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The Demarcation of Land and the Role of Coordinating Property Institutions

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We use a natural experiment in nineteenth-century Ohio to analyze the economic effects of two dominant land demarcation regimes, metes and bounds (MB) and the rectangular system (RS). MB is decentralized with plot shapes, alignment, and sizes defined individually; RS is a centralized grid of uniform square plots that does not vary with topography. We find large initial net benefits in land values from the RS and also that these effects persist into the twenty-first century. These findings reveal the importance of transaction costs and networks in affecting property rights, land values, markets, and economic growth.

Beginning at a white oak in the fork of four mile run called the long branch & running No 88° Wt three hundred thirty eight poles to the Line of Capt. Pearson, then with the line of Pearson No 34° Et One hundred Eighty-

> eight poles to a Gum. (Example of parcel description under metes and bounds demarcation; Stetson 1935, 90)

> The beauty of the land survey . . . was that it made buying simple. . . . Every one of these quarter-quarter sections had its own address, as in ¼ South-West, ¼ Section North-West, Section 8, Township 22 North, Range 4 West, Fifth Principal Meridian. (Description of the American rectangular system of demarcation; Linklater 2002, 180–81)

I.   Introduction

Land demarcation is one of the earliest activities of organized human groups. It defines property boundaries, parcel shapes, and plot locations and, hence, is a foundation for land use and land markets.[1] Two demarcation regimes have dominated historically: metes and bounds (MB) and the rectangular system (RS).[2] MB is easily the most prevalent and is found in parts of every continent for both agricultural and urban land. RS was used extensively by the ancient Romans and is now found in large regions of the United States, Canada, and Australia, as well as on a smaller scale in urban areas throughout the world (Libecap and Lueck 2011; Libecap, Lueck, and O'Grady 2011).

   In this paper, we provide the first analysis of the economic consequences of land demarcation using a natural experiment in which the two systems were placed adjacent to one another because of exogenous historical factors.[3] Our empirical setting is central Ohio, where land in the Virginia Military District (VMD) was demarcated by MB and was (and still is) surrounded by land demarcated under RS. Using detailed microdata, we examine the effects of the two arrangements on parcel shapes, values, property rights security, and trading.

   These two demarcation regimes are striking examples of centralized versus decentralized institutions. MB is decentralized, whereby each individual defines parcels independently and idiosyncratically using nonstandard, impermanent natural features (rocks, streams, trees); structures (walls, monuments); and adjacent properties ("southwest corner of Benjamin Beasley's survey"). Parcels are not uniform in shape or size, there is no general addressing format, boundaries often are temporary and vague, and property descriptions are based on local knowledge. The RS, however, is centralized, whereby each parcel is predefined as

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[1] Throughout the paper, we use the terms "parcel" and "plot" synonymously.

[2] We use the English term "metes and bounds." Metes refer to a boundary defined by direction and distance between terminal points. Bounds refer to local boundary descriptions.

[3] We find no legal or economic scholarship on this topic, and even major property law treatises (e.g., Dukeminier and Krier 2002; Merrill and Smith 2007) merely describe the American RS.

part of a standardized system of identical squares within a large grid. The system designates shape, size, and (directional) alignment independent of topography. The resulting network provides information on the location and dimensions of each parcel, even to those at great distance from the plot location.

Although the RS constrains demarcation relative to MB, its standardization creates more precise and, as we show, more secure and exchangeable property rights. We argue that the uniform structure of the RS lowers enforcement costs, lowers trading costs in land markets, and lowers coordination costs in infrastructure investment, such as for roads and fences along property borders. These benefits, however, come at the cost of inflexibility during demarcation. By not accounting for local geography, the square grid may not be optimal in rough terrain for using the most productive potential of the land. By contrast, the more flexible MB allows for customization of parcel shapes, sizes, and alignment in response to topography. Our empirical investigation examines the trade-offs and consequences of these important, different property institutions on parcel definition and value.

Our analysis uses microlevel data from the natural experiment in land demarcation in Ohio. We find that the decentralized MB produces more irregular parcel sizes, shapes, and alignment than RS does and that these differences are amplified in more rugged topography. We also find that per-acre land values generally are greater under RS and that this estimated effect is strongest in flat terrain where values are estimated to be 20–30 percent higher. We further find large net benefits in the adoption of the RS in the early nineteenth century and that this demarcation institution has long-lasting consequences. Population densities, land use, and values dramatically diverge in the sample region between 1850 and 2000 between RS and MB areas that are otherwise similar. These results imply that property institutions can generate differential patterns of long-term economic growth.

We argue that these findings are attributable to lower transaction costs and better property rights enforcement under the centralized, uniform RS.[4] We draw these conclusions because we also find that there are fewer land market transactions and more property disputes under MB. The key advantage of RS is that the original grid acts as a public good that, once established, secures property rights for any plot defined as a square or collection of squares in the grid. As long as the terrain is relatively

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[4] These results are consistent with the transaction cost analysis of Coase (1960), Williamson (1975), and Barzel (1982) and the network analysis of Baird, Gertner, and Picker (1994), Dixit (2003), and Farrell and Klemperer (2007). Our findings that land demarcation patterns and effects persist over long periods are also consistent with the literature that addresses the effect of institutions on economic growth (e.g., North 1990; Acemoglu, Johnson, and Robinson 2002; Acemoglu and Johnson 2005).

flat, there are small productivity gains from deviating from the grid, and therefore the gains from lower transaction costs and more secure property rights come at little or no cost other than the up-front cost of defining the system. Where terrain is more rugged, however, we find that some RS plots are more uniform and less productive than they would have been under more flexible MB. Our findings are consistent with the notion that RS generally reduces the costs of using the market and for reorganizing plots as conditions change.

The paper is organized as follows. Section II describes the U.S. land demarcation system and the natural experiment in Ohio, where MB and RS were placed next to one another. Section III motivates the empirical analysis by considering the two demarcation regimes as planner's problems. Section IV describes the data and provides empirical analysis of land demarcation patterns, land values, boundary disputes, land markets, the net benefits of RS, and the long-term effects of the RS. Section V summarizes the findings and discusses the role of demarcation systems as coordinating devices to lower transaction costs in land markets and in creating institutional path dependence.

II. RS and MB Demarcation in the United States

Both MB and RS land demarcation systems are found in the United States (McEntyre 1978). Because of historical and exogenous events, these institutions are occasionally found together and thus provide natural experiments in land demarcation.

A. U.S. Land Demarcation

MB was inherited from England and generally replicated in the 13 original states, as well as in Kentucky, Tennessee, parts of Maine, Vermont, and West Virginia (Marschner 1960, 27, 34–35; Price 1995, 212; Linklater 2002, 32–40).[5] MB, however, formally ended in other areas of the United States with the enactment of the Land Ordinance of May 20, 1785, for disposing of federal lands in the western territories (Donaldson 1884, 149; Treat 1910, 36; Hibbard 1939, 37; Gates 1968, 59; Linklater 2002, 116, 117). A central motivation for the law was to raise revenue through land sales that could be stimulated by more secure property rights and lower transaction costs (Donaldson 1884, 17; Hibbard 1939, 1; Gates 1968, 61). During congressional debate over the 1785 Land Law, members supported RS because of "the thousands of

[5] An analysis of demarcation systems in the colonial United States and across the British Empire is provided in Libecap et al. (2011). MB also was used where Spanish and Mexican land grants were prevalent. Its impact in California is examined in Libecap, Lueck, and Lopes (2010).
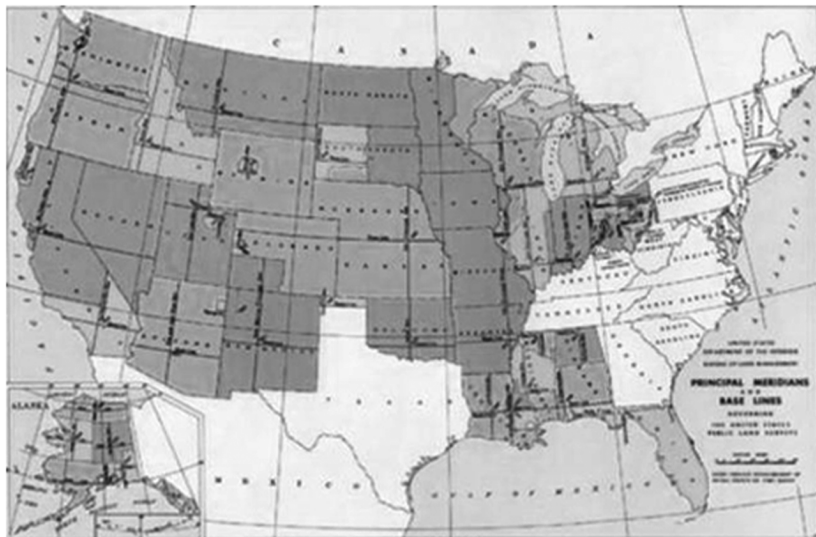
Fig. 1.—Extent of rectangular system in the United States. Source: "Rectangular Survey System," Land Prints, Angels Camp, CA (http://www.landprints.com/LpRectangularSurvey System.htm).

boundary disputes in the courts" under MB (White 1983, 9). In promoting the legislation, Alexander Hamilton emphasized that "the public lands should continue to be surveyed and laid out as a grid before they were sold" (quoted in Linklater 2002, 117).[6] The location of RS and MB within the United States is shown in figures 1 and 2, which reveal the MB dominating along the eastern seaboard and RS dominating everywhere west. Texas uses its own RS system. The figures also reveal the network structure of the RS.

The centralized U.S. RS uses an array of meridians, baselines, townships, and ranges to demarcate land.[7] This system began with the first survey in eastern Ohio on the Pennsylvania border at an initial point with a precise latitude and longitude ("point of beginning," as described in Linklater [2002] and Hubbard [2009]). Next, a principal meridian (a true north-south line) and a baseline (an east-west line perpendicular to the meridian) are run through the initial point. There are 37 sets of principal meridians/baselines, all defined by longitude and latitude, in

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[6] The advantages of RS were stressed in the British colonial policy of the eighteenth and nineteenth centuries and in congressional debate over the U.S. Land Law of 1785 (Libecap et al. 2011).

[7] Townships under the RS are grid locations. They are different from political jurisdictions called townships, which are found in many U.S. counties and used also for data aggregation by the U.S. census. The RS, officially, is the Public Land Survey System (http://www .nationalatlas.gov/articles/boundaries/a_plss.html).
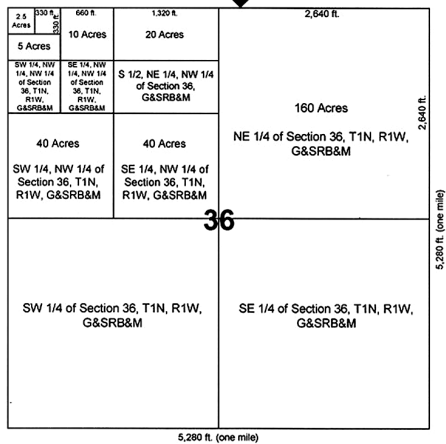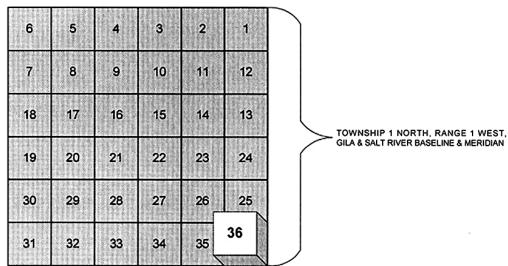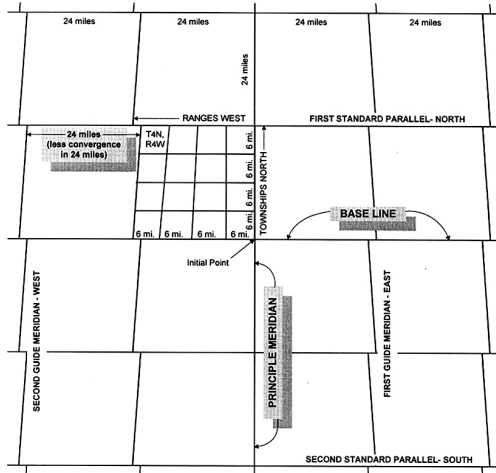
FIG. 2.—Details of rectangular system in the United States. Source: "Rectangular Survey System," Land Prints, Angels Camp, CA (http://www.landprints.com/LpRectangularSurvey System.htm).

this large system—32 in the continental United States and five in Alaska—that fix demarcation within their area.

