NBER WORKING PAPER SERIES

CREATING AMERICAN FARMLAND:
GOVERNANCE INSTITUTIONS AND INVESTMENT IN AGRICULTURAL DRAINAGE

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Working Paper 30081
http://www.nber.org/papers/w30081

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
May 2022, Revised May 2023

Previously circulated as “The Institutional Costs of Adaptation: Agricultural Drainage in the United States.” The authors thank Carl Kitchens, Karina Schoengold, David Hennessy, Michael Castellano, Mary Hansen, Dale Hoover, Ted Feitshans, Tom Grennes, Jane Shaw, P.J. Hill, and Bill Eagles, as well as participants at the 2022 ASSA Meetings, 2022 Cliometric Conference, 2022 NBER Summer Institute, NBER/USDA Conference on Economic Perspectives on Water Resources, Climate Change, and Agricultural Sustainability, and Iowa State Department of Economics seminar for their helpful comments. We are grateful for financial support from USDA: NIFA-Hatch #1017720 and NIFA-Multistate #1020662. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

Creating American Farmland: Governance Institutions and Investment in Agricultural Drainage
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NBER Working Paper No. 30081
May 2022, Revised May 2023
JEL No. N51,N52,Q1,Q15,Q54

ABSTRACT

The U.S. Corn Belt, relatively flat and covered with thick glacial soils, is famously responsible for the bulk of U.S. corn production. Development of this central part of the continent came with remarkable technical progress—in seed varieties, mechanization, fertilization, and pest control. Little of this development could have occurred without decades of investment in farmland itself, through the methodical application of drainage. We trace the economic forces that drove wide-scale drainage in the eastern United States and present empirical evidence that a key institutional innovation, the drainage management district, facilitated investment. Today, over 50% of corn produced in the Corn Belt comes from counties with high natural soil wetness requiring artificial drainage. States in our sample adopted drainage district laws between 1857 and 1912, and we estimate artificial drainage facilitated by management districts across all eastern states increased the value of agricultural land in counties with high natural soil wetness by 20-37% ($16.8-18.7 billion in 2020 dollars). Although the broader implications of drainage were largely unforeseen at the time, the conversion led to the loss of more than half of the 215 million acres of wetlands estimated to have existed in the contiguous United States at colonization.

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1 Introduction

A dramatic feature of 19th and 20th century agricultural development in the Midwest and Eastern U.S. was the application of drainage technologies to remove water from saturated lands. (See, for example, M. Bogue (1951) and A. Bogue (1963)). A significant portion of the United States, including the upper Midwest, the Mississippi River Basin, and the eastern Coastal Plain, have soil with high natural wetness; and of the 215 million acres of wetlands estimated to exist in the contiguous United States at colonization, 124 million had been drained by 2019, 80-87% for agricultural purposes (McCorvie and Lant, 1993; Tiner, 1984)[1]. Without drainage, much of the present-day Corn Belt, in Ohio, Indiana, Illinois, Iowa, and Minnesota, would be ill-suited for agriculture.

Drainage ditches in combination with subsurface drain tile (first used in Upstate New York in 1835 and adopted across the upper Midwest in the following decades) made drainage economical for widespread adoption. Some of the draining was carried out over broad areas of swampy and submerged land — like the 25 mile by 100 mile Great Black Swamp, which in the 1850s drained into Lake Erie at modern-day Toledo. Draining also occurred at smaller scales on undulating fields in Indiana, Illinois, and Iowa that were only partially or seasonally submerged. Settlers in these areas began farming higher, drier ground first and, over time, converted and drained lower swales into additional farmland. [2]

The distribution of poorly drained lands in North America coincides closely with relatively flat topography, in the upper Midwest as a result of glaciation and in the lower Mississippi and Southeast on the low lying coastal plain. Recognition of the value of drainage investment on such lands came early. In 1880, it was estimated that drainage of unimproved wetlands increased sale value by a factor of five (Prince, 2008). Yet capturing this increased value typically required significant coordination among neighboring landowners, which initially was absent.

