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Demolishing Distance: Technology, Mobility, and Legibility in Early 20th Century Puerto Rico

By

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Introduction

> *The building and operating of railroads in the island of Porto Rico would be one of the most important factors in developing its resources. . . It would enable the producer to get his crop to market at reduced cost, would enhance the values of property, build up towns and cities, elevate the people, [and] advance their civilization. . .*
>
> — Report of the United States Insular Commission to the Secretary of War, 1899

How does the development and deployment of mobility-enhancing technology impact the development of the state? Based on the broad historical trajectory of industrialization, popular theories of technological-political interaction suggest a positive linear relationship between expanding technological capabilities and expanding state capacity. Key to these theories is the (often implicit) notion that technologies can be classified on a spectrum according to their tendency to enhance or frustrate political centralization. The secular trend of linked expanding state and technological power is therefore read as a causal trajectory driven by the inevitable path of scientific discovery - or perhaps by a positive feedback cycle between centralizing states and centralizing technologies. However, many technologies are relational in their effect; outcomes at the system level depend on *where* a new technology is inserted into the existing structure. Indeed, policy discussions about the "dual" (military-civilian) potential of particular technologies have long indicated the flexible *positional* nature of technological-political interactions. In this thesis, I employ a range of computational methods to demonstrate the advantage of a more structuralist approach by testing its explanatory power against the traditional state-centric approach.

The case example used is the expansion of the highway and railroad network in Puerto Rico at the beginning of the 20th century. During this time, the United States had just taken over colonial possession of the island from Spain. Compared to the old Spanish colonial administrator, the new American rulers were in a much different structural position relative to the local elite and wider population of Puerto Rico, and they faced strong incentives to shift away from the old dynamic. The American administration explicitly developed and deployed technology to drive change in its favor.

In only twenty years of rule, the American administration built or financed more than four times as many kilometers of highway and railroad as the Spanish government had in over 400 years.[1] It funneled generous appropriations from the US Congress, the vast majority of its own tax revenue, and a sizable amount of debt into the construction of state-of-the art infrastructure including highways, railroads, sewage and water systems, electrical systems, telegraph lines, schools, and hospitals.[2] Those twenty-odd years from 1898 to 1920 will constitute the period under study in this analysis.

This boom in infrastructure development should rightfully be understood as the direct application of technology by the state for economic purposes. The statements of the administrators demonstrate that their goal in developing this infrastructure was to thereby expand the island's production of cash-crops for market (sugarcane in particular). The "civilizing" colonial narrative was, in this instance, primarily tied to turning subsistence production and "wilderness" into surplus production that was legible to the market. Technological investment in the form of infrastructure construction was the primary mechanism for achieving this switch.

This situation broadly conforms to James Scott's theory of technological-political interaction - which inspired this research.[3] However, Scott's more linear, state-centric approach must be expanded in order to account for complex interactions between the state, market, local elites, and population at large. In Scott's theory, the state is positioned vis-a-vis the population at large. The population is "legible" to the state to the degree that its productive activities are known to it and can be appropriated by it. This legibility is limited by a number of primarily material factors, nearly all of which are mitigated over time by the development of technology.

[1] Based on personal calculations of road and rail infrastructure in QGis software. Approximately 500 kilometers of infrastructure existed in 1898 (the year of US takeover), while approximately 2600 Kilometers existed in 1920, making the ratio of US-built to Spanish built infrastructure: $(2600-500)/500 = 4.2$

[2] The main primary sources used throughout this thesis are: Customs and Affairs, "Report of the United States Insular Commission to the Secretary of War Upon Investigations Made into the Civil Affairs of the Island of Porto Rico", Interior Office of the Commissioner, "Report of the Commissioner of the Interior for Porto Rico", and Porto Rico, "Annual Report of the Governor of Porto Rico". The first source is a special report made following the US takeover. Starting in 1901, the Governor of the island wrote an annual report to congress, and included appendices which contained reports by each of the Governor's secretaries. In 1900, the Secretary of Interior's report was sent separately, hence why it is cited separately. These reports provide direct insight into the goals and mentality of the American administrators. Generally, I will cite the Annual Governor's reports collectively, except when a specific claim that appears in only one of the reports is cited.

[3] Scott, *The Art of Not Being Governed*: Scott, *Seeing Like a State*.

Using the Puerto Rican case as an example, I show how legibility is better understood in relational terms. Different factions and sub-units of the state challenge or compete with its legibility of the populace. Applications of technology which purportedly should boost the state's legibility of the populace instead limit it by empowering these local or factional rivals even more. Reframing the problem in these structuralist terms, I draw on primary sources and an array of computational methods to empirically analyze the relational consequences of the transportation network constructed by the early American administration of Puerto Rico.

I show that, contrary to the predictions of Scott's theory, the highway and railroad development actions of the state were focused on funneling legible forms of production to the market and curbing the political power of the local elite, *even to the relative detriment of the legibility of the overall population to the state*.

These results are not merely a restatement of historical narratives about the capture of colonial state machinery by powerful foreign corporate interests. I show that infrastructure development in potentially lucrative non-sugar regions is comparatively neglected, that investment in sugar regions is not limited to areas of US-firm ownership, and that the structure of network construction in sugar regions is highly legible, even though this comes at the expense of legibility elsewhere. All of these points suggest a state that is navigating the ascent of a broad new agricultural elite over an old one, rather than a total economic takeover.

More importantly and more abstractly, these results demonstrate that the trajectory of political-technological interaction is not a foregone conclusion, but is actively shaped by deliberate choices regarding how to deploy technology given a complex structural context.

Background

> *The power of the state to deploy distance-demolishing technologies—railroads, all-weather roads, telephone, telegraph, airpower, helicopters, and now information technology—so changed the strategic balance of power between self-governing peoples and nation-states, so diminished the friction of terrain, that my analysis largely ceases to be useful.*

— James Scott, *The Art of Not Being Governed*

As stated in the introduction, the starting point for this exploration is one of the most well known models of technological-political interaction: James Scott's legibility theory. Scott argues that the cost of acquiring knowledge about a population and the cost of converting a population's economic output into usable resources are the two major factors limiting the growth and development of the state. He labels these "legibility" and "appropriability", respectively, though I will hereafter refer to them collectively as "legibility".[4]

This model of political evolution is binary. The state is positioned as a distinct entity composed of the class, bureaucratic, and military organs that constitute it, and the wider population is classified according to the degree to which it is controlled by the state. States are "centripetal population machines"[5] whose main aim is pull in an ever wider pool of subjects, primarily for the purpose of expanding power and tax revenue. The population at large is motivated by the basic set of human needs and desires; it has some mix of preferences for security, wealth, and freedom. It accepts or rejects subjectivity to the state according to the balance of these preferences the state can fulfill or destroy.