   On each side of a principal meridian, land is divided into 6 × 6-mile square units called townships. A tier of townships running north and south is called a range. Each township is divided into 36 sections; each section is 1 square mile and contains 640 acres, so there are 23,040 acres in a township. The square sections that constitute a township are numbered in the boustrophedon manner from 1 to 36, beginning in the northeast corner of the township. Each section can be subdivided into halves and quarters (or aliquot parts). Each quarter section (160 acres) is identified by a compass direction (northeast, southeast, southwest, northwest). Each township is identified by its location relative to the principal meridian and baseline. For example, the seventh township north of the baseline and third township west of the first principal meridian would be "T7N, R3W, first principal meridian." This grid system of aligned squares comprising section and townships covers the entire American landscape where it was authorized, regardless of the terrain, including land as diverse as the Great Plains and the Rocky Mountains.[8]

B.   A Natural Experiment in Ohio: The Virginia Military District

The natural experiment in land demarcation in Ohio is the result of two distinct land acts of Congress in 1784 and 1785. Ohio was established as a state in 1803 and was the first part of the federal domain to be governed by this legislation. All of the state was placed under the RS except for the VMD, which was placed under MB.[9] The VMD was granted to Virginia in 1784 by Congress before the creation of Ohio and before the 1785 Land Ordinance that created the RS.[10] Virginia used MB demarcation, first as a colony and later as a state. Virginia selected the

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   [8] The RS also governs both private and public land. The RS does, however, contain internal systemwide adjustments to the grid. To correct for the curvature of the earth, slight corrections are made to the shape of some sections. This adjustment occurs every four townships, or every 24 miles. Adjustments are also made to the square sections where grids originating from different principle meridians meet each other, resulting in irregular parcels. This typically occurs at state borders. Both Alaska and California have more than one principal meridian, and some meridians extend beyond a single state. Although the RS constrained parcels to be square, various U.S. land laws authorized different size distributions (Gates 1968). It is also possible to privately customize fields within square plots.
   [9] The VMD covers 4.2 million acres of land (about 16 percent of Ohio) along the northern border of the Ohio River, between the Scioto and Little Miami rivers. For discussion of the Ohio land survey and land distribution, see Donaldson (1884, 197–98), Treat (1910, 52–63), Gates (1968, 70–71), and Knepper (2002).
   [10] The original U.S. states often made large claims to western lands, and Congress compensated them for relinquishing their claims. The VMD was such an arrangement between the United States and Virginia (Treat 1910, 6–90; Hibbard 1939, 10–14; Gates 1968, 37–57).

region to reward its veterans through the granting of warrants that could be used to secure land (Hubbard 2009).[11] These warrants often were subsequently sold to land developers or settlers (Peters 1930). In the settlement of all of Ohio, migrants were substantially the same, initially emigrating from the northeastern United States and the South and, by 1840, from Germany.[12]

The processes for demarcating and claiming land in Ohio were different for RS and MB lands. For farmers to obtain RS land, the federal government first surveyed parcels into square 640-acre sections, as the law required, and then made them available to individuals at the local land office, often the county seat. Individuals located a square parcel or collection of squares and obtained title through purchase and registration of the transaction (Donaldson 1884, 197, 200; Treat 1910, 35, 47–63; Hibbard 1939, 39; Gates 1968, 69–71). Under MB there was no presurvey by the government and no external constraint on individual plot demarcation. Claimants first located a plot of land of any shape, marked its perimeter on trees or other natural or human monuments, filed the claim or "entry" at the local land office (again at the county seat), hired a surveyor to formally measure the boundaries, and then recorded the surveyed plot at the land office and received title.[13] Thus, as a result of exogenous actions regarding the distribution of Ohio lands, the RS and MB came to govern adjacent and nearly identical areas. We use this event to examine the economic effects of demarcation.

III. Demarcation Regimes as Two Different Planner's Problems

The question of how to demarcate a very large area of land (26,206,963 acres in Ohio and 1,434,802,156 acres ultimately in the entire continental federal domain) generated policy debate in Congress in 1784 and 1785 (Hibbard 1939, 37; Gates 1968, 59; Linklater 2002, 116, 117).[14] This setting naturally lends itself to the use of a social planner framework, one for MB and one for RS, to organize and motivate our empirical investigation. A planner's perspective highlights the essential characteristics and trade-offs involved between decentralized MB and centralized RS.

In both scenarios, the planner is given a large rectangular tract of land to be allocated among a set of homogeneous farmers and demar-

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[11] Once a certificate of rank and service was presented to a court of law in Virginia for authorization, the Virginia Land Office in Richmond issued a warrant to either the veteran or his heir or assignee.

[12] See http://lib.oh.us/evolution/regions/vamd.html for migration patterns in Ohio.

[13] The VMD claiming process is described in Peters (1930) and Thrower (1966, 43).

[14] This is the land area of the continental RS states as shown in fig. 1. Square-mile data from the U.S. census are converted to acres, at 640 acres per square mile.

cated according to the constraints of each institution. The tract implicitly contains a large number of tiny square plots, so the planner essentially will form individual parcels of various shapes by assembling these small squares. There are diminishing returns to scale in farming due to limits on each farmer's span of control so that it will be optimal to have multiple farmers with separate parcels. The planner's objective under both systems is to choose the allocation and parcel demarcation that maximizes the net value of the entire tract.[15]

Initially, we assume that planners' decisions take place in a setting in which there are no transaction costs or related network benefits. That is, there are no enforcement costs, no information costs in determining the location or shape of parcels in trading, and no costs from the failure to align property boundaries for addressing, fencing, and infrastructure investment. The only costs for the MB planner are the constant per-acre costs of surveying individual parcels because demarcation and survey are not provided by the decentralized system. The RS planner, however, is endowed with a large predefined grid so that demarcation costs are sunk. The only costs for the RS planner are those from deviating from the grid.[16]

First, consider the planner's problem under MB. When the overall tract is flat, it is reasonable that the optimal solution to the planner's problem will resemble a set of identical, aligned (pointed in the same direction) square parcels. Squares have several productive features. Because the tract is fully demarcated, squares fill the interstitial space between parcels.[17] Like many rectilinear plots, they also have productivity advantages for agricultural and urban use (Barnes 1935; Lee and Sallee 1974; Amiama, Bueno, and Alvarez 2008). Squares have straight edges and simple angles for field cultivation and building construction, and their uniformity facilitates the allocation of labor and capital inputs to land in production.[18]

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[15] We assume that the external boundary is enforced collectively or otherwise by a sovereign. The value maximization assumption is consistent with the historical land policy objective described in the text. Because the original tract can be viewed as a tract with a finite number of tiny square plots that are assembled into parcels, the planner's problem can be viewed as a programming problem that, given appropriate restrictions on farming technologies, should have a well-defined solution.

[16] The assumption of fixed per-acre survey costs for the MB planner and positive survey (or deviation) costs for the RS planner means that marginal demarcation adjustment costs are zero for the former and positive for the latter.

[17] Squares are one of just three regular polygons—triangles, rectangles (squares), and hexagons—that can create patterns, with a common vertex and no interstitial space (Dunham 1994).

[18] Indeed, squares commonly were chosen by the Romans and in the reorganization of fields under the enclosures in England (see references in Libecap et al. [2011]). Squares have relatively low perimeter-to-area ratios (p/a) that lower demarcation and enforcement costs (Johnson 1976). The dimensions of a square also imply $p/a^{1/2} = 4$, which we use in our empirical analysis.

Rough topography, however, may change this MB solution. With irregular terrain, square parcel demarcation may no longer conform to the most productive parts of the land. Accordingly, deviations that allow parcels to follow land contours or streams may enhance productivity. Under these conditions, the MB planner may choose to assemble parcels of variable shapes, sizes, and alignment to better exploit the landscape.

Consider now the planner's problem under RS, which is nearly identical to the MB planner's, except that, with the grid endowment, the planner can assign parcels as original squares or collections of them without incurring any demarcation costs. As with the MB planner, the advantages of squares in flat terrain imply that the optimal solution also will resemble a set of identical, aligned square parcels. In more rugged terrain, however, the RS planner likewise may want to assign parcels that deviate from squares, but such adjustments are more constrained than under MB because of the extra costs of deviation from the grid.

Accordingly, with zero transaction costs, both MB and RS likely will yield identical parcel patterns with level topography. As ruggedness increases, we do not expect to see square parcels under MB because more irregular shapes are preferred and feasible given the flexibility of the system. The rigid RS, however, limits such otherwise valuable modifications so that more squares are retained. These conditions suggest that there will be greater variation in parcel dimensions under MB than RS in more rugged areas. In theory, some land could be so rugged that it becomes optimal to completely abandon grid-based plots under RS, and on such land, MB and RS should produce similar irregular plots, but our empirical findings suggest that none of the terrain in southwest Ohio is nearly this rugged.

Now consider the impact of transaction costs and variable survey costs on the MB and RS planning decisions. These costs suggest additional trade-offs between the two regimes. Although decentralized MB allows flexibility for farmers to individually tailor their parcels to topography and thereby increase productivity, in the aggregate this feature likely increases the costs of property rights definition and enforcement, the costs of trade, the costs of information, and the costs of coordination. MB parcels are bounded by temporary and often vague features of the land, potentially leading to overlapping claims and future conflicts over boundaries. Undemarcated gaps left between parcels, especially in rough terrain, where survey costs will be higher, also can result in subsequent competition for control. Locally defined, irregularly shaped plots can raise measurement costs in exchange and thereby narrow markets to only those knowledgeable of local practices. Similarly, idiosyncratic locations, shapes, and alignment can increase addressing costs and coordination in construction of roads and fencing along property borders.

By contrast, the centralized RS grid should provide more secure property rights because boundaries are predefined as straight lines with known locations. The costs of exchange similarly should be lower. With its fixed network of uniform, aligned squares and externally defined addresses based on latitude and longitude, markets can be expanded, and measurement costs in land transactions will be reduced. Joint infrastructure investment along straight boundaries also should be less costly to coordinate.

In the empirical work below, we show that the demarcation patterns suggested by these two planner's problems generally are present in the data. The MB plots in the VMD more often involve irregular shapes, and the relative prevalence of irregular plots in the VMD is more obvious in areas that are not flat. Further, we find greater variance in plot shapes and alignment in the VMD, and this variance increases in a more rugged landscape.