Drainage from farm-scale to projects in excess of 100 square miles came to include the use

[1] Draining vast areas of the Midwest to convert prairie to farmland also had unintended consequences, notably 20th century algal blooms in lakes and a hypoxic Dead Zone in the Gulf of Mexico. (See, for example, Rabotyagov et al. (2014) and Mitsch (2017)).

[2] "Typically, the farmer who settled on the wet prairie broke his high ground first and looked to lowlands and sloughs for pasture and prairie hay. 'Knoll farming' one granddaughter of the pioneers called such practice. [Reference in original.] But prairie farms of this sort were not fully improved until artificial drainage had tamed the wet prairie."(Bogue, 1951, p.83)

of levees along the Mississippi and other waterways, often in combination with large pumping operations. Large or small scale, drained land was an essential input into the production of Midwestern crops—mainly corn, oats, and wheat. The coordinated action required to finance, route, and build the open ditches that served as outlet drains for tiled fields required innovations in drainage institutions, which combined with advances in engineering and tile manufacture allowed drainage to begin in earnest in the second half of the 19th Century (McCrory, 1928).

Ownership of American wetlands in the mid-19th century had passed from the federal government to the states through a series of Swamp Land Acts (1849, 1850, and 1860), which allocated to 15 states nearly 85 million acres, provided the lands were reclaimed via drainage (Fretwell, 1996). There was little or no initial improvement under the Acts, and potential farmland with poor natural drainage subsequently passed from state to county and ultimately individual ownership. Because piecemeal ditching was ineffective absent open outlet channels and coordination, the implementation of widespread drainage in a state required the passage of "[d]itch laws or drainage laws authoriz[ing] the organization of drainage undertakings which required groups of farmers to participate." (Prince, 2008)

In this paper we examine how the drainage management districts that resulted from these laws enabled broad-scale investment in drainage. Drainage often requires coordination over areas of several square miles (640 acres to the square mile) or more, while farms in the wet prairie counties typically were smaller, around 150 acres, due to both increasing costs of monitoring labor on larger farms and government land allocation policies (Allen and Lueck, 1998; Prince, 2008). Drainage districts allowed landowners to retain rights to operate their farms at the scale that economic factors dictated, while ceding one property right "stick" — drainage — to a local elected body. By granting to districts taxing and eminent domain authority, drainage district laws provided sufficient legal structure for collective investment in drainage, for which we find strong evidence.

We use a newly constructed data set on the passage of drainage district laws combined with data from the U.S. agricultural census from 1860 to 1969, as well as Geographic Information System data on soil wetness and topography, to compare agricultural outcomes in counties with high natural soil wetness relative to others. Our empirical approach relies on drainage district legislation providing benefits primarily in counties with high natural soil wetness. Today in the entire U.S., around 20% of improved agricultural production (by area and value) and around 38% of corn production occurs in the high natural soil wetness counties we examine. Using fixed effect estimators robust to the staggered treatment of drainage legislation, we show that after legislation, naturally wet counties saw relative increases in both improved acres and land value. We infer that the coordination afforded by these laws was sufficient for widespread investment. Our estimates suggest that the passage of drainage district laws increased the total value of agricultural land in these counties by 20% to 37%.[3]

Other technological innovations were critical to the development of modern American agriculture, notably the mechanization that allowed intensive application of power to farming (see Olmstead and Rhode (2001) on the impact and diffusion of the tractor) and the development of new seed varieties (see Olmstead and Rhode (2011)). Unlike these innovations, drainage represented the precondition work of creating farmland. Also different, the adoption of tractors occurred on a farm-by-farm basis, while drainage investment required coordination and novel governance institutions. While technical innovations in drain tile and excavation were critical to the development of drainage, we point as well to the importance of the transaction costs of collective action and the institutional innovation that addressed them.

Often, the literature on agricultural development and productivity has focused on technological change and the diffusion of knowledge and productivity enhancing inputs (see for example Griliches (1957) on hybrid corn). Other work has noted the apparent importance of institutions that allow the development of markets and management of risk (see Barrett et al. (2010)). Given long-standing questions about divergent agricultural productivity across countries (Gollin et al., 2014), our work suggests that institutional changes that lower transaction costs and facilitate collective investment in farmland are also important for explaining agricultural development.