Legibility is influenced primarily by two core material factors: the friction of terrain, and the form of production. Terrain that is easier to traverse is more legible; the cost of marching armies and bureaucrats decreases alongside the overall cost of movement. Likewise, forms of production that produce value which can more easily be confiscated and transported are more legible. Scott, who is focused on the pre-modern period, primarily frames this in terms of which crop is under cultivation, with some crops being much more legible than others. However, the concept can easily be extended to industrial production and the trade of services.

Both of these factors are relative to the state's own capacities. Just as some populations might be less legible than others, a weak state will be able to render less of the same populace legible than a strong state in the same situation. This is where the role of technology emerges. Populations that desire to evade the state can choose to proactively adopt less legible methods

[4]Scott, *The Art of Not Being Governed*.
[5]Scott pg. 64.

of production, or to live in terrain or conditions where its mobility is high relative to that of the state's agents. The state, for its part, can employ a number of organizational and technological methods to neutralize the evasive capacities of the populace.

Legibility and Technology

The above background provides context for the pessimistic disclaimer quoted at the beginning of this section. As technology improves, so too does the state's ability to neutralize the evasion strategies of the populace. With the advent of modern industrial technology, the balance of legibility has shifted so decisively in the state's favor that the pre-modern dynamic breaks down entirely, and the whole population is rendered legible.

However, as Scott implicitly acknowledges, legibility is *relative*. An event which resulted in an absolute increase in the mobility of the state's armies would not increase legibility if the same event increased the mobility of the population even more. This implies that the development of state-evasion technologies is perfectly possible. In fact, the existence of such technologies has already been analyzed by some observers.[6] It also implies that legibility can be, to some extent, strategically modulated based on the potential advantages of doing so.[7]

In the broader field of technology studies, there is a widely investigated class of technology labeled as "dual-use". This refers to techniques or artefacts that have both civilian and military applications.[8] This same concept applies to Scott's model. Many technologies have both state-aiding and state-evading applications. If roads are built out from the capital, they aid the state, but if they are built within or between regions beyond the capital, they may aid the evasion and resistance efforts of those outside of the state.[9]

[6] Dourado, "Metapolitical Explorations."

[7] For example, landholders - ordinarily averse to the eyes of the state and the associated taxation - might strategically opt to make themselves legible when they desire the state's protection of their property claims. See: Sanchez-Talanquer, "One-Eyed State."

[8] The classic examples of a dual use technology is the process used to produce chemical fertilizers, which can also be used to create explosives. Nuclear, aerospace, biological, and computational technologies are also commonly cited.

[9] See: Boone, "Territorial Politics and the Reach of the State": Giraudy and Luna, "Unpacking the State's Uneven Territorial Reach": Carl Muller and Cederman, "Roads to Rule, Roads to Rebel."

This challenge becomes even more troublesome when one considers the argument that *nearly all technology is dual use*, given the right context. So long as the state is at least partially embedded in society, generic increases to human ability - when selectively distributed to agents who support the state - will increase the state's capacity to render the population legible. Likewise, identical abilities distributed selectively to opponents of the state will reduce its capacity.

I do not mean to imply that all technology is fully flexible in this regard. When it comes to state centralization versus evasion potential, all technologies clearly fall somewhere on a spectrum. By their nature, some technologies favor development and use by large-scale state-like institutions. In fact, one explanation of why the past 200 years of technological development seems so intimately linked with the parallel increase in state power and scale is that certain industrial technologies - highways and railroads included - kicked off an increasing returns to scale positive feedback loop. Large states were better able to deploy these technologies in a way that advantaged them and made them grow bigger, and upon growing bigger they were able to develop and leverage even larger scale technologies, and so on.[10] Along a similar line of logic, opponents of large states and market forces have argued that intermediate or small scale technology is the key to transitioning to more locally autonomous and ecologically sustainable forms of political organization.[11] These arguments are all in line with Scott's statements about the direction of technological-political interaction in the modern era.

I do not dispute any of these claims. I merely suggest that their character is too deterministic. The "essential properties" of a given piece of technology are too often emphasized over the context of its use.[12] This entire thesis is an exercise in bringing the use-context of technology back into the discussion of technology and legibility.

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[10] Cowen, "Does Technology Drive the Growth of Government?"

[11] Schumacher, *Small Is Beautiful*.

[12] In this regard, I am in agreement with the general approach suggested in Mayntz and Hughes, *The Development of Large Technical Systems*.

Technolgical Use-Context

A structure-sensitive analysis of technological-political interaction requires breaking from a binary 'state vs non-state' framing in favor of a more multi-function and multi-scale view. A multi-function view acknowledges the various goals, interests, and action arenas of the state. A state's economic, fiscal, ideological, and military goals need not be aligned, nor need they be perfectly in-sync with the various organs it uses to accomplish them. A multi-scale view acknowledges the diverse entities that compose the state at various levels of aggregation. Governments may have central political and bureaucratic bodies, but regional and local components also exist. The same can be said for society in general. A theory of technological political interaction needs to account not only for the various capacities of these components to develop technological capacities and the effect of doing so, but also these capacities and effects *given their current structural position* within the larger system.

Nothing I suggest here is new. Scholarship of Latin American politics in particular frequently uncovers the role of infrastructural development in the dynamics of center-local-populace politics. In some cases, local elites cooperate with the populace in the provision of public goods to weaken central control.[13] In other cases, the central government uses infrastructure to weaken the influence of local elites, much to the gratitude of the populace.[14] In many cases, the results of a given technology-infrastructure policy are unpredictable, resulting in cycling, or compromise.[15] Structural accounts of contextual technology use are integral to historical accounts of rapid technological-political shifts ranging from the Meiji Restoration[16] to American Industrialization.[17]

The only innovation here is an attempt to apply this approach to the question of technology-legibility interaction in particular, and to do so in a way that yields empirically testable predictions. I draw on a long line of research into positional influence from the field of sociology and

[13]Cabal, "Elite Conflict and Developmental Public Goods in Revolutionary Mexico."
[14]Giraudy and Luna, "Unpacking the State's Uneven Territorial Reach."
[15]Saylor, *State Building in Boom Times*.
[16]Beasley, *The Meiji Restoration*.
[17]Bensel, *Yankee Leviathan*.

network analysis to predict the pattern of Puerto Rican transportation infrastructure development based on the stated goals of the colonial administration and its structural starting position vis-a-vis the market, local elites, and the general population. I then test these predictions against the actual pattern of development. Using a variety of primary sources, I reconstruct the pattern of development and the properties of the lands it connected in the form of a transportation network for 1900, 1910, and 1920. I measure various structural properties of these networks, and compare them to the properties of random networks constructed under similar constrains to determine significance. If the predictions derived from my structural approach are more accurate predictors of significant properties of actual highway and railroad development than the more binary approaches laid out above, it will demonstrate the advantage of considering use-context in future discussions of technological-political interaction. It will nudge us to think of technology not just as *what*, but also as *when*, and *where*.

The Case of Puerto Rico

What infrastructure development predictions would a structural approach make in the case of Early 20th Century Puerto Rico?

At the turn of the 20th century, the Spanish government ceded possession of the Puerto Rican territories to the US government, following the Spanish-American war. This takeover represented a clear shift in the interests of the central government vis-a-vis the local elites and general population. During the Spanish period, cash-crop production was concentrated around medium scale coffee cultivation. This cultivation was done largely on *haciendas*, which were owned by the local elite *hacendados* who utilized various forms of servile labor.[18]

Neither the central nor local governments stood to benefit from extensive transport investment. Significantly expanding agricultural output would require mechanization and reward scale, neither of which was in the interests of the majority of independent *hacendados*, nor particularly applicable to the coffee crops they were largely associated with.[19] The Spanish

[18] Wagenheim, *Puerto Rico*.
[19] Ayala and Bergad, *Agrarian Puerto Rico*.

government saw the island primarily as a strategic military outpost used to protect its hold on much more economically valuable Caribbean holdings such as Cuba.[20] For much of Spanish rule, the island's finances were subsidized by grants from Mexico, rather than taxes on cash-crop economic output.[21] The primary road built during all of Spanish rule, the so-called 'military road' from San Juan to Ponce (the administrative capital and second-largest city, respectively) reflects these priorities.

This system was clearly tilted in favor of the local elites. With an aloof central government primarily preoccupied by military affairs, they constructed a patronage system where taxes were used to support the salaries of officeholders.[22] Likewise, public land was often distributed to individual elites as a political favor. The taxes used to support this rent-seeking behavior were easily avoided by wealthy members of the elite, and fell disproportionately on subsistence farmers. This tax-avoidance was achieved through outright bribery of the central tax collectors, but was also a feature of the tax system itself. Property taxes were assessed on the bases of profit, not land value. Consequently, wealthy property owners could exploit multiple loopholes to make their production appear unprofitable, while smaller scale farmers selling their surplus on the market lacked such means of tax avoidance.[23] This method of taxation also discouraged the production and export of cash-crops at high volume - another reason there was little incentive to develop transportation infrastructure.

The new American government then inserted itself into this context. Contrary to the Spanish government, this new colonial administrator was much closer, and much more keen to actively manage the Island's affairs. It's own political and economic actors - the US Congress, incoming bureaucrats, and the US sugar corporations - had decisively different motives from the outgoing Spanish government and Puerto Rican local elite. The nearby continental United States had a massive internal market with an insatiable appetite for sugar and other tropi-

[20] Wagenheim, *Puerto Rico*.
[21] Wagenheim.
[22] Quintero-Rivera, "The Cambridge History of Latin America": Customs and Affairs, "Report of the United States Insular Commission to the Secretary of War Upon Investigations Made into the Civil Affairs of the Island of Porto Rico."
[23] Porto Rico, "Annual Report of the Governor of Porto Rico."

cal agricultural products.[24] Free trade with the United States was established quickly after its takeover of Puerto Rico, which made the export of these products extremely profitable.

Furthermore, unlike the Spanish government, the American administrators had no social or political ties to the existing Puerto Rican elite, and thus no self-interested reason to care about their interests. Indeed, the local elite were if anything an obstacle to the American administrations goals. Their political opposition and control of the labor supply added friction to the processes of transferring workers into sugar production. Naturally, many of the elite cooperated with the American government, and many new members of the elite were minted as a result of profits from the sugar industry.[25] Nonetheless, those who still held onto rent-seeking or coffee producing activities would be in opposition to this new power, and would try their hardest to politically mobilize the same common laborer whom they had previously exploited.[26]

Predictions

With the knowledge that the American government and it's local allies did indeed triumph by the end of the period,[27] a structural analysis can make certain predictions about how the highway and railroad networks would have developed to help achieve this goal. The American administration was not primarily concerned with the collection of tax revenue, so it would not be predicted to have prioritized connections to San Juan compared to the null assumption. It likewise should not have prioritized general connectivity throughout the network, as mobility to sugar regions would have been more important than general mobility. It absolutely would have prioritized connections from sugar regions to ports, even to the detriment of other goals.

Assuming local elites were primarily concentrated in cities (county capitals), the general labor force lived in the rural areas, and the sugar-producing elite were cooperative with the central administration while the coffee-producing elite were in opposition, it is also possible to make

[24] Indeed, it has been argued that this was a significant motive for its military expansion not just in the Caribbean, but also into Hawaii and the Philippines in the early 20th century. See: Quintero-Rivera, "The Cambridge History of Latin America."

[25] Ayala and Bergad, *Agrarian Puerto Rico*.

[26] Ayala and Bergad.

[27] The historical sources cited here are all in agreement on this point

several predictions about intra- and inter- regional dynamics. In network analysis, “assortativity” refers to how likely similar areas are to be connected. In an assortative network, areas tend to be more connected to similar areas, while in a disassortative network, areas tend to be more connected to dissimilar areas. If the basis of similarity between areas is their designation as major cities (county capitals), a disassortative network would maximize the control of the local elite over the surrounding population while limiting the escape mobility of said population.[28] A more assortative network would benefit the central government and general population vis-a-vis the political elites.[29]

The American government should therefore be expected to have built a more assortative network overall. Assortativity among sugar areas would be particularly crucial, as any failure to control local elite would jeopardize it’s primary stated goals. In coffee regions and general non-sugar regions, it is unclear whether this metric would have been quite as crucial. Increasing assortativity would represent a policy of actively weakening local control and strengthening central control, but consolidating influence over the sugar regions might have been sufficient, so long as local power in non-sugar regions didn’t grow as a result.

A similar metric is modularity, which describes the degree to which a network is split into modules - cliquish regions that are more heavily connected to one another than they are to regions outside the clique. Modularity should tend to decrease legibility from areas outside the module, but mutually increase it within the module. This partly depends on how accessible modules are to one another. Disassortative modules connected by their centers created a nested hierarchical structure where local powers are highly legible to the center, but they control access to the populace. Assortative modules maximize central legibility of local powers but minimizes central legibility of the general populace. Reductions in modularity tend to increase average mobility over longer distances but particular connections determine which group will most benefit. As such, this metric cannot really be predicted, but must be interpreted in tandem

[28]Travel speed between the local elite in each county capital and the surrounding regions would be maximized, while travel speed between peripheral areas would be minimized.

[29]Travel speed between capitals would be maximized, allowing the central government to quickly traverse nodes of local power, while the general population would have relative escape mobility between rural zones, and would be less tightly integrated into nodes of local power.

with other variables after the fact to determine whether the results tended to benefit the central governments goals.

There are two ways this approach could end up being rejected by the evidence. First, If any major predictions are not only missed, but contradicted, the approach considered here could be considered false (not liable to generate convincing explanations). The neglect of the american government to develop port access and control over sugar regions would be one example. Another would be if local elite control significantly grew. Second, if the correct predictions do not offer any insight that could not have been gained with Scott's theory, or any other theory that does not consider technological use-context, the approach considered here could be considered redundant (not liable to generate unique explanations).

Methodology

> *The crying need of the island is above all things roads. The peculiar configuration of the insular surface and the frequent and continued rains which fall in all parts of the country render intercommunication impossible for weeks at a time except where military roads have been constructed.*
>
> — Annual Report of the Governor of Porto Rico, 1901

Puerto Rico is administratively subdivided into counties, which are further divided into barrios. These units broadly conform to natural geological boundaries, and have similar land areas and population. To construct a transport graph that could be subjected to network analysis, this continuous topographic space was abstracted into discrete vertices and links between said vertices. Each barrio was defined as a vertex, with its geographic position vis-a-vis the other vertices being represented by the population center or geographic centroid of the barrio. Edges between these vertices were weighted to represent the travel time (in minutes) between each vertex pair.

Rather than measuring travel paths between all barrios, the computational expense of network construction was significantly decreased by only measuring paths between neighboring barrios at second-degree rook contiguity.[30] Paths between county capitals were also measured at second degree rook contiguity. Hereafter, when I refer to “neighbors” or “neighboring barrios” I’m using the notion of adjacency defined by second-degree rook contiguity (including second degree rook contiguity between county capitals, where that applies).

With the location of barrio vertices and time cost of travel paths between these vertices calculated, a network object could be constructed. Although highway and railroad networks were created and identified separately, the primary sources suggest that the central government saw them as part of an integrated transport system, having different costs and strengths, but being built to achieve the same ends[31]. Furthermore, initial analysis of both networks examined separately revealed both to have largely similar effects on the overall structure of the island’s transport network structure. Complex interactions between these separate lines of transport was minimal, as the the impact of both technologies combined did not substantively differ from the sum of each technology separately. Consequently, they are treated as one system when measuring metrics.

Four networks are therefore tested: one with travel times based only on walking, and one with travel times based on all methods of transport for each of the years 1900, 1910, and 1920. To calculate important metrics, each vertex (barrio) was also assigned six attributes: whether the barrio contained a major port, whether the barrio contained a county capital, the barrio’s agricultural classification (sugarcane, coffee, or other), and the barrio’s population in 1899, 1910, and 1920.

Data Sources

Primary source data was derived from a combination of online and archival sources, and was used to determine barrio population, agricultural classification, port or county capital status,

[30] Rook contiguity means barrios that share a land border are considered neighbors, but diagonal counties who only have a touching corner are not considered neighbors. The name is derived from the move set of a rook in the game of chess. “Degree” in this context refers to number of extensions, with a barrio’s first degree neighbors only being those that immediately border it, second degree neighbors including its immediate neighbors and their immediate neighbors, and so on.

[31] Porto Rico, “Annual Report of the Governor of Porto Rico.”

transportation method cost functions, and the location of highway and railroad lines.

GIS data, including county boundaries, barrio boundaries, and DEM files (land elevation) where taken from the US Census Bureau. Barrio population figures were also taken from the Census bureau, but had to be transcribed manually from primary source census documents.[32] One of the most significant archival sources was the "Governors Report on Porto Rico", which is explained in a footnote on page 2. Maps from these reports,[33] alongside topographic maps from the the USGS[34] were used to determine the location and extent of transportation infrastructure in each of the three periods under review. These maps were also used to identify the location of ports, county capitals, and sugar centrals. The Governor's reports included information about traffic composition and flow, general commentary about transport priorities, and land-use statistics used to make barrio agricultural classifications. Barrios devoting more than 10% of their land to the production of sugar or coffee were classified as sugar or coffee lands, depending on the majority crop. Most cases were quite clear-cut. Classification of the small number of edge-cases was decided based on proximity to sugar centrals, and the class of neighboring barrios.

Two maps constructed based on these GIS data are shown below. The first depicts Puerto Rico's topography. Elevation and terrain ruggedness are an essential component of legibility, and were of course used to construct the networks, so a map identifying the location of the Island's mountains should be quite helpful to the reader. The second map depicts the the major infrastructural, political, and economic features of the Island. This map should contextualize all subsequent discussion of the transportation network. Highways were eventually build into (but rarely between) the mountainous coffee regions, but only after redundantly covering most of the regions that already had passenger rail service. Railroads were almost never built into these regions, despite the possibility of doing so in many cases.

[32]War Department, "Report on the Census of Porto Rico, 1899": Department of Commerce, "Thirteenth Census of the United States": Department of Commerce, "Fourteenth Census of the United States, Bulletin."

[33]Bureau of Public Works, "Map of Island of Porto-Rico Showing Roads, Rail Roads and Light Houses": Interior, "Road and Railroad Map of Porto-Rico," 1910: Interior, "Road and Railroad Map of Porto-Rico," 1920.

[34]Survey, "Historical Topographic Map Collection."

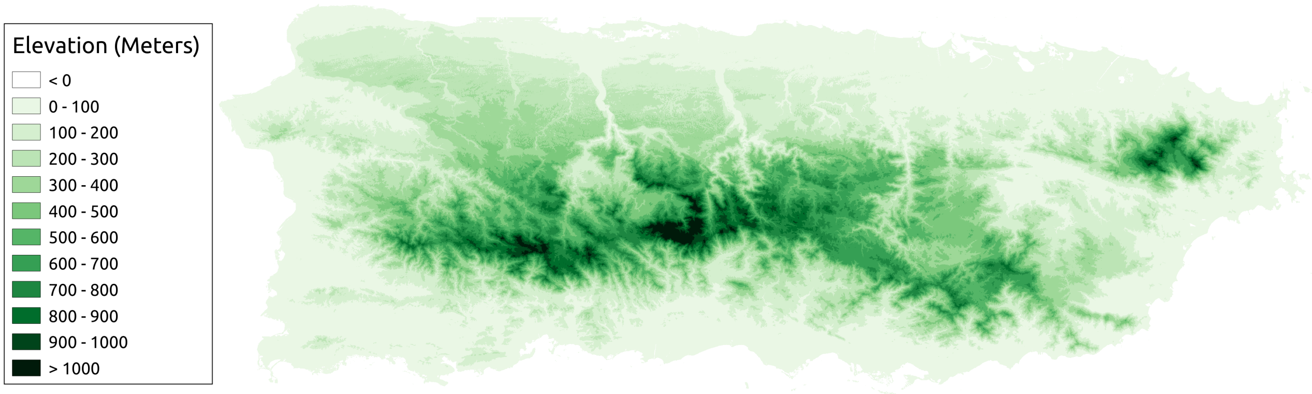

Figure 1: Elevation Map

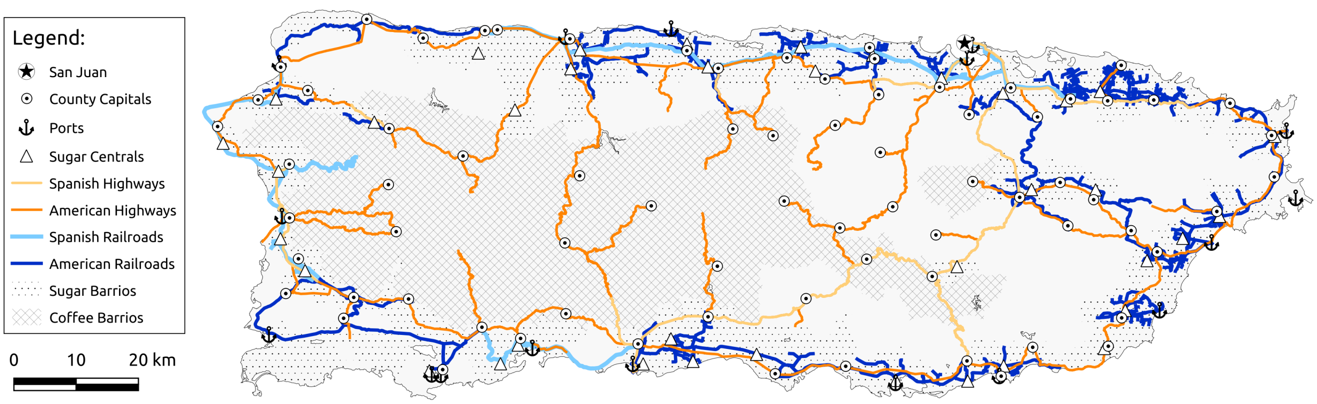

Figure 2: Infrastructure Map 1920

Network Construction in QGis

Edge weights between vertices (representing travel times between barrio population centers) were determined based on walk, railroad, and highway speeds as a function of ground slope multiplied by distance. This was determined for all neighboring barrio pairs on the walk network, and only between pairs containing transport infrastructure for the highway and railroad networks. The walk network was constructed by creating a line grid spaced at 0.002 Arc-Seconds.[35] Elevation data from the DEM files was then used to calculate the incline gradient along each line segment.

To determine travel time across each line segment, a formula which related incline gradient to average walking speed was needed. The most well known of these is Tobler's Hiking Function (THF), which is a Laplace distribution centered at a -5% gradient with a peak of 6 kilometers per hour. The speed over flat ground is 5 kilometers per hour. This adequately models the fact that human hikers walk faster on slightly downhill slopes than on flat or comparative uphill slopes. However, The flat ground speed of 5 kmph and top speed of 6 kmph are both commonly criticized as overestimations.[36] This flaw, combined with recent empirical data supporting the superior performance of a modified Laplace distribution for modelling average human walking performance[37] and primary source data suggesting the deleterious effects of weather and climate on walking speeds in Puerto Rico in particular[38] lead me to adopt a more conservative version of THF which places 4.5 kmph as the top speed and has a higher tolerance for steeper gradients.[39]

Using the resulting walk speed function combined with line length, the directional time cost (in minutes) to cross each line segment was calculated. Network analysis tools within the GRASS module of QGis were then used to calculate the shortest paths between the population

[35] About 212 meters at Puerto Rico's Latitude

[36] For example: Goodchild, "Beyond Tobler's Hiking Function."

[37] Michael Campbell, "Using Crowdsourced Fitness Tracker Data to Model the Relationship Between Slope and Travel Rates."

[38] Porto Rico, "Annual Report of the Governor of Porto Rico."

[39] The exact function used is: $velocity = 4.5e^{-2|gradient+0.05|}$ compared to THF: $velocity = 6e^{-3.5|gradient+0.05|}$

centroids of each neighboring pair of barrios.[40] These paths became the 'walk-only' network, which represents the connectivity of Puerto Rican barrios before any transportation infrastructure was put in place.[41]

Highway and railroad networks were first drawn as vector line layers in locations inferred from the maps cited above. These lines were snapped to the same grid used to calculate walking costs, in order to use the same slope measurements and segment lengths. They were connected to barrio population centroids with 1.5 kilometer buffers, meaning a barrio was considered connected to a segment of the highway or railroad if it's population centroid was within 1.5 kilometers of any part of the line. Shortest paths between neighboring barrios using the highway and railroad infrastructure was then calculated for all connected barrios. The costs used to calculate these paths were based on separate formula for highway and railroad speed as a function of slope.

For highways, this speed was based on horse locomotion. The function assumed a mix of walking and trotting gaits to maximize distance traveled by balancing speed with endurance costs. Speed for each gait was taken from a variety of cross-referenced sources.[42] The influence of incline on horse speed was taken from a series of physiology articles written on that exact question.[43] These data were used to fit a function that follows a modified Laplace distribution.[44] A minimum of 5 kmph was established in order to compensate for measurement errors of slope along certain segments of the highway grid.[45]

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[40] As stated previously, calculating travel time only between barrios at second-degree rook contiguity was a choice forced by the computational limits of using a single laptop. The computation took several hours to complete. A more intensive operation, such as calculating shortest paths between all nodes, would have taken several days and therefore been unfeasible. Likewise, increasing the number of points or density of the line grid would tend to scale the computational expense rapidly. Given the limitations, I adopted what I believe to have been the best balance between detail and cost.

[41] Similar procedures to calculate walk-time networks from geographic data are relatively common in the experimental archaeology literature, where they are often used to infer the path of major migration routes. An advanced example, which incorporated sight lines and leveraged major computational resources to calculate an all-to-all network at continent scale is: Stefani Crabtree, "Landscape Rules Predict Optimal Superhighways for the First Peopling of Sahul."

[42] For example: Program, "Horse Locomotion."

[43] Z. T. Self and Wilson, "Speed and Incline During Thoroughbred Horse Racing": R. J. Williams, "Heart Rate, Net Transport Cost and Stride Characteristics of Horses Exercising at Walk and Trot on Positive and Negative Gradients."

[44] $velocity = 10e^{-13|gradient+0.05|} + 5$

[45] Line segments were placed on a regular grid, and slope was measured between the start point and end point

The decision to base highways speeds on horse locomotion rather than automobile mechanics was made on the basis of a review of the relevant primary source material. Most importantly, traffic composition statistics from 1910 demonstrate that automobiles were a negligible proportion of highway travel methods at the time, with mule, horse, carriage, and wagon traffic constituting the overwhelming majority both in number of vehicles and tons of freight.[46] Second, reports from Puerto Rico,[47] as well as independent research from the time[48] indicate that the macadam roads used throughout the island at the time were not only ill-suited for automobile travel at faster-than-horse speeds, but were also actively degraded by the progression of automobiles. The only road surface capable of supporting any significant amount of automobile traffic was asphalt, which was developed in the 1910's, but only covered a small fraction of the road surface by 1920. As such, it is safe to assume that even in 1920, the primary mode of transportation on Puerto Rican highways was by horse.

The railroad cost function was a flat rate of 32.187 kmph based on direct primary source quotation[49] and calculations from the 1910 timetable of the main passenger line in the Island.[50] This speed was not adjusted along line segments as a function of slope, because rail speed is extremely sensitive to slope. Consequently, even the minor and rare slope errors mentioned previously were enough to seriously compromise any slope-sensitive rail speed function to the point where even a global minimum speed could not compensate, as it did for the highway speed function. Given that rail speed is so sensitive to slope, it can be assumed that no rail in the empirical network was built where the slope would have rendered the speed prohibitively

of each line. Therefore, some line segments dip off of cliffs or across valleys in a way that greatly exaggerates the actual slope that a person moving in that region would have traveled. These line segments with exaggerated slope only minimally interfere with the shortest walking paths calculation, which searches the entire grid and can thus compensate with minor adjustments in routing. Highway and railroad shortest path calculations, however, are significantly effected, as they only search the very small fraction of the grid where said infrastructure exists. Consequently, they usually must make major adjustments in routing when a segment with an exaggerated slope is encountered, or, if there are no nearby alternate paths, they include the exaggerated cost and thereby greatly exaggerate travel times between barrios with rugged terrain. A minimum speed neutralizes the effect of these outliers without impacting travel time calculations along segments with an accurately measured slope.

46 Porto Rico, "Annual Report of the Governor of Porto Rico."

47 Porto Rico.

48 Mail, "The Modern Macadam Road."

49 Estimations in the 1901 Report of the Governor placed the line speed at 15 to 20 mph (20 mph = 32.187 kmph): Porto Rico, "Annual Report of the Governor of Porto Rico."

50 Porto Rico, "San Juan - Ponce."

slow, so a flat rate is not deleterious to the accuracy of the shortest path calculations on the empirical network.

However, when setting the parameters for the network randomizations it was essential to remove any paths from the sample pool on which rail construction would have been literally impossible on account of slope. (The point of randomization is to test against realistic counterfactual patterns of highway and railroad development, so impossible or illogical paths need to be excluded). Gradients of greater than 15% were never encountered on adhesion railroads of the time.[51] To add some additional tolerance for slope error, a 20% gradient cutoff was used to determine which paths would have been impossible for railroads to climb, and remove them from the randomization sample pool.

Network Assembly

With shortest paths between neighboring barrios having been calculated using each transport network (walk, 1900, 1910, and 1920), edge lists were extracted from QGis and used to construct networks in the R programming language. At this stage, all 4 networks were structurally identical; all of the same nodes were connected. The difference was the weight of each edge, which corresponded to the number of minutes it took to travel in either direction between a given edge pair using the available infrastructure. To investigate the structural properties of the network, I converted the network from weighted and directed to unweighted and undirected using a simple cutoff. Any two nodes which were directly linked by a path that took less than 75 minutes to traverse in either direction were considered connected, and all other nodes were considered unconnected.

The assumption here is that influence and community membership are a function of temporal distance. Interaction is highest amongst those who can reach one another the quickest, and it decays to a zero as that distance increases. The specific cutoff value used is of course arbitrary, and depends on the frequency of interaction one defines as necessary for nodes to

[51] Isaac, "On the Use of Locomotive Power on Gradients of 1 in 17 and Curves of 300 Feet Radius on Railways in America."

influence one another. Eight hours - a day's travel - was the most intuitively sound cutoff to use, but it resulted in a network that was too interconnected for structural analysis to be fruitful. The next most intuitively plausible cutoff was "a daily trip": the maximum distance a person might be expected to travel on a daily basis to commute to work, visit friends, or run errands. Depending on the person and context, this usually ranges from 0.5 to 2 hours. The cutoff used - 75 minutes - is simply the midpoint between these two values.

Network metrics as they appear in the results section were calculated using a combination of custom functions and functions built into the R `igraph` package. Metrics derived from the full network apply to each node, and use every available connection between nodes. Metrics were also calculated on subnetworks according to barrio crop classification. These metrics use all available connections, but only measure the effect on nodes belonging to the stated subnetwork.

All distance metrics represent node population-weighted averages (distances to and from more populated barrios are given more weight, proportionally). This population weighting is done in order to hold the potential effect of barrio population on infrastructure decisions constant. Any differences in effect should therefore not be attributable to population fluctuations.

As detailed above, all network links are unweighted, so distance metrics represent the average number of "steps" between two nodes, where a direct connection is equal to one "step" (which equates to 75 of fewer minutes of real-world travel time, as per the cutoff value used to construct the networks). Modularity and assortativity metrics are summary statistics by design, so they did not need to be averaged.

Significance Testing

Significance testing was conducted by bootstrapping 1000 random networks for each of the transport networks, and comparing the distribution of metrics derived from each series of random networks to the observed metrics for their corresponding transport network. The point of this exercise is to generate a realistic sequence of counterfactual networks by holding constant the unchanging structural elements, while randomizing whichever ‘treatment’ elements were changed. This allows us to determined whether the effects observed in the empirical networks are the result of the particular *pattern* of changes made, or are merely the result of the *number* of changes made.

For the transport networks used here, the treatment variable is the particular set of new connections created as a result of highway and railroad construction. The unchanging base structure is the location of each barrio (the number of vertices and contiguity of each vertex), and the connections that already exist in the walk-only network. A full shuffle of links is inappropriate, as it would also randomize the actual terrain and barrio locations. Instead, I created a “counterfactual” highway and railroad network by taking the hiking paths between each barrio and county capital at the stated contiguity and using the horse speed and train speed functions to calculate what the hypothetical travel time between said points *would* be if a highway or railroad line were built along that path.[52] I then applied the standard 75 minute cutoff when converting the networks to unweighted. Finally, I removed all connections that were present in the walk only network.

The result was a realistic sample pool (for road and rail separately) which included every new connection that was *actually* made by the empirical networks, as well as every other realistic new connection that was possible to make given the same physical constraints. The randomization function draws the same number of links from each sample pool as new connections of each type (highway or railroad) found in the inputted empirical transportation network. It then merges these randomized counterfactual connections back onto a copy of the base walk-only network, and outputs the same metrics measured for the empirical network. Repeating this process 1000 times for each transport network, I generated a distribution of random network metrics. The significance of metrics in the corresponding empirical network was then determined at the $p = 0.05$ threshold by comparing them to 2.5th and 97.5th percentile values of the associated distribution of randomized network metrics.

[52]The aforementioned 20% gradient cutoff was applied to railroad lines.

Results and Analysis

The Results table and constructed networks are displayed below, for reference. A sample randomized network is displayed alongside each observed network, to make the comparison visually easier and to contextualize the numerical results.

Metric	Subgraph	Walk	1900			1910			1920		
			Net	L	U	Net	L	U	Net	L	U
Distance to Network	All	30.73	20.66	14.83	21.66	**14.29**	7.95	10.61	**13.24**	6.73	8.49
	Sugar	29.62	17.94	14.56	22.22	9.98	8.11	11.07	8.74	6.76	8.83
	Coffee	29.96	**23.50**	12.42	19.55	**17.99**	6.30	8.56	**17.60**	5.38	6.86
	Other	25.46	16.43	13.69	19.65	**12.71**	7.68	10.17	**11.71**	6.56	8.22
Distance to San Juan	All	29.35	16.13	14.34	22.36	10.99	7.02	11.72	**10.12**	5.71	9.39
	Sugar	27.91	12.93	12.56	20.86	8.05	6.44	10.68	6.97	5.10	8.41
	Coffee	37.09	22.85	17.36	28.44	**16.70**	8.19	14.32	**16.27**	6.68	11.58
	Other	21.54	11.99	11.84	17.91	9.19	6.46	10.45	8.46	5.47	8.78
	All Capitals	26.92	13.83	12.20	20.39	8.55	5.82	10.28	7.76	4.59	8.30
	Sugar Capitals	23.57	11.16	10.04	17.35	6.97	5.12	9.02	6.03	3.97	7.21
	Coffee Capitals	36.81	21.26	15.94	28.78	13.83	7.49	14.54	**13.49**	5.92	11.26
	Other Capitals	23.25	**12.07**	12.13	20.60	8.06	6.18	11.47	7.28	5.15	9.47
Distance to Port	All	8.60	**7.59**	4.54	5.94	**5.17**	2.65	3.20	**4.99**	2.35	2.74
	Sugar	3.93	3.24	2.47	3.62	**1.62**	1.83	2.25	**1.51**	1.67	1.97
	Coffee	14.20	**13.17**	5.96	9.02	**9.78**	3.12	4.27	**9.87**	2.72	3.52
	Other	7.84	**6.41**	4.77	6.36	**5.48**	3.09	3.93	**5.19**	2.79	3.36
Modularity	All	0.88	0.87	0.86	0.88	**0.85**	0.82	0.84	**0.84**	0.81	0.83
	Sugar	0.92	**0.89**	0.90	0.92	0.88	0.88	0.90	**0.86**	0.87	0.90
	Coffee	0.85	0.85	0.82	0.85	**0.84**	0.78	0.81	**0.84**	0.76	0.79
	Other	0.85	0.85	0.83	0.85	**0.84**	0.80	0.83	**0.83**	0.79	0.82
Capital Assortativity	All	-0.10	**0.00**	-0.07	-0.02	0.10	0.05	0.12	0.16	0.10	0.17
	Sugar	-0.14	**0.02**	-0.14	-0.08	**0.11**	-0.08	0.03	**0.17**	-0.04	0.07
	Coffee	-0.09	**-0.09**	-0.08	0.02	**-0.09**	-0.02	0.12	**-0.09**	0.01	0.16
	Other	-0.08	-0.08	-0.08	-0.01	-0.06	-0.07	0.05	-0.02	-0.05	0.08
Crop Assortativity	Sugar	0.54	**0.55**	0.52	0.54	**0.53**	0.48	0.51	**0.51**	0.46	0.49
	Coffee	0.75	0.74	0.73	0.75	**0.74**	0.70	0.73	**0.73**	0.69	0.72
	Other	0.62	0.61	0.59	0.61	0.56	0.54	0.58	0.52	0.52	0.56

Figure 3: Results Table. Metrics for observed networks are displayed under the "Net" column for each year. Lower and upper 95% confidence interval bounds for simulated network metrics are displayed under the "L" and "U" columns, respectively. Significant values (falling outside of the relavent confidence intervals) are displayed in bold. See "Network Assembly" section above for description of metrics.

The 1900 network was primarily built by the Spanish government, so it was predicted to have structural properties that reflect the pattern of political authority at the time. Export oriented connections should be weak, and legibility oriented connections should emphasize legibility of the populace at large by the central and local governments, but not of the local governments by the central government.

The 1910 and 1920 networks, however, were built by the American government, so their structure was predicted to align with the goals of the new colonial administrator. Export and sugar oriented connections should be prioritized, and legibility of the local governments to the central government should take precedence over broader social legibility (in contrast to the predictions of Scott's theory).

Distance to Network reflects labor mobility, and is therefore a proxy for the population's evasion potential compared to both local and central powers. This metric is significantly higher than the null expectation for most regions at most times. It *did* in absolute terms, but not nearly as much as it could have with a similar investment in infrastructure. Clearly, neither colonial overlord was primarily motivated to build infrastructure for the purposes of providing general public goods. This is not at all surprising in the Spanish case, but *is* a little surprising in the American case, given that the American government might have been incentivized to at least increase labor mobility from non-sugar regions to sugar regions.

Distance to San Juan represents a major failure for Scott's theory. When given the chance to invest massively in the very kind of distance-demolishing technology that linear theories of technology-legibility interaction such as Scott's suggest were *the* reason for the triumph of legibility over state evasion in the modern era, The state - at least in Puerto Rico's case - systematically neglected to invest in legibility relative to other goals. The approach suggested here, however, predicted this result, especially for the American administration.

Nonetheless, predictions for this metric slightly misfire when it comes to the coffee regions. I indicated that the US government was incentivized to undercut the power of it's opponents among the local elites by extending legibility to the coffee capitals, but though it did add connections to coffee capitals, it neglected these connections compared to other goals, and it was

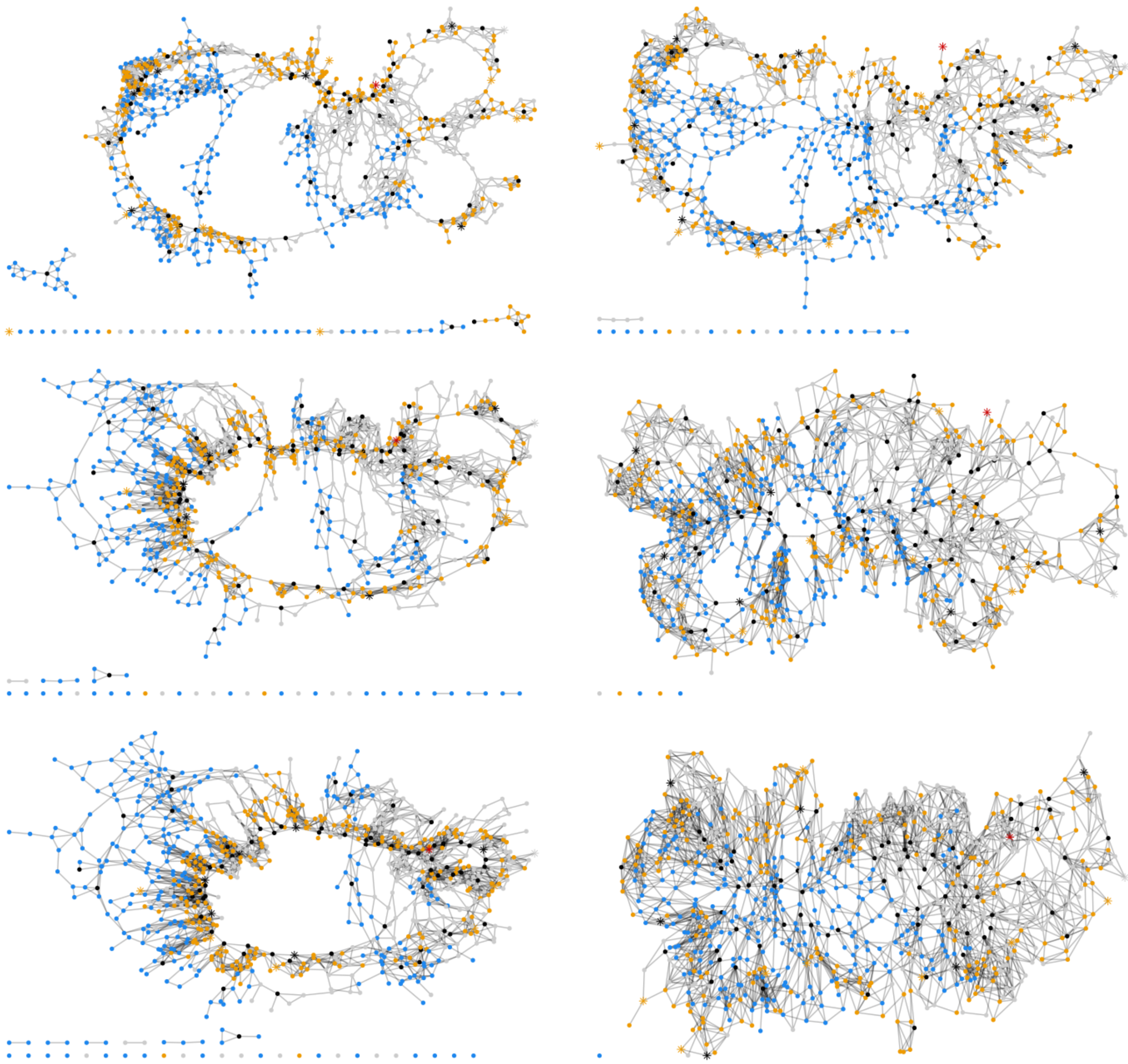

Figure 4: Observed (left) versus Randomized (right) Network in 1900 (top), 1910 (middle), and 1920 (bottom). Sugar barrios are orange, coffee barrios are blue, capitals are black, San Juan is red, and other barrios are grey. Ports are represented by an asterisk (*) shape. Note in particular the large number of coffee barrio isolates, and the increasingly centralized ring-like structure of the sugar barrios in the observed networks compared to a random development pattern

not careful to make these connections in a way that undercut local control of the populace by increasing assortativity or decreasing modularity.

In fact, the American colonial administration seems to have chosen a development path that significantly *ignored* its erstwhile local rivals in the coffee regions of the island. Evidently, the expense of constructing infrastructure in those regions was simply not worth the gain in positional influence.

This exact line of reasoning leads to the places where the strongest evidence in favor of the use-context approach to technology can be found. The US government's near-exclusive focus on sugar export-oriented development is quite clear. Sugar regions are the only lands that are significantly *more* (rather than less) closely connected to ports than the null expectation. This is especially noteworthy given that sugar growing land - mostly being located on the coast - is already close to ports.

Similarly, sugar regions are the only places that are less (rather than more) modular than the null expectation, and are the only places that consistently have a higher level of capital assortativity than the null expectation. The pattern of highway and railroad development actually overdetermines these outcomes, as these lines of transport greatly and redundantly overlap in sugar regions.

In structural terms, a region with decreasing modularity and increasing assortativity is becoming more internally integrated in a way that does not favor the influence or centrality of any particular point. Travel speed from capital to capital and rural barrio to rural barrio both increase, while the relative influence of capitals over rural barrios weakens. In this situation, the influence of local elites over the population at large quickly erodes as the population's general evasion mobility increase. Meanwhile, the local centers of power (diminished in positional authority as they are) become more easily traversable in sequence by a central authority. The general population, while not as legible to the center as a more specially optimized structure would make it, is nonetheless closer to the state's grasp than if regional modularity had been maintained.

In other words, the structural situation that obtains in the sugar barrios as a direct result of the state's pattern of technological deployment is precisely the one that would best serve the state's goals in a use-context framing of the problem. The region was integrated in way that is not only more governable from the center, but much more resistant to the future rise of uncooperative local elites, and much more optimized for monocrop production for export.

Conclusion

> *Many of them in the interior are living far from roads or other means of communication. . . in much the same condition as the Indians whom Columbus found in Porto Rico. . . A system of small villages disseminated throughout the island, convenient for labor in the fields, would tend to bring civilization into regions now virtually a wilderness.*
>
> — Annual Report of the Governor of Porto Rico, 1907

The concept of legibility was originally developed by Scott on the basis of anthropological and ethnographic research. However, its materialist roots and sensitivity to the details of topographic position have always made it amenable to a structuralist empirical analysis. The role of technological change - when modeled as an uneven alteration in structural conditions - is thereby possible to incorporate into such an analysis. Until now, it remained to be seen whether this approach had anything new or interesting to add to the discussion of technological-political interaction. With the results produced by this thesis, I believe I have made a convincing case that this approach is not only valuable, but that its potential future value is far from realized.

In the case of early 20th century Puerto Rico, the new American colonial administrator unleashed a massive and rapid deployment of technological might. From the standpoint of more linear models of technological-political interaction, this event should have resulted in a great re-centering of the lines of transport on the administrative capital. Expectations drawn from colonial history would have predicted a generalized form of export-oriented development. Instead, the state deployed its limited resources in a manner that not only significantly and systematically pursued export oriented sugarcane production, but did so in a way that optimally restructured transport networks to weaken local rivals and achieve regional integration.

Crucially, this prediction would have been difficult to make and impossible to test without an approach to technological-political interactions that focuses on the structural use-context of the technology in question.

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