The planner framework, however, does not provide clear implications as to which system should provide more valuable farmland after each has been implemented. The MB system encourages potentially productive customization of plots' characteristics to terrain features, whereas the RS grid provides more secure property rights for plots that are anchored to it. We provide empirical evidence that the RS did indeed produce more valuable land. We conjecture that this result demonstrates that secure property rights and associated transaction cost and network benefits from the aligned grid produced by RS are of great value. We support this conjecture by documenting the greater prevalence of property disputes and reduced market trading under MB.

IV. Empirical Analysis of Land Demarcation Regimes

This section describes the sample selection process, summarizes the data, and presents estimates of the effects of demarcation regimes. It also provides evidence of the early net present value (NPV) of the RS and its long-term effects. The Appendix describes the data and related issues.

A. Sample Regions

Our empirical analysis uses two primary sample regions that are shown in figure 3. The first region (fig. 3A) covers 39 Ohio counties that are in or adjacent to the VMD, so that both MB and RS systems are included. Within this area, analysis is performed at the county and township levels to analyze the differential effects of RS relative to MB. The second region (fig. 3B) is a subset of this 39-county area and consists of townships that border but are not bisected by the VMD boundary. The smaller sample
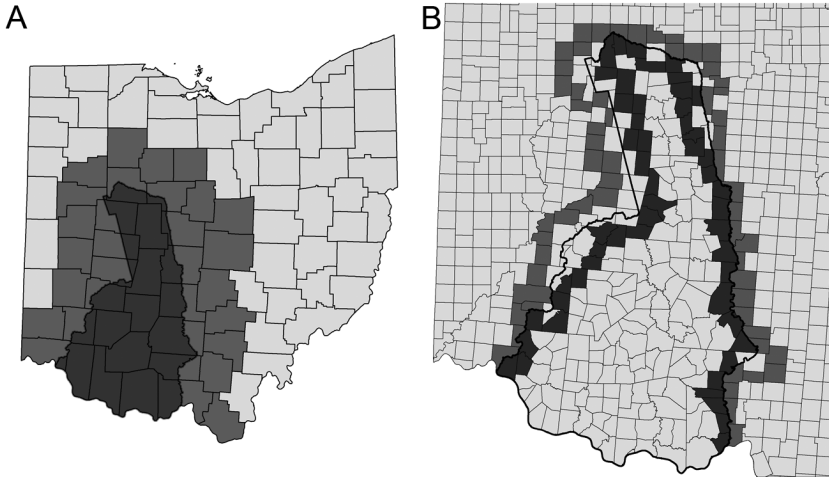
FIG. 3.—Ohio and the Virginia Military District. *A*, 39-county region: metes and bounds (MB) is dark shaded; rectangular system (RS) is lighter shaded. *B*, Border townships: MB is darker; RS is lighter. Source: Calculated by authors.

is advantageous because it narrows the range over which unobservable parameters can vary and restricts the demarcation treatment to a binary variable.

Table 1 provides comparative statistics for natural and demographic characteristics of the two sample regions and shows that the two areas are very similar. Indeed, we cannot reject the null hypothesis that the two areas have the same land characteristics (e.g., soil quality, terrain ruggedness, stream density) and initial patterns of human settlement (e.g., place of birth, occupation, population density) at the 5 percent level in either sample.[19] The similarity of these areas validates the setting of the natural experiment.

B.   Data

We use data from several sources to estimate the effects of demarcation regimes. Table 2 presents summary statistics for the samples used in our empirical analysis. Data on legal disputes, however, are described below in the subsection where they are used.

To facilitate clear comparisons between the two demarcation regimes,

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[19] While not significantly different in the full sample, the VMD lands are slightly flatter and of higher quality and lower stream density (less swampy) than neighboring RS lands. Because Virginia chose the VMD before the implementation of the RS, it may be that the land was perceived of to be higher quality than what might have been chosen alternatively. This selection bias would shift value estimates of the RS downward.

TABLE 1
COMPARISON OF RECTANGULAR SYSTEM (RS) AND METES AND BOUNDS (MB)
LAND IN 1850

	COUNTY SAMPLE*			BORDER TOWNSHIP SAMPLE[†]		
	Mean			Mean		
SAMPLE CHARACTERISTIC	MB	RS	t-Statistic	MB	RS	t-Statistic
Natural:						
Terrain ruggedness (0 = flat; 1 = vertical)	.032	.035	−.26	.022	.027	−.64
Soil quality (prime farmland fraction)	.27	.24	.62	.20	.26	−1.63
Stream density (length/area$^{1/2}$)	11.3	13.2	−1.12	. . .	. . .	. . .
Demographic:						
Born in Virginia (%)	23	17	1.48	22	18	.78
Farmers (%)	94	94	.07	93	91	.96
Average age of landowner (years)	44	44	−.06	44	43	.33
Population density (per mile²)	40	58	−.80	36	42	−1.36

NOTE.—Averages are weighted by total acres; t-statistics are from a two-sample t-test on the difference between the two averages (H_0: MB − RS = 0). Differences are not statistically significant at the 5 percent level.

* MB = 13, RS = 26.
† MB = 37, RS = 41.

we collect economic data as close as possible to the time of initial settlement. Data on farmland values, farm attributes, and individual occupants are taken from the 1850 and the 1860 U.S. Census of Agriculture and matched to entries from the U.S. Census of Population. These are the first censuses to provide the comprehensive farm and personal information needed for our analysis. County-level data on land transactions as measured by conveyances are taken from reports by the State of Ohio in 1858 and 1859.[20] Additional county-level census data on farmland values, population, and acres in farms are collected from the 1850–1997 U.S. censuses, for analysis of long-term effects.

For our analysis of parcel demarcation, we use data calculated from a digitized parcel map of very early (1825) Ohio properties first published by Sherman (1922). The digital data set allows us to spatially link parcel metrics to other geographic data sets of topography, soil, and distance to population centers. These metrics include area, perimeter-to-area ratio, sides, and alignment. Area is measured in acres. The perimeter-to-area ratio is always the perimeter divided by the square root of area to keep the units in the numerator and denominator the same but is simply presented in the discussion and tables as "perimeter-

[20] We report the data as transactions for 1858 and 1859 in terms of the mean number of farms in both years.

to-area" from this point forward. Parcel alignment is designed to measure deviation from the RS baseline of north-south alignment. Our variable *alignment* is the deviation in degrees of the longest parcel side from true north. For example, a square parcel in the RS aligned to true north would have an alignment of zero (degrees). In contrast, a parcel aligned exactly northeast-southwest would have an alignment of 45.[21] Once census data from individual farm and population entries are matched, they too are linked to the digital parcel map. It was not possible to exactly match all census entries with the original farm-level parcel locations, so township and county means are used with parcel-level information in our analysis.

Our empirical measure of terrain, *ruggedness*, measures the landscape on a 0–1 scale, where 0 is flat and 1 is vertical. This is a critical variable used throughout the analysis. To give empirical context, we note that surveyors, engineers, and other land professionals typically describe terrain in terms of "percent slope," which refers to the change in elevation for a unit change of horizontal distance. For example, a 45-degree angle corresponds to a 100 percent slope and would be equivalent to $t = 0.5$ in our measure.[22] A grade greater than 5 percent is very steep for a highway, and productive farmland typically is found with slopes of 0–5 percent (Food and Agriculture Organization 1993). In our 437-township sample, the average township slope ranges from 0.5 percent to a maximum of 24.5 percent and has a mean value of 5.4 percent.

C. Empirical Analysis

Size, Shape, and Alignment of Parcels

In this subsection, we use parcel data to examine how MB and RS regimes affect parcel shapes and configuration in varying topography. To begin, figure 4 clearly demonstrates differences in demarcation patterns under RS and MB in VMD border regions of different terrain. Both figure panels show 10 × 15-mile areas where MB and RS demarcation are adjacent. Figure 4A involves nearly flat terrain (average slope

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[21] Geographic information system (GIS) measurement limitations restrict alignment to values from 0 to 45, and thus it is an imperfect measure. The exact construction of alignment and the GIS limits in its calculation are described in the Appendix. For square parcels, constraining values to [0, 45] is not a problem since all sides of a square are the same length. For example, a square aligned at 45 degrees is identical to a square aligned at −45 degrees. For nonsquare parcels, however, there is asymmetry in alignment. For example, a rectangle aligned 45 degrees (northeast) is clearly distinct from a rectangle aligned −45 degrees (northwest). Because we constrain values to [0, 45], the variation in alignment of nonsquare MB parcels is underestimated.

[22] A 90-degree angle has a percent slope of +∞. The formula for converting percent slope into angle degrees is angle = arctan (slope/100), where angle is in degrees and arctan is the trigonometric function.

TABLE 2
Summary Statistics

Variable	Definition	Mean	SD	Min	Max
	A. Township Data: Parcel Shape Complexity and Variation Estimates (N = 437)				
Perimeter-to-area ratio	Ratio of parcel perimeter to square root of area	4.3	.4	4.0	5.6
Parcel sides	Number of parcel sides	4.8	1.1	4.0	10.6
Perimeter-to-area ratio SD	Designed to measure variation in parcel shape	.4	.4	.0	2.2
Parcel sides SD	Designed to measure variation in parcel shape	1.2	1.0	.0	5.7
Alignment SD	SD of parcel alignment	4.2	5.1	.0	18.3
Parcel size coefficient of variation	Designed to measure variation in parcel size	.5	.5	.0	2.4
RS	Fraction of township in RS	.69	.46	0	1
Ruggedness	Slope measure with value range [0, 1], where 0 is flat land	.03	.04	.00	.15
Parcels	Number of parcels in township	43	30	1	202
	B. County Data: Market Transactions Estimates (N = 39)				
Conveyances	Total number of land conveyances (thousands)	.29	.23	.04	1.23
Farms	Total number of farms (thousands)	1.92	.59	1.05	3.52
RS	Fraction of county in RS	.65	.40	0	1
Ruggedness	Slope measure with value range [0, 1], where 0 is flat land	.03	.03	.01	.12
Prime farmland	Fraction of soil area designated as prime farmland	.24	.13	.02	.49
Acres of farmland	Acres of farmland in county (millions)	.24	.05	.14	.39
	C. Township Data: Land Value Estimates, Full Sample (N = 774)				
Value per acre	Average farmland value per acre (1860$)	35	35	2	540
RS	Fraction of township in RS	.69	.46	0	1
Ruggedness	Slope measure with value range [0, 1], where 0 is flat land	.03	.04	.00	.15
Prime farmland	Fraction of soil area designated as prime farmland	.24	.15	.00	.76
Distance to market	Miles to nearest county seat	8.8	3.6	.6	17.7
Average age of owner	Average age of landowner	44	6	23	72
1860	Dummy variable for 1860	.47	.50	0	1
Acres of farmland	Estimated acres of farmland in township (thousands)	16.9	5.9	1.1	55.4
	D. Township Data: Land Value Estimates, Border Sample (N = 135)				
Value per acre	Average farmland value per acre (1860$)	40	45	2	479
RS	Dummy variable for township in RS	.56	.50	0	1

TABLE 2
(*Continued*)

Variable	Definition	Mean	SD	Min	Max
Ruggedness	Slope measure with value range [0, 1], where 0 is flat land	.02	.03	.00	.13
Prime farmland	Fraction of soil area designated as prime farmland	.22	.14	.01	.63
Distance to market	Miles to nearest county seat	7.5	3.3	.6	13.8
Average age of owner	Average age of landowner	44	6	30	72
1860	Dummy variable for 1860	.48	.50	0	1
Acres of farmland	Estimated acres of farmland in township (thousands)	16.7	6.6	6.7	55.4

NOTE.—RS = rectangular system; SD = standard deviation.

is ∼1 percent), whereas figure 4*B* involves rougher topography (average slope is ∼16 percent). In figure 4*A*, it is evident that the parcels under MB are largely rectilinear and sometimes nearly square but with no general alignment. In the RS areas, all parcels are aligned squares, except those along the Scioto River that forms the VMD boundary. In figure 4*B*, parcels under MB demarcation are highly irregular, varying in size, shape, and alignment, whereas, again, parcels under RS are uniformly square.

The relationship between topography and parcel shape and alignment for each demarcation regime can also be examined with scatter plots. Using a sample of townships for the VMD region, figure 5 shows four charts in which different parcel measures are plotted against ruggedness.[23] We use squares to denote RS townships and circles to denote MB townships. Figures 5*A* and 5*B* show the perimeter-to-area ratio and the number of parcel sides, respectively. Both of these measures will be 4 for squares. It is clear that for RS townships, the observations for both measures are clustered tightly around 4, regardless of terrain ruggedness. MB observations show much more variance and also have larger values for both the number of sides and the perimeter-to-area ratio. It is also clear that MB leads to more irregular plots, and there is also an indication that this effect becomes more pronounced in more rugged terrain. Figures 5*C* and 5*D* repeat this plot exercise by illustrating the relationship between the coefficient of variation in parcel size and the standard deviation in parcel alignment with ruggedness.[24] In these pan-

[23] This sample uses only those townships that are either completely RS or completely MB.

[24] We use the coefficient of variation instead of the standard deviation for the analysis of parcel size variation under MB, claiming that more rugged terrain encouraged substantially smaller plots on average. The scaled-down plot sizes in these areas yield smaller standard deviations that reflect decreasing mean values rather than increasing parcel homogeneity. Since the coefficient of variation is mean normalized, we judge it to be a better indicator of parcel size variation.
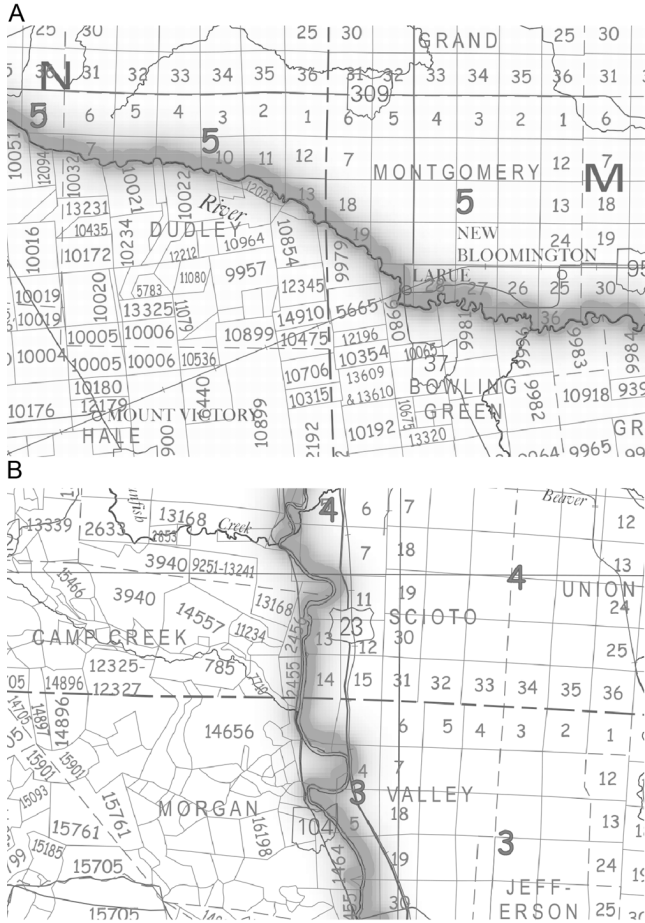
Fig. 4.—Sections of Ohio showing original rectangular system and metes and bounds demarcation. *A*, Eastern Hardin County and western Marion County, northern edge of Virginia Military District (VMD) in flat terrain (10 × 15 miles). *B*, Southern Pike County and northern Scioto County, southeast edge of VMD in rough terrain (10 × 15 miles). Source: McDonald et al. (2006).

els, RS townships show less variation and little or no impact from increases in ruggedness. MB townships, however, show more variance and increases in variance for larger values of terrain ruggedness.[25]

The patterns revealed in these figures indicate that although square parcels may be desirable in flat areas under both systems, they appear to be more difficult to create under MB, which lacks the coordinating

[25] Similar plots can be seen for the standard deviation in the perimeter-to-area ratio and the standard deviation in the number of sides.
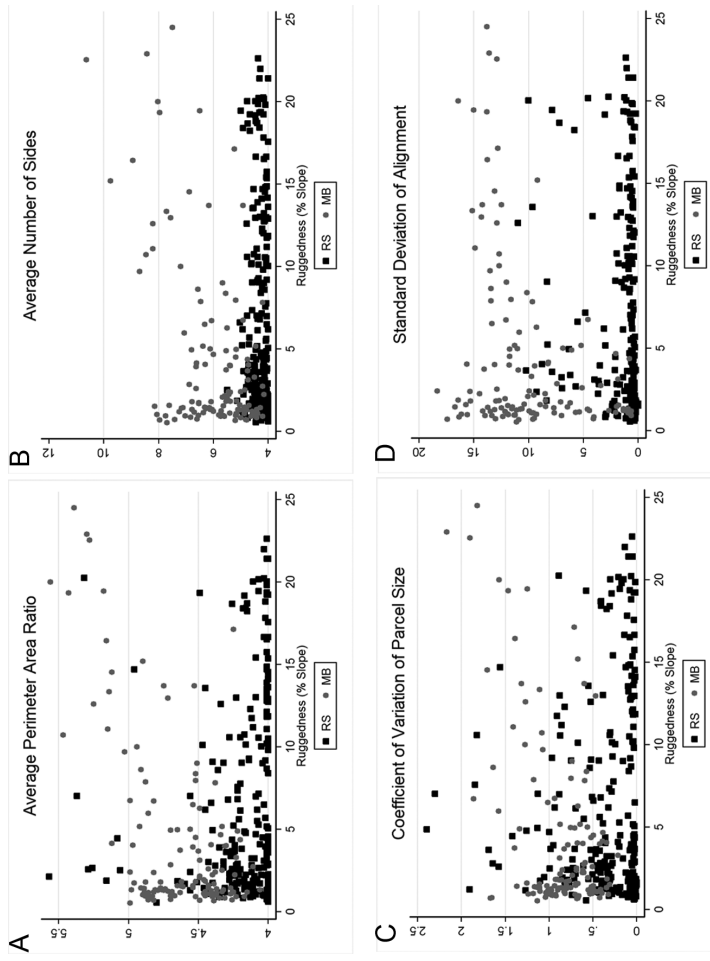
Fig. 5.—Relationship between ruggedness and parcel shape and alignment. *A*, Parcel shape: perimeter-to-area ratio. *B*, Parcel shape: number of sides. *C*, Variation in parcel size. *D*, Variation in parcel alignment. MB = metes and bounds; RS = rectangular system.

benefits for demarcation of the centralized RS grid. At the same time, while more irregular plots are useful under more rugged topography, the constraints of the RS raise the marginal costs of deviating from squares, relative to the more flexible MB.

The scatter plots in figure 5, however, are only suggestive. To more precisely determine how RS and MB affect shapes, we use parcel characteristics aggregated over township i to estimate

$$P_i = \alpha + \beta t_i + \theta RS_i + \gamma(t_i RS_i) + \varepsilon_i. \tag{1}$$

In (1), P_i represents measures of parcel shape complexity (average number of sides, average perimeter-to-area ratio) and the variation in parcel dimensions (standard deviation of sides, standard deviation of perimeter-to-area ratio, standard deviation of alignment, coefficient of variation of size). Parameters are t_i, the average terrain ruggedness in the township, and RS_i, the fraction of the township under RS demarcation. The observations are weighted by the number of parcels in the township, and the coefficients include α, which represents the parcel outcome found in flat areas under MB demarcation; β, which represents the change in MB outcomes for a unit change in terrain ruggedness; and $\theta + \gamma(t_i)$, which represents the effect of the RS system on the outcome in a specified terrain.

We estimate equation (1) using the larger sample that includes land governed by both MB and RS and show the results in table 3. We report estimates of both observed parcel complexity of shape (perimeter-to-area ratio and number of sizes) and the variation of parcel shapes and sizes under the two systems. For these estimates, we have centered the shape variables at the dimensions of a square (perimeter-to-area ratio = 4; number of sides = 4), and the ruggedness variable is normalized in all columns so its coefficient represents a unit increase in the outcome variable for a standard deviation increase in ruggedness.[26]

The estimates of the constant in table 3 columns 1 and 2 confirm the information from figure 5 and imply that an average MB parcel has 5.6 sides and a perimeter-to-area ratio of 4.6 in flat land.[27] The estimates show that increases in ruggedness increase the complexity of parcel shapes, in terms of both the number of sides and the perimeter-to-area ratio. A standard deviation increase in terrain ruggedness increases the perimeter-to-area ratio by 0.2 and the number of parcel sides by 0.7 under uncoordinated MB demarcation. This change in shape choice reveals the implicit individual economic benefits from allowing claimants to shift to irregular boundaries to account for varying topography.

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[26] In the plots in fig. 5, we used the raw values for the number of sides and the perimeter-to-area ratios.

[27] The estimated constant is equivalent to $\alpha - 4$ from eq. (4) because we centered the outcome data on the values for squares.

TABLE 3

ESTIMATES OF PARCEL SHAPE COMPLEXITY AND VARIATION: TOWNSHIP LEVEL IN VIRGINIA MILITARY DISTRICT REGION

	SHAPE COMPLEXITY		SHAPE, SIZE, AND ALIGNMENT VARIATION			
INDEPENDENT VARIABLE	Perimeter-to-Area Ratio (1)	Number of Sides (2)	Perimeter-to-Area Ratio SD (3)	Number of Sides SD (4)	Parcel Size Coefficient of Variance (5)	Alignment SD (6)
RS	−.32***	−1.37***	−.46***	−1.76***	−.33***	−9.02***
	(.05)	(.15)	(.06)	(.15)	(.06)	(.47)
Ruggedness	.20***	.70***	.12***	.31***	.25***	1.17***
	(.01)	(.12)	(.01)	(.10)	(.03)	(.19)
RS × ruggedness	−.20***	−.68***	−.13***	−.28***	−.25***	−.84***
	(.04)	(.12)	(.04)	(.10)	(.04)	(.22)
Constant	.55***	1.62***	.79***	2.37***	.80***	9.94***
	(.03)	(.14)	(.04)	(.14)	(.04)	(.45)
R^2	.44	.77	.40	.70	.34	.78
F-statistic	155	120	121	126	69	480

NOTE.—Results are reported from regression models of parcel shape characteristics. Dependent variables are column labels. The parameter estimates for the independent variables are reported with robust standard errors in parentheses. Observations ($N = 437$) are weighted by number of parcels in a township. RS = rectangular system; SD = standard deviation.

*** $p < .01$.

Table 3 columns 1 and 2 also show that parcels in the RS have fewer sides and a lower perimeter-to-area ratio, indicating that the RS constrains parcel shapes. When the constraints of the RS are imposed, an average parcel in flat land yields 4.2 sides and a perimeter-to-area ratio of 4.2. Although this average is much closer to square than the MB average, it is not exactly square.[28] Indeed, the RS varied in precision in its early years as surveyors learned to implement the system, and there were also general RS adjustments noted in Section II (Pattison 1957; White 1983; Knepper 2002; Hubbard 2009).

The estimate of γ—the coefficient on the interaction term—is nearly identical in absolute value to the estimate of β, implying that the restrictions on parcel shape prescribed by the RS are resilient to changes in terrain. The estimates shown in table 3 columns 3 and 4 show the effect of ruggedness and demarcation regimes on the variation in parcel shape. Also, terrain ruggedness significantly increases the variation of parcel shapes within MB townships, but the outcomes in the RS are by and large immune to this effect.

The estimates shown in table 3 columns 5 and 6 show the effect of ruggedness and demarcation regimes on the variation in parcel size and alignment. The estimates in column 5 show that parcels in RS townships exhibit about one-half the size variation in flat land compared to MB, and as terrain becomes more rugged, MB variation increases whereas RS variation is unaffected. The estimates in column 6 show that the standard deviation of parcel alignment is reduced under the RS. In particular, the estimate of α is approximately 10 and is statistically significant, indicating that MB parcels are not perfectly aligned in flat land. The estimate, however, is statistically significantly different from 13, the standard deviation expected if parcel position were random.[29] This outcome as well as the patterns indicated in figure 4A suggest that among early nineteenth-century settlers there was some informal local coordination of parcel alignment in MB townships in flat terrain, even in the absence of a grid system.

Land Values under RS and MB

To estimate the effects of demarcation regimes on land values, we employ data from the two township samples (full and border) of average

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[28] Although the number-of-sides estimate is statistically indistinguishable from 4, the perimeter-to-area ratio is significantly different at the 5 percent level. This deviation from a square likely reflects the influence of areas in which independent early government surveys within the RS met at awkward angles, and surveys were truncated along the VMD border.

[29] A randomly chosen alignment would be have continuous uniform random distribution over the range [0, 45] in degrees. The standard deviation of this distribution is 12.99.

per-acre farmland values constructed from the 1850 and 1860 censuses. We rely on township averages because they are the smallest spatial units we have from the census data. The basic estimating equation is

$$\ln V_i = \alpha + \beta t_i + \theta \mathrm{RS}_i + \gamma(\mathrm{RS}_i t_i) + \boldsymbol{C}_i' \Phi + f(X_i, Y_i) + \varepsilon_i, \quad (2)$$

where V_i is the per-acre land value in the ith township, $\boldsymbol{C}_i$ is a row vector of exogenous determinants of farmland values (e.g., soil quality, distance to market),[30] and $f(X_i, Y_i)$ is a function of longitude (X) and latitude (Y) coordinates and the associated regression coefficients. The RS demarcation variable (RS_i) takes two forms: in the full sample, it is the fraction of the township within the RS system, and in the border township sample, it is a binary RS indicator variable. In equation (2), θ represents the network and production benefits of RS, γ represents the forgone benefits from adjusting boundaries to terrain, and the total RS effect is represented by $\theta + \gamma(t_i)$.

Our control variables account for land characteristics, and we weight each observation by acres of farmland. Among the controls is a spatial control function based on longitude and latitude coordinates for each observation.[31] Including a spatial function in the specification allows us to control for potential confounding variables that flow continuously over space and take advantage of the discrete change in the demarcation system that occurs at the VMD border in order to estimate the RS effect.

Table 4 shows the estimates from eight specifications, four for each sample. The estimated coefficients for four specifications and two different samples are reported.[32] Specification 1 in each sample uses only ruggedness and the interaction term as controls and provides a useful benchmark for specifications 2–4, which use a more complete set of exogenous economic and spatial control variables. The results show a positive and statistically significant estimate of θ—the RS effect on land values in flat land—and a negative estimate of γ, indicating that the RS effect is smaller and perhaps even negative in more rugged terrain. As reported in the table, the full-sample estimates show a larger RS effect that is less sensitive to terrain compared to the border sample.

To discuss the size of the estimated effects, we rely on specification

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[30] We exclude other possible determinants of land value such as population density and farm size in our specification because of their complicated relationship with the demarcation system and land values, issues we address below.

[31] Unless otherwise stated, we use linear functions of latitude and longitude: $f(X, Y) = \rho_1 X + \rho_2 Y$. Higher-ordered polynomials for $f(X, Y)$ are used as a robustness check later in the paper. Coordinates are measured at the centroid (geometric center) of the township or county observation.

[32] Although land value data are drawn from the 1850 and 1860 censuses, all values are in constant 1860 dollars, and we add a year fixed effect to account for overall growth in land values between the census years. We experimented with specifications (not reported here) that controlled for percentage born in Virginia and Ohio, and our results did not qualitatively change.

TABLE 4

ESTIMATE OF LAND VALUE PER ACRE (1860$): TOWNSHIP LEVEL

INDEPENDENT VARIABLE	FULL SAMPLE				BORDER SAMPLE			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
RS	.18***	.39***	.31***	.34***	.25	.31**	.25**	.20
	(.06)	(.06)	(.07)	(.07)	(.15)	(.12)	(.12)	(.13)
Ruggedness	−1.62	−5.47***	−4.11***	−.78	3.20	−6.02**	−6.58***	−2.58
	(1.12)	(1.24)	(1.27)	(1.43)	(3.40)	(2.68)	(2.36)	(3.98)
RS × ruggedness	−3.87***	−3.22**	−2.51*	−2.64*	−5.77	−6.53	−6.72**	−6.36**
	(1.42)	(1.48)	(1.39)	(1.51)	(5.96)	(4.00)	(2.84)	(3.10)
Latitude and longitude	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Quadratic spatial function	No	No	No	Yes	No	No	No	Yes
Additional controls	No	No	Yes	Yes	No	No	Yes	Yes
Observations	774	774	774	774	135	135	135	135
Adjusted R^2	.213	.393	.431	.549	.082	.440	.524	.524
F-statistic	99.43	96.78	72.81	65.71	6.062	9.480	11.54	10.78

NOTE.—Estimated coefficients for the natural logarithm of per acre farmland values for four specifications for both the full township sample and the border township sample are shown. Heteroskedasticity-robust standard errors clustered at the township level are reported in parentheses. In specification 1, the outcome is only regressed on variables corresponding to the reported coefficients, a constant, and a year fixed effect. Specification 2 controls for linear functions of latitude and longitude. Specification 3 includes controls for terrain ruggedness, soil quality, distance to market town, and a quadratic in average farmer age. Specification 4 includes squared terms for latitude and longitude and a cross-product term. Observations are weighted by total acres of farmland. RS = rectangular system.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

3 in both the full and the border samples.[33] The full-sample estimates show a 31 percent increase in land values in flat land due to the RS, and the border-sample estimates show a 25 percent increase. When evaluated at the mean values of ruggedness, the RS effect is a 23 percent increase in land values in the full sample and an 8 percent increase in the border sample. In both samples, the distribution of ruggedness exhibits a considerable positive skew, and the effect at the median level of ruggedness is perhaps more instructive. At the median terrain value, the RS results in 27 percent higher land values per acre in the full sample and 17 percent higher values in the border sample.[34]

We find that as terrain becomes more rugged, there is a point at which the (per-acre) value of land under MB demarcation is larger than under RS.[35] In the full sample, this break-even point is at a ruggedness measure of 0.12 (about a 20 percent slope), but values greater than this level occur in less than 5 percent of the observations in our county sample. In the border sample, the break-even point is lower (at 0.04, or a 6 percent slope) but still rather steep for farmland. This difference in the border area is due to both lower estimates of the RS effect for flat land in that sample and the increased sensitivity of the RS effect to changes in terrain. Still, more than 80 percent of the border observations have values of ruggedness that are below this threshold.

Figure 6 uses our estimates to indicate the townships in the full-sample region, where per-acre land values are predicted to be higher under RS (*shaded*) and where there is no statistically significant difference in land value from switching the current demarcation system (*hatched*).[36] The areas shown in figure 6 where predicted land values are higher under RS are in the flattest part of the sample. The townships where there are no statistically significant shifts in land value from a change from the current regime (MB to RS or vice versa) are in the more rugged southeastern portion of the VMD region. Table 5 shows the summary

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[33] Although specification 4 controls more flexibly for continuous variation over space, the added quadratic terms are highly collinear with measures of terrain ruggedness in our sample and complicate our interpretation.

[34] We also developed a sample of 456 farms from Warren County, split by the RS and MB systems, using 1867 farm maps and 1870 census information. With those data, we estimated the impact of RS on land values relative to the MB and found similar effects. See Libecap and Lueck (2009) for details.

[35] This threshold value $\bar{t} = -\hat{\beta}/\hat{\gamma}$ comes from the estimate of eq. (4).

[36] We use a 5 percent significance threshold and the parameter estimates from the full sample from table 4 (specification 3). If we use the more conservative border sample, the pattern is similar, although there are more areas with no statistical difference in value and some in the southeast under RS, where values would be higher under MB. These effects, however, do not fully reflect the network benefits of the RS, and hence we rely on the broader sample that we believe is more representative of the overall contribution of the RS. The results also are shown for 567 townships in the 39-county region. This is a larger sample than used elsewhere, where we are more limited because of insufficient individual data in the census.
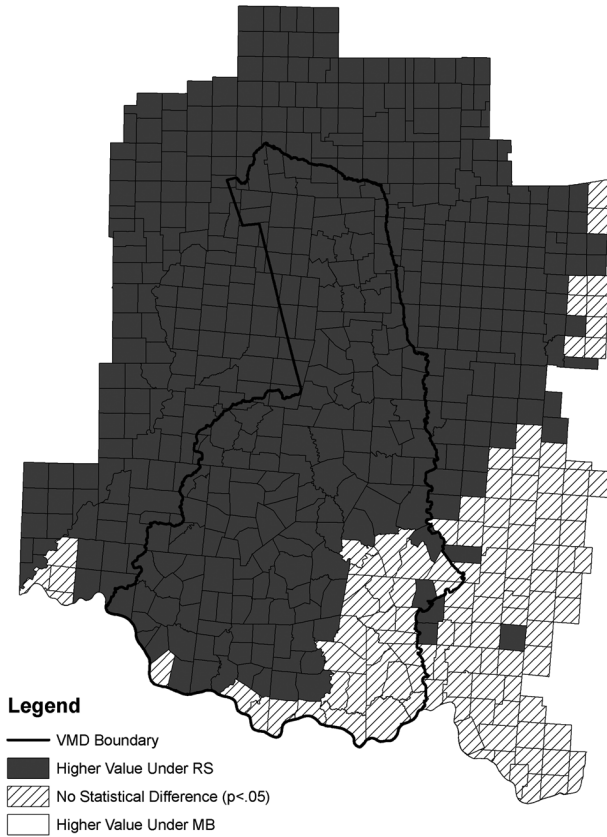
Fig. 6.—Effect of metes and bounds and rectangular system (RS) on land values. Value effects are from estimated coefficient values, using the full sample, with 5 percent significance (see table 5). VMD = Virginia Military District.

statistics for the slope ruggedness for the townships used in figure 6 and also shows the number of townships with predicted value changes for MB and RS.

Demarcation and Property Disputes

We view our results on land values as evidence that the apparent greater precision of property rights definition provided by RS is more valuable than the greater flexibility in allocations that MB allowed. We examine the history of property disputes, in order to investigate the source of these differences in MB and RS. Our findings indicate that RS is a more

TABLE 5
Terrain Ruggedness and Estimated Land Value Change with Change in
Demarcation Regime

	Ruggedness (% Slope)	Observations
Summary statistic:		
Mean	5.16	
Median	2.36	
Standard deviation	5.64	
Minimum	.54	
Maximum	24.50	
Predicted effect:		
Higher value under MB	>19.9	14
Higher value under MB ($p < .05$)	>100.0*	0
Higher value under RS	<19.9	553
Higher value under RS ($p < .05$)	<9.7	456

Note.—Calculated from estimated coefficients in table 4, full sample, specification 3, using 567 townships. MB = metes and bounds; RS = rectangular system.
* Actual cutoff value at $p = .05$ is larger but not well defined.

secure system of property rights, with attendant lower transaction costs, than MB.

The historical literature on American land policy repeatedly references conflicts over boundaries and titles in MB areas. Richard Anderson, a land surveyor in the VMD and in Kentucky (also an MB state) in the late eighteenth and early nineteenth centuries, reported that "perishable" or moveable landmarks such as trees and stones often created multiple claims to the same property, inviting disputes.[37] In his examination of Ohio lands, William Peters (1930, 26, 30, 135) concluded that there was more litigation due to overlapping entries, uncertainty of location, unreliable local property markers, and confusion of ownership in the nineteenth century in the VMD than in the rest of Ohio combined. By centralizing and fixing boundaries, RS should have minimized this potential for border conflict and lowered the costs of enforcing property rights.

Lacking a coordinated framework for positioning and demarcating properties under MB, parcels often were delineated with respect to one another, as indicated by the evidence of some aligned parcels as shown in figure 4A and in the empirical results reported in table 3, column 6. If, however, adjacent property borders could not be verified conclusively, if that survey were found to cover too much land, or if the surveys overlapped, then titles for each of the affected properties could be voided by the courts. The 1835 case *Porter v. Robb* (7 Ohio Pt. 1 206, 211) illustrates the problem of boundary mistakes in an uncoordinated

[37] Richard Clough Anderson Papers, University of Illinois Library, Champaign-Urbana.

system: "Stephenson's entry calls for the upper line of Dandridge; Waters' calls for the upper line of Stephenson; Crawford's for that which is the north line of Waters'. . . . The return of the county surveyor shows that Dandridge's upper line is twenty poles too far up the creek. . . . This twenty poles is on Stephenson's entry. . . . This threw Stephenson twenty poles on Waters' entry. . . . This caused Crawford, by having to begin at a corner of Waters', to be thrown a considerable distance farther from the Ohio."

This excerpt clearly shows how mistakes or disputes over demarcation for a parcel under MB adversely affected a long chain of parcels beginning with those adjacent to the parcel in question. This potentially costly string of problems has its source in decentralized and uncoordinated demarcation under MB. Under RS with its coordinated network, such problems could not occur because each parcel was independently located in the geographically based system.

Additionally, it was not uncommon for a survey registered with the local land office to have property descriptions that were too vague for a succeeding claimant to know exactly where the property was situated in order to locate around it. Indeed, Hutchinson (1927, 117) and Rubenstein (1986, 240) described a practice of surveyors in the VMD and in adjacent Kentucky of recording claims very broadly and vaguely in an effort to preempt later claimants, who would be challenged with assertions of superior equitable title.[38]

Further, because shapes and sizes were not uniform and because property boundaries were vaguely described under MB, claimants inadvertently claimed the same land (*McCoy's Lessee v. Galloway*, 3 Ohio 282 [1827]; Hutchinson 1927, 117; Rubenstein 1986, 240). Ohio court opinions repeatedly noted the difficulty of titles under MB (e.g., *Nash v. Atherton*, 10 Ohio 163, 167 [1840]) and that conflicts with associated title uncertainty could last a long time. For example, in 1880 in *Morrison v. Balkins* (6 Ohio Dec. repr. 882), the court ruled on an effort to quiet title to some 120,000 acres that had been in dispute for 60 years.

To more systematically examine the effect of demarcation on land disputes, we searched compendiums of nineteenth-century Ohio court cases and then turned to Westlaw and Lexis/Nexis for case reports (see the Appendix). The cases covered are those argued before the Ohio Supreme Court for properties under both MB within the VMD and RS for the rest of Ohio.[39] We divide the cases into three categories, although they often overlap: boundary disputes, validity of entry/patent disputes,

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[38] This practice is similar to the use of so-called submarine patents (Gallini 2002, 147).

[39] These had the greatest implications for case law but leave out conflicts presented before the lower Courts of Common Pleas, for which data were not readily available. The effect of any bias in this sample is unclear. The Supreme Court might have addressed the higher-valued cases, so that we are missing smaller border disputes.

TABLE 6
NINETEENTH-CENTURY OHIO SUPREME COURT PROPERTY DISPUTE RATES

Disputes (per 1,000 Parcels)	MB (VMD Region)	RS (Remainder of Ohio)	Ratio of Dispute Rates (MB/RS)
Boundary	1.46	.37	3.95
Validity of entry/patent	8.61	.26	33.12
Validity of survey	2.48	.08	31.00
Total	12.54	.71	17.66

SOURCE.—Geospatial data set in McDonald et al. (2006).
NOTE.—Data are normalized by dividing by the total number of parcels corresponding to each group and multiplying by 1,000. Total number of parcels in metes and bounds (MB) = 6,856 and in rectangular system (RS) = 61,688. VMD = Virginia Military District.

and validity of survey disputes. Boundary disputes are cases in which title was not also at issue. Validity of entry disputes are cases in which titles were challenged for a variety of reasons. Validity of survey disputes are cases in which the property survey was questioned.[40]

Table 6 summarizes the results. It shows dispute rates per 1,000 parcels under MB and RS and the ratio of the dispute rates: MB rates divided by RS rates. It is clear that the rates are far higher for MB lands than for RS lands in all three categories of disputes, although validity of patents and surveys was a central source of conflict under MB. Overall, the data show that the dispute rate is nearly 18 times higher under MB for the nineteenth century than in the rest of Ohio.

Within the RS, boundary disputes were generally adverse-possession cases involving conflict between adjacent landowners over land located along their common property boundaries. The validity of title cases in RS involved failure to comply with procedural requirements for obtaining patents or filings with county recorders or land offices under federal land law. Survey dispute rates were much less frequent under RS, reflecting the requirements that individual surveys follow section lines, that parcels be squares, and that government-hired surveyors lay out sections, townships, and ranges in the grid before entry under the provisions of the federal law.

[40] Boundary disputes not involving title challenges include cases in which two different surveys claim the same land (e.g., *McArthur v. Phoebus*, 2 Ohio 415 [1826]). In these cases, the general question is which survey was valid and which was invalid. Boundary disputes involving title validity included cases in which rejection of the boundary included rejection of the deed due to multiple surveys of and titles to the same land. Validity of deed cases beyond boundary disputes hinge on whether a deed or patent validly describes the land it grants.

TABLE 7
ESTIMATES OF LAND TRANSACTIONS: COUNTY LEVEL (1860)

Independent Variable	(1)	(2)	(3)	(4)
RS	.45**	.47**	.71**	1.05***
	(.20)	(.19)	(.30)	(.31)
Latitude and longitude	No	Yes	Yes	Yes
Quadratic spatial function	No	No	No	Yes
Additional controls	No	No	Yes	Yes
Adjusted R^2	.10	.22	.25	.37
F-statistic	5.3	4.2	4.8	10.1

NOTE.—Estimated coefficients for four specifications of the natural logarithm of con-
veyances per farm are shown. Heteroskedasticity-robust standard errors are reported in
parentheses. Column 1 reports the simple correlation coefficient between the rectangular
system (RS) and the outcome. Column 2 controls for a linear function of latitude and
longitude. Column 3 adds controls for terrain ruggedness and soil quality. Column 4 adds
squared terms for latitude and longitude and an interaction. All specifications include a
constant. Observations ($N = 39$) are weighted by total acres of farmland.
    ** $p < .05$.
    *** $p < .01$.

Land Market Activity under RS and MB

To examine the effect of demarcation on land market activity, we use
data for the 39-county region on the total number of land conveyances
by county collected by the State of Ohio commissioner of statistics in
1858 and 1859 (table 2, panel B).[41] To estimate the effect of demarcation
regimes on land transactions, we use

$$\ln T_i = \alpha + \beta t_i + \theta RS_i + C_i'\Phi + f(X_i, Y_i) + \varepsilon_i, \qquad (3)$$

where T_i is total conveyances (or transactions) for county i normalized
by the number of farms,[42] C_i is a row vector of exogenous determinants
of farmland values (e.g., soil quality, distance to market), and $f(X_i, Y_i)$
is the spatial control. The RS demarcation variable (RS_i) is the fraction
of the county within the RS system.[43] Estimates for four different spec-
ifications of (3) are reported in table 7.

   The results for all specifications indicate that there are substantially
more land transactions in RS areas relative to MB, although the results
are sensitive to the set of control variables used. The estimates from
table 7 columns 3 and 4 imply that conveyances per farm are 71–105

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   [41] If the RS resulted in nonoptimal constraints in rugged terrain, transaction activity
could reflect subsequent parcel adjustment. As we show, however, in our sample of very
flat terrain, this effect may be small. Without time series, we have no way to observe these
patterns.
   [42] We average the number of transactions from 1858 and 1859 and divide by the number
of farms reported in the 1860 U.S. Census of Agriculture.
   [43] Because we have no expectation about the role of the RS_t interaction for land market
activity under varying terrain, we do not include an interaction term in our estimates.

percent greater in RS areas than in MB regions.[44] Although the sample is small, the estimates suggest that key advantages of centralized demarcation and contributors to higher land values were the lower costs of transacting land under RS. This is consistent with the interpretation of RS clarifying and strengthening property rights to land and providing information about its location. This was an important contribution in a region undergoing dynamic economic changes from in-migration, new production technologies, and new industries.

Net Benefits of the Rectangular System

The estimates of the effects of RS on land values suggest significant early benefits from RS demarcation, but these values alone do not indicate whether the net benefits were positive. By coupling available information on the costs of establishing the RS with our estimation results from the land value analysis, we calculate the net value added from the RS system, relative to MB, for the 26 counties in our study region that are wholly or partially outside the VMD. To calculate a NPV of the RS, we use a formula that makes use of our estimated RS premium from the land value estimates and available data on survey costs:[45]

$$\text{NPV}^{\text{RS}} = (\text{RS premium per acre} \times \text{acres in RS}) \quad (4)$$
$$- (\text{RS survey costs per acre} \times \text{acres in RS}).$$

The benefits of RS in equation (4) are the estimated RS premium per acre times the 5.9 million RS acres in the sample region. The costs of RS in (4) are the per-acre survey costs times the same area. We expect there to be continued costs of enforcement under MB, but the arguments in (4) implicitly assume that this is capitalized into the value of land governed by MB, and thus the RS premium incorporates this factor. The RS benefits come from the estimates of θ (direct RS effect on land values) and γ (effect of RS when interacted with topography) from the township border specifications in table 4.[46] Benefits are calculated at the county level and then summed to get the total RS benefits in the 26 counties in our sample area that are governed by the RS regime.

[44] When we add controls for population density of the county, the estimated increases in conveyances per farm for specifications 3 and 4 become 41–73 percent and are statistically significant. When we further control for average farm size, the estimated increases are 74–104 percent and are statistically significant.
[45] The formula in (4) is imperfect, however, because it does not include the costs of designing the RS and of individually demarcating plots under the alternative of MB, neither of which is available.
[46] These border-sample estimates are more conservative than the full-sample estimates and more stable across specifications. Also, because the RS treatment variable is binary, the interaction term does not contain any measure of ruggedness from MB parts of the township. We use specification 3, where $\beta = 0.25$ and $\gamma = -6.72$.

For each county i, we first calculate the per-acre premium (δ_i) from the RS in county i using the estimates of θ and γ. This premium may be positive or negative, depending on the terrain ruggedness of the county, and is calculated by using the predicted land values for each county (see the Appendix for details).[47] Using this premium, we then calculate the RS benefit for county i as the product $V_i A_i RS_i \delta_i$, where V_i is the average census (1860) farmland value per acre, A_i is the total farm acreage in county i, and RS_i is the fraction of county land governed by the RS. When these county RS benefits are summed over the 26 counties, we have an estimated \$7 million (1860 dollars) increase in farmland value attributed to the RS system.[48] This implies a per-acre benefit of approximately \$1.18 (1860 dollars).

To estimate the costs of the RS, we rely solely on survey cost information because of the data limitations on administrative and other setup costs. Historians, including Stewart (1935), Pattison (1957), and White (1983), discuss early survey costs and find that they ranged from \$2 to \$3 per mile. It was common that only sections or half sections were surveyed along with township and range lines by federal surveyors. Counting township borders (avoiding duplication for adjacent townships) as well as borders for section and half section lines in the RS region and using the higher survey costs of \$3 per mile gives total survey costs of approximately \$82,000–\$123,000, depending on whether sections or half sections were surveyed.[49] Even though these survey cost measures are rough estimates, they clearly are swamped by the direct benefits of the RS.

We can also estimate what land values might have been if the VMD had been under RS demarcation. A calculation similar to the one used for RS lands indicates that another \$7 million in farmland value could have been gained by implementing an RS in the VMD.[50] This is roughly 8 percent of the total value of farmland in the VMD (1860 census). The potential per-acre gain in the MB areas is estimated at \$2.04, which actually exceeds the gain found in the RS counties in our sample. The reason for this higher per-acre effect in the VMD compared to the surrounding RS land is that there is slightly flatter land in the VMD on average than in the surrounding RS lands in our sample.

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[47] These estimates imply a 25 percent increase in value for flat land from RS, and it decreases in rougher topography.

[48] In 2009 dollars, this corresponds to \$186 million, using the consumer price index.

[49] Using GIS software, we measure the lengths of county and township borders. We specify shared borders to avoid double counting. Using the total number of non-VMD townships in each county, we add 60 miles of surveying per township for our estimate of costs using sections and 96 miles of surveying per township for half sections. The total mileage from the categories is multiplied by \$3 for total cost.

[50] Survey costs would be lower than those calculated for the RS counties, as the VMD occupies about 70 percent less area.

Long-Term Effects

In this subsection, we examine the persistence of the RS value benefits for early nineteenth-century Ohio into the modern era, and we consider their implications for economic growth. Long-term effects of the RS through the twentieth century are estimated using panel data at the county level. We pool the cross-sectional specification in equation (2) over time τ to estimate

$$L_{i\tau} = \alpha_\tau + \beta_\tau t_i + \theta_\tau RS_i + \gamma_\tau(t_i RS_i) + \boldsymbol{C}_i'\Phi\tau + f_\tau(X_i, Y_i) + \varepsilon_{i\tau}, \qquad (5)$$

where L_i is the (long-term) outcome measure, and separate coefficients are estimated for each time period, τ. In different specifications, L_i is the natural logarithm of farmland value per acre, the natural logarithm of population density, and the fraction of county area in farmland. These are county-level panel data taken from the 1850–1997 U.S. census. Estimating specification (5) allows us to examine the pattern and duration of economic outcomes related to the demarcation system.

Table 8 reports period-specific RS coefficient estimates θ_τ. As shown in the table, the RS areas have significantly higher farmland values. This positive RS effect persists, although it varies considerably between time periods. The percentage increase in land values is comparable to, and often larger than, the values found in the full-sample specification at the township level. RS counties are also associated with higher population densities. This relationship becomes larger and more significant over time, suggesting faster urbanization in RS counties. Correspondingly, we see gradually less county land devoted to agriculture in the RS region over time. Although we do not have a complete data series for the time period examined, the number of manufacturing establishments as listed periodically in the U.S. census between 1850 and 1950 also expands in the RS region relative to the MB.[51]

The reported results in the table suggest long-lasting transaction cost and network advantages from the centralized RS that contributed to greater economic growth in its areas, relative to those under the decentralized MB regime. The history of frontier settlement suggests how initial demarcation differences could have continuing economic effects.

During the nineteenth century, U.S. frontier areas competed intensely for settlers. Land was the abundant factor, relative to labor and capital, and regional boosters sought to differentiate their locations by developing transportation sites and emphasizing natural resource endowments (e.g., coal, soil) to attract additional settlement, entrepreneurs, and business (Boorstin 1965, 123; Hamer 1990, 34; Cayton 2002, 25).

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[51] Kerr and Kominers (2010) describe how agglomeration forces influence the formation of firm/market clusters in a manner that may have applied in the nineteenth-century U.S. frontier.

TABLE 8
LONG-TERM EFFECTS: ESTIMATES OF RS COEFFICIENTS, COUNTY LEVEL

| | OUTCOME VARIABLE | | |
YEAR	ln Farmland Value/Acre	ln Population Density	Fraction of County in Farmland
1850	.37	.81**	.11
1860	.46**	.87**	.07
1870	.54**	.95***	.04
1880	.57***	.96***	.01
1890	.48**	1.10***	−.03
1900	.48**	1.20***	−.05**
1910	.31	1.37***	−.05**
1920	.19	1.48***	−.07**
1925	.38*	1.55***	−.09**
1930	.59**	1.62***	−.09*
1935	.52**	1.61***	−.12***
1940	.55**	1.60***	−.14***
1945	.46**	1.67***	−.16***
1950	.47**	1.73***	−.16***
1954	.46**	1.78***	−.14**
1959	.64**	1.82***	−.21***
1964	.46**	1.85***	−.24***
1969	.46**	1.88***	−.27***
1974	.39***	1.87***	−.28***
1978	.21	1.84***	−.27***
1982	.28**	1.83***	−.26***
1985	.60***	1.83***	−.28***
1992	.43**	1.82***	−.27***
1997	.38**	1.80***	−.28***
R^2	.90	.52	.82

NOTE.—Estimated coefficients on the rectangular system (RS) variable from eq. (5). The spatial controls are latitude and longitude of the county centroid and an interaction between the two. Standard errors are clustered at the county level and not reported. Population data for 1925, 1935, 1945, and 1954 were not directly available and were averaged from the nearest available data before and after the missing observation. Observations ($N = 936$) are weighted by county acreage.

  * $p < .1$.
  ** $p < .05$.
  *** $p < .01$.

Communities unsuccessful in this initial competition diminished in importance and faded as population and commercial centers over time (Monkkonen 1990, 128; Wade 1996, 33–35, 66, 336).

In this competitive setting, the transaction cost advantages of the RS in coordinating demarcation, in raising land values, in reducing disputes, in promoting road and other infrastructure investment, and in facilitating land transactions would be especially critical. These were developing agricultural societies in which land was (and is) the major
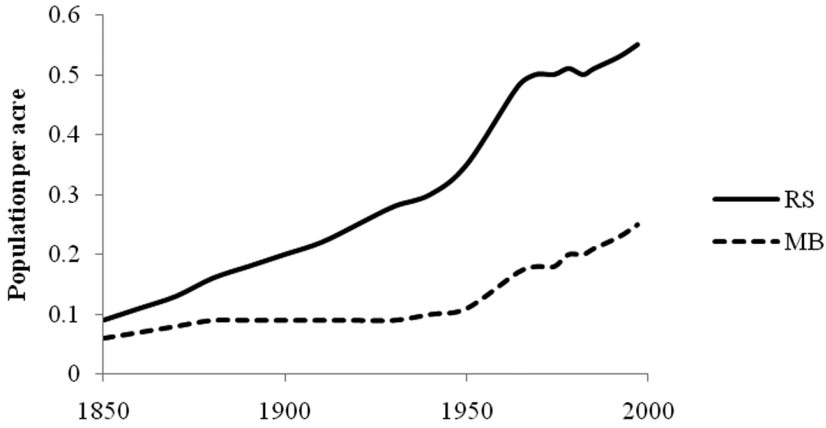
F_{IG}. 7.—Population density over time in rectangular system (RS) and metes and bounds (MB) regions in our sample. Averages are taken from county-level population census data and weighted by total county acreage. Averages from counties that straddle the Virginia Military District border are additionally weighted by the fraction of county area in each demarcation region.

asset, land markets were critical parts of the economy, and capital gains in land were the major sources of wealth accumulation (Ferrie 1994).

Figure 7 shows the population density over time in the 39-county VMD region of Ohio that used both RS and MB demarcation. It is apparent from the figure that the two areas, otherwise similar in initial natural and demographic conditions, had very different subsequent population growth patterns from 1850 through 2000. The RS area grew, whereas the MB area lagged.[52] Because the demarcation system was the major difference between these regions, we speculate how this property institution may have influenced the distribution of economic growth.

It is plausible that these differential patterns are rooted in the initial competitive advantage of the RS in attracting settlers due to its beneficial effects on property security, use, and exchange. Higher population densities in turn generate path dependencies in attracting further in-migration, market development, and economic activity in the manner outlined by Glaeser and Gottlieb (2009) and illustrated for portage sites for eastern U.S. cities by Bleakley and Lin (2010). The experience of differential demarcation regimes, one that allowed for individualized adaptation to terrain and one that centralized and standardized parcels for broader economic activities, suggests the micromechanics by which property institutions can affect long-term economic growth.

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[52] See Duranton (2007, 2008) for how agglomeration effects can differentially affect the growth of cities.

V.   Summary Remarks

We exploit a natural experiment in land demarcation systems in nineteenth-century Ohio to examine the effects of two fundamental property rights institutions: MB and the RS. We find that RS leads to higher land values, fewer border and title disputes, and more land transactions. There are substantial net gains from implementing the RS in our study region and similar potential net benefits from converting from MB. The RS effect persists into the late twentieth century. These findings demonstrate the contribution of the RS as a coordinating institution that clarifies property rights and lowers transaction costs throughout the network. These systemwide benefits expand land markets by defining property rights clearly with uniform, useful shapes; aligned, straight boundaries; and standardized addresses. The rigidity of the grid, however, limits individual parcel modification in response to topography. Terrain ruggedness mitigates the advantages of RS.

The trade-offs of centralized and localized demarcation systems are similar to those encountered in requiring uniformity in other institutions, such as standardization in language, currency, measurement of commodities, and uniform contracts. Some value is lost, particularly when local choice or practices are important, but value is gained in network benefits and lower transaction costs.