2 Geology, Technology, and Drainage Economics

2.1 Agricultural Drainage

The macro-determinant of need for drainage in the United States is geology. The pre-Wisconsin and Wisconsin glaciation deposited swaths of flat, fertile soil across the upper Midwest. Figure 1

[3] There is some evidence that improved drainage also reduced malarial infections, increasing agricultural productivity (Malpede, 2022). Our estimates include any productivity related effects of drainage.

shows the high correspondence of drained acres in 1969 to the limit of the Wisconsin Ice Sheet, and to a lesser extent earlier ice sheets.[4] In the Southeast, the flat coastlines of the Atlantic Ocean and Gulf of Mexico seabeds have received repeated alluvial deposits from rivers over millions of years and rising and falling sea levels over millennia have deposited flat layers of marine sediment. Today, these flat coastal plains include the Texas Gulf, the Mississippi River Valley up to Illinois, and include almost all of Florida and the eastern seaboard. Southeast U.S. drainage corresponds closely to these plains.

In wet and poorly drained soils, excess water in the root zone of cultivated crops can create waterlogging, preventing the absorption of oxygen and drastically reducing yields or killing the plants entirely. Water tables can be lowered if nearby drainage provides a pathway for water out of the plant root zone. From Colonial times, open ditches were dug to remove excess standing water and to lower water tables. The earliest attempts at drainage in the Midwest, in 1818, were of this type (Prince, 2008, p. 205). However, ditches proved impractical for agricultural production in many cases. The ditches themselves, typically three to five feet deep, were labor-intensive and because they bisected fields at frequent intervals, they reduced the available land surface and made planting and harvesting difficult. Methods for draining water while maintaining the integrity of the land surface via underdrainage were required for practical use.

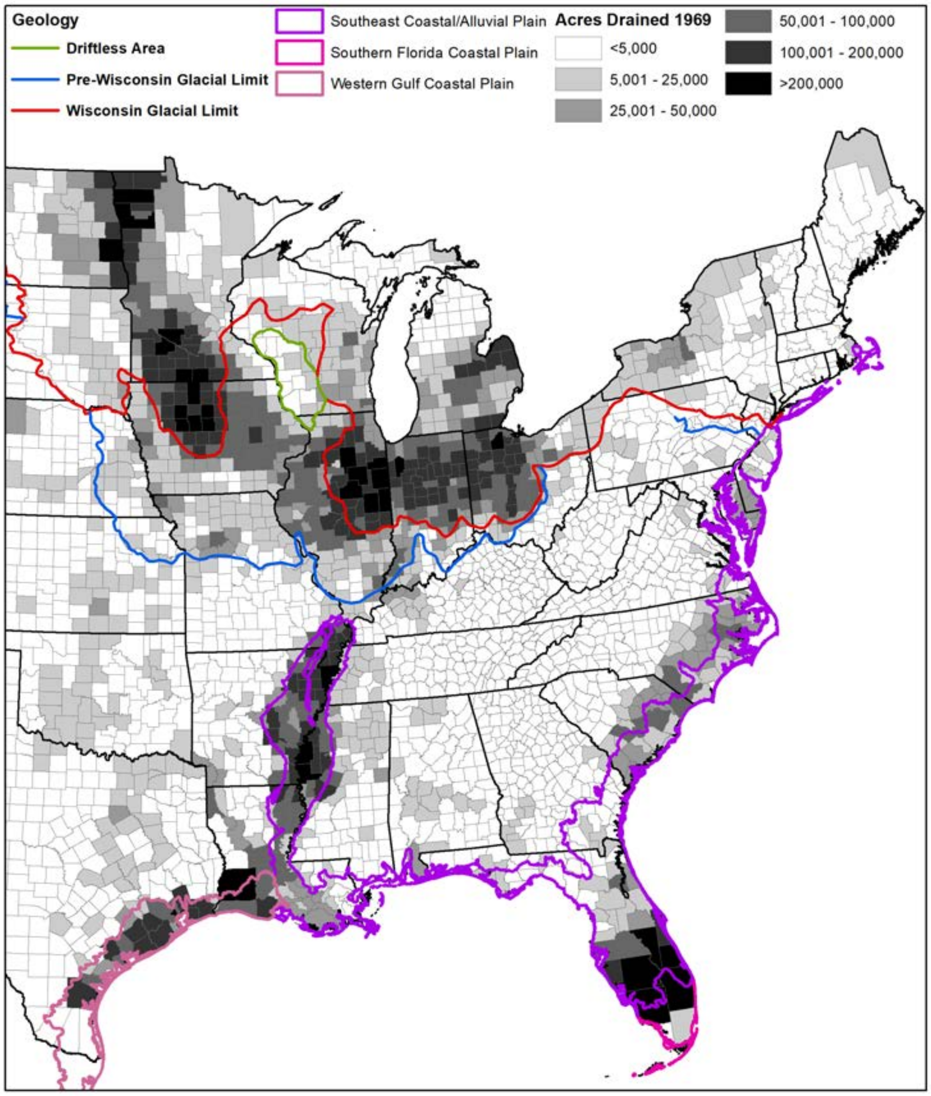
Stone and pole underdrainage was utilized in urban settings throughout the 19th Century, but was broadly uneconomical for agriculture. Other methods like buried brush drainage and mole drainage, where a thin leg attached to a torpedo-shaped implement is drug through the ground, were inconsistent and effectiveness declined within a few years of their first use.

The technology that ultimately replaced digging ditches in much of the country was the laying of drain tile. Installing drain tile involved digging a trench in which flat clay tiles were laid end to end and covered with a second, inverted-V, layer of tile, creating a porous water channel. The tile was covered again with soil. The resulting subterranean channel drained water above it down to its level, typically four feet below the surface. Unlike open ditching, installed tile was invisible and allowed farming above it.[5]

[4] It is interesting to note the complete absence of drainage in Wisconsin's Driftless Area, a region never under the ice sheet and therefore not flattened or deposited with glacial loess by retreating ice. This area is noted for its steep hills and valleys, in contrast to the surrounding areas.

[5] Modern land drainage follows the same principle, but involves the burying of perforated, corrugated, plastic tubing using advanced drilling and trenching machines. While still called "tile drainage," the technology bears little superficial

Figure 1: Drainage and Geology



Drain tile was not uniformly adopted, and its suitability varied across time and space. Tile was well suited for use in the glaciated regions of the Midwest but was not as successful on the Atlantic Coastal Plain and Mississippi Delta where the need for additional investment in levees and pumping as well as challenges related to flat topography near sea level limited its effectiveness. These regions developed drainage using a combination of in-field ditching, levee systems, pump houses, and tile in select areas.

Drain tile allowed subsurface drainage on the farm, but it was not useful unless the water had somewhere to go, typically into a network of off-farm drainage ditches. This required coordination, initially to solve free rider and holdout problems that arose in the construction of multi-user ditches. Coordination also was required once a drainage network was established because maintenance of an individual farm's drain tile had off-farm effects. Clogged drain tile on one farm could cause flooding on upstream farms in the network.

While digging ditches is an iconic example of low capital intensity production, advances in complementary digging technologies paralleled those in the manufacture of drain tile itself. Such advances beyond men and shovels included the development in the 1880s of the dipper dredge, the horse drawn Pratt Ditch Digger, and the Blickensderfer Tile Drain Ditching Machine. The latter could dig a four-foot ditch in only one pass, "powered by a single horse, one man, and one boy." (Yannopoulos et al., 2020) Application of fossil fuel power followed in 1892 with the introduction of the steam powered Buckeye Trencher. In 1908 gasoline-powered internal combustion engines began to replace steam engines, as they did in tractors (see Olmstead and Rhode (2001)). In the early 20th century, efficient dragline excavators came to replace dredges.

Like investment in agricultural production generally, the development of drainage was shaped by local fertility and climate as well as changes in input and output prices. For instance, the panic of 1873 and subsequent fall in farm prices reduced demand for drainage, while emerging transportation networks lowered the cost of moving tile, increasing the cost effectiveness of drainage investