *Journal of Anthropological Archaeology* 5: 39-113.
- Moore, I.D., Grayson, R.B., and A.R. Ladson, 1991. Digital Terrain Modeling: A Review of Hydrological, Geomorphological, and Biological Applications. *Hydrological Processes* 5: 3-30.
- Morgan, C., 2012. Modeling Modes of Hunter-Gatherer Food Storage. *American Antiquity* 77:714-736.
- Norder, J. W., 2003. *Marking Place and Creating Space in Northern Algonquian Landscapes: The Rock-art of the Lake of the Woods Region, Ontario*. Unpublished Ph.D. dissertation, University of Michigan, Ann Arbor, MI.
- O'Gorman, J. A., 2007. The Myth of Moccasin Bluff: Rethinking the Potawatomi Pattern *Ethnohistory* 54:373- 406.
- O'Gorman, J.A. and W.A. Lovis, 2006. Before Removal: An Archaeological Perspective on the Southern Lake Michigan Basin. *Midcontinental Journal of Archaeology* (special issue: *The Potawatomi Removal*, edited by Mark Schurr) 31: 21 - 56.
- O'Shea, J. M., 2003. Inland Foragers and the Adoption of Maize Agriculture in the Upper Great Lakes of North America. *Before Farming: The Archaeology of Old-World Hunter-Gatherers* 2(3):1-21.
- O'Shea, J. M. and C. M. Milner, 2002. Material Indicators of Territory, Identity, and Interaction in a Prehistoric Tribal System. In: W.A. Parkinson (ed.), *The Archaeology of Tribal Societies*. International Monographs in Prehistory, Ann Arbor, pp. 200-226.

- Palace, M., Keller, M., Asner, G., Hagen, S. and B. Braswell. Amazon Forest Structure from IKONOS Satellite Data and Automated Characterization of Forest Canopy Properties. *Biotropica* 40(3): 141-150.
- Richards-Rissetto, H. and K. Landau, 2014. Movement as a Means of Social (Re)production: Using GIS to Measure Social Integration Across Urban Landscapes. *Journal of Archaeological Science* 41: 365-375.
- Schneider, R., 1942. Report of Cleaning out a Cache Pit. *Totem pole* 10(1):5.
- Schumacher, J. P., 1918. Indian Remains in Door County. *Wisconsin Archeologist* 16(4).
- Tanner, J. 1940[1830]. *An Indian Captivity (1789-1822)* (edited by E. James). Occasional Papers, Reprint Series No. 20. California State Library, San Francisco.
- Theobald, D. M., Reed, S.E., Fields, K., and M. Soule, 2012. Connecting Natural Landscapes using a Landscape Permeability Model to Prioritize Conservation Activities in the United States. *Conservation Letters* 5: 123-133.
- Van Buskirk, J., 2012. Permeability of the Landscape Matrix between Amphibian Breeding Sites. *Ecology and Evolution* 2: 3160-3167.
- Wernke, S., 2012. Spatial Network Analysis of a Terminal Prehispanic and Early Colonial Settlement in Highland Peru. *Journal of Archaeological Science* 39: 1111-1122.
- Whallon, R., 2011. An Introduction to Information and its Role in Hunter-Gatherer Bands. In: R. Whallon, W. A. Lovis and R. K. Hitchcock (eds.), *Information and Its Role in Hunter-Gatherer Bands. Ideas, Debates, and Perspectives* 5. Cotsen Institute of Archaeology Press, University of California Los Angeles, Los Angeles, pp. 1-28.
- Whelan, C. S., A. R. Whitaker, J.S. Rosenthal and E. Woohlgemuth, 2013. Hunter-Gatherer Storage, Settlement, and the Opportunity Costs of Woman's Foraging. *American Antiquity* 78: 662-678.
- White, D. A., and S.B. Barber, 2012. Geospatial Modeling of Pedestrian Transportation Networks: A Case Study from Precolumbian Oaxaca, Mexico. *Journal of Archaeological Science* 39: 2684 – 2696.
- Wiessner, P., 1982. Risk, Reciprocity and Social influences on !Kung San Economics. In: E. Leacock and R. B. Lee (eds.), *Politics and History in Band Societies*. Cambridge, Cambridge University Press, pp. 61-84.
- Yarnell, R. A., 1964. *Aboriginal Relationships between Culture and Plant Life in the Upper Great Lakes Region*. University of Michigan Museum of Anthropology, Anthropological Papers no. 23, Ann Arbor.

654 Zedeno, M., Hollenback, K. and C. Grinnell. 2009. From Path to Myth: Journeys and the
655 Naturalization of Territorial Identity along the Missouri River. In: J. Snead, C. Erickson, and J.A.
656 Darling (eds.), *Landscapes of Movement: Trails, Paths, and Roads in Anthropological*
657 *Perspective*. University of Pennsylvania Museum of Archaeology and Anthropology,
658 Philadelphia, pp. 106-132
659
660 Zeller, K.A., McGarigal, K., and A.R. Whiteley. 2012. Estimating Landscape Resistance to
661 Movement: A Review. *Landscape Ecology* 27: 777-797.

Figure Captions

Figure 1. Northern Michigan, showing Douglas and Burt Lake

Figure 2. Documented Cache Pit Clusters around Burt and Douglas Lake (cluster overlap due to map scale)

Figure 3. Survey Area, Cache Pit Clusters, and Generated Random Points

Figure 4. Calculated Distance to Inland Lake (done to 3km from lake to avoid edge effect, analyses clipped to survey area)

Figure 5. Calculated Compound Topographic Index (for whole DEM, analyses clipped to survey area)

Figure 6. Storage Permeability Grid (output of resistant-kernel analysis; areas below the overall grid mean are shown in black and then the rest of the grid is coded in hierarchical increasing permeability by quantiles above mean)

Figure 7. Living Sites and Increasing 1-km Buffers (buffers dissolved for each site)

Figure 8. Distance from Living Site by Mean Permeability Value (for the buffer of that distance)

Figure 9. Number of Known Cache Pit Clusters Incorporated at Each Increased Distance Buffer from Living Sites

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9