Despite the demonstrated benefits of RS, the patterns of MB and RS demarcation exogenously imposed in the eighteenth century remain today. This persistence indicates that the net gains from institutional change in shifting from MB to RS in rural areas, once in place, are low because of the adjustment costs involved. To change demarcation, the adjacent incumbent property owners must agree on boundary adjustments and the distribution of the costs and returns of refencing, new building and road construction, past investments in land, and heterogeneous land quality. Further, the network contributions of the RS are public goods that are not fully internalized by individual landowners in demarcation adjustment. The advantages of the RS network require a large area and a stable sovereign or owner to capture the long-term gains, so that RS is not worth the setup cost in all situations, especially in the most rugged topography. Finally, changes in technology can dramatically alter the cost of implementing demarcation systems. Before the eighteenth century, large-scale surveying was prohibitively costly, so something like MB was all that was possible.[53] Global positioning systems, GIS, and other geographic technologies that allow the demarcation of irregular boundaries can make MB parcel boundaries more permanent,

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[53] The Romans, however, had mastered surveying and used it to implement their own RS system (Libecap and Lueck 2011). Among other things, the fall of Rome led to the loss of the technology of surveying, for a millennium.

but MB would still not provide the network benefits contained in RS demarcation.

Appendix

A. Observations

Geographical boundaries for Ohio counties, townships, parcels, and the VMD were obtained from the shape file published in McDonald et al. (2006). The shape file represents a digitized map of the original land subdivisions in Ohio (OLSO), styled after Sherman's (1922) map. The "original" land subdivisions represent very early ownership patterns, although they do not appear to have been the first sales of federal or Virginia land to private claimants. Some of those transactions were very large, and no parcel is of that size. Land speculation and subdivision were common throughout the Ohio frontier, and these parcels were subdivided as census data on farm sizes reveal. Farms were much smaller still. The mean parcel size in the RS was 637 acres, with a standard deviation of 113; for the VMD, the mean was 813, with a standard deviation of 611. Mean farm size (acres) for 1850 in MB was 173 (SD = 235), and in RS it was 130 (SD = 59). For 1860, the MB mean was 157 (SD = 235), and the RS mean was 130 (SD = 59). (Parcel data are from Sherman [1922], and farm sizes are from the 1850 and the 1860 census sample.)

B. Definition of Variables

Perimeter-to-area ratio of parcel.—Perimeter (feet) and area (square feet) were calculated for each parcel using the OLSO data set (McDonald et al. 2006). Perimeter-to-area ratio is calculated as perimeter/area$^{1/2}$.

Number of parcel sides.—Sides to a parcel are calculated by counting polygon vertices from a modified version of the OLSO data set (McDonald et al. 2006). Polygons in the original data set contain redundant vertices that are artifacts of the digitization process. To correct for this, we modified the data set with an algorithm based on a method developed by Douglas and Peucker (1973) and Lee (1996). The remaining sample represents the unique vertices of the parcels.

Parcel alignment.—Our parcel alignment variable is the deviation in degrees of the parcel's longest side from true north and is designed to measure deviation from the RS baseline of north-south alignment. To calculate alignment, we first measure θ, the orientation angle of the longest side of a parcel from the OLSO data set (McDonald et al. 2006). The angle θ is measured from a true north-south baseline and has the range $[-90, 90]$ measured in decimal degrees. We calculate alignment as the minimum of the pair $(|\theta|, (90 - |\theta|))$ in order to equate the multiple values that represent the same parcel alignment. The resulting range of alignment is $[0, 45]$ and is best suited for measuring square parcels. To illustrate, consider the measure of alignment for a square. Since the choice of the longest side is arbitrary, the value of θ for the square has four distinct possibilities. Our alignment measure, however, will be the same, regardless of which side is chosen. The capability of GIS software means that our

alignment variable is not a perfect measure of parcel alignment. There are two issues. First, ideally we would measure the angle of the longest axis of a parcel to handle irregular shapes, but GIS software can measure only smooth sides of parcels. Second, in general, measuring angles of parcels from a north-south baseline will yield a measure that has the range $[-90, 90]$ since values larger than $|90|$ are redundant. But since GIS will always identify a long side of a parcel, it will calculate dramatically different values for parcels that are in practice perfectly square and aligned with each other. Our measure, which limits values to $[0, 45]$, solves the problem of squares but underestimates the variation in alignment for nonsquare parcels, which are overwhelmingly found in MB demarcation. For more information, contact the authors.

Ruggedness.—Ruggedness indexes the average surface slope of the terrain within the boundaries of an observation (township, county). Slope is calculated from 30-meter (1 arc second) digital elevation models taken from the U.S. Geological Survey National Elevation Dataset. The slope of a given cell in a digital elevation model is calculated using the change in elevation from eight neighboring cells with a range of $[0, 90]$, where 0 represents flat land. We calculate ruggedness as slope/90, with a possible range of $[0, 1]$. For more information, contact the authors.

Distance to market.—Represents the straight-line distance (miles) between the centroid of an observation and the nearest county seat. Locations of county seats were manually digitized from a map of Ohio county seats prepared by the Ohio Department of Natural Resources (2002).

Stream density.—We calculate the length of streams (miles) within county borders. Stream density is calculated as length of streams/area$^{1/2}$. Only streams classified as having year-round flow were used. Stream data come from a hydrography shape file based on digital line graph data from U.S. Geological Survey quadrangle maps and prepared by the Ohio Department of Natural Resources (2002).

Percent prime farmland.—Represents the fraction of area classified as "prime farmland" within the boundaries of an observation. Soil classifications are taken from microdata in the Natural Resources Conservation Service Soil Survey Geographic Database and are based on inherent soil characteristics. The measure does not include areas classified as "prime farmland (when irrigated)."

Farm value.—The U.S. Census of Agriculture reports farmland value that includes the value of land and buildings as well as total farm value that additionally includes the value of livestock and implements. In the paper, we report estimates using the farmland value, although we have also estimated our specification using total farm value and found similar results.

Spatial controls.—The two-dimensional spatial control coordinates (X, Y) are in terms of distance and are calculated at the centroid (center of mass) of observations from the OLSO data set (McDonald et al. 2006). The coordinates are derived by transforming spherical latitude and longitude values to a two-dimensional surface through the process of map projection.

C. Data Sampling

VMD and adjacent counties.—The following 39 counties included in the analysis are listed with percent in VMD in parentheses: Adams (100), Allen (0), Auglaize (0), Brown (100), Butler (0), Champaign (32), Clark (18), Clermont (100), Clinton (100), Crawford (0), Delaware (14), Fairfield (0), Fayette (100), Franklin (40), Greene (67), Hamilton (9), Hancock (0), Hardin (41), Highland (100), Hocking (0), Jackson (0), Knox (0), Lawrence (0), Licking (0), Logan (58), Madison (100), Marion (15), Miami (0), Montgomery (0), Morrow (0), Pickaway (57), Pike (64), Ross (70), Scioto (48), Shelby (0), Union (100), Vinton (0), Warren (42), and Wyandot (0).

Township-level analysis.—Ohio data from the 1850 and 1860 censuses of agriculture and population were entered into Excel from microfilm copies of the original schedules. The population schedules were obtained from Ancestry.com and Geneology.com, and the agriculture schedules were obtained from the National Archives. Both census years were sampled to secure a sample of sufficient size for analysis. We were not able to match census entries with the original parcel maps, which apparently is a common problem. Counties partially or completely in the VMD, as well as counties adjacent to the district, were sampled. For 1850, these included Adams, Allen, Auglaize, Brown, Butler, Delaware, Fairfield, Fayette, Franklin, Greene, Hamilton, Hancock, Hardin, Highland, Hocking, Knox, Lawrence, Licking, Logan, Madison, Marion, Miami, Montgomery, Ross, Scioto, Shelby, Union, Vinton, Warren, and Wyandot. For 1860, the same counties were sampled except for Miami, Shelby, Union, Vinton, Warren, and Wyandot, which were unavailable because these original surveys were destroyed before microfilming. In the analysis, individual observations are averaged by township. Because of the lost county data for 1860, we have 768 township observations rather than potentially 874 (437 townships in the VMD and adjacent counties each for the two censuses). The 1850 census was sampled at approximately a 10 percent rate, but a 5 percent rate was used for the more comprehensive 1860 census. Data from the U.S. Census of Agriculture were matched to the farmers population census records for the corresponding years. The matches were made using a searchable electronic database available by description at Ancestry.com. For both census periods, we were able to match an average of over 60 percent of the farms.

County-level analysis.—Annual conveyance data for 1858 and 1859 are from Nevins (1859, 1860, respectively). The mean value for the 2 years is used in the regressions: 1860 was not available to us. Population and county size are from the 1860 census (University of Virginia, Geospatial and Statistical Data Center, http://fisher.lib.virginia.edu/collections/stats/histcensus/php/county.php).

D. Ohio Court Analysis

We searched compendiums of Ohio court cases in the nineteenth century and then turned to Westlaw and Lexis/Nexis for case reports (Mason 1914; Estrich, McKinney, and Gulick 1928–35; Page 1936). The Lexis/Nexis search used the terms "boundary," "quiet title," "trespass," and "ejectment."

E.   Calculation of NPV for RS

The method to calculate δ_i, the per-acre RS premium for county i, is based on the estimate from

$$\ln(V_i) = \alpha + \beta \text{ruggedness}_i + \theta \text{RS}_i + \gamma(\text{ruggedness}_i \times \text{RS}_i) + \varepsilon_i.$$

It is possible to calculate δ_i from $\beta + \theta \times \text{ruggedness}_i$ for every county (using $\beta = 0.25$ and $\gamma = -6.72$ from table 4, border specification 3), but this method does not account for the county-specific land values. Instead, we first calculate two predicted values of V_i for each observation. When $\text{RS}_i = 1$, we use $V_i(1) = \exp(\alpha + \beta \text{ruggedness}_i + \theta + \gamma \text{ruggedness}_i)$, and when $\text{RS}_i = 0$, we use $V_i(0) = \exp(\alpha + \beta \text{ruggedness}_i)$. To obtain δ_i this way, we calculate (i) the value that the RS system adds to the RS observations (i.e., observations outside the VMD) and (ii) the value that RS would have added to the MB observations (i.e., observations within the VMD). For this we define the variable $V_i(j, k)$, where j is the location where observation i is found, and k is the demarcation system (i.e., $\text{RS}_i = k$). We therefore have the following values:

1. $V_i(\text{RS}, 1)$: The value of an RS observation (i.e., outside of the VMD) under an RS system. This is what we observe.
2. $V_i(\text{RS}, 0)$: The value of an RS observation (i.e., outside of the VMD) under an MB system. This is the counterfactual.
3. $V_i(\text{MB}, 0)$: The value of an MB observation (i.e., within the VMD) under an MB system. This is what we observe.
4. $V_i(\text{MB}, 1)$: The value of an MB observation (i.e., within the VMD) under an RS system. This is the counterfactual.

For existing RS land, the value added by the RS is $V_i(\text{RS}, 1) - V_i(\text{RS}, 0)$, and for existing MB land, the value added by the RS is $V_i(\text{MB}, 1) - V_i(\text{MB}, 0)$. To get the value added, we must multiply the observed value by a markup. We then divide the value-added equation by the observed value. For RS observations,

$$\delta^{\text{RS}} = \frac{V_i(1) - V_i(0)}{V_i(1)} = \frac{\exp(\theta + \gamma \times \text{ruggedness}_i) - 1}{\exp(\theta + \gamma \times \text{ruggedness}_i)}.$$

For MB observations,

$$\delta^{\text{MB}} = \frac{V_i(1) - V_i(0)}{V_i(0)} = \exp(\theta + \gamma \times \text{ruggedness}_i) - 1.$$

These values of δ are then used with data on acreage, share of land in each demarcation regime, and land values to calculate the countywide change in value from RS.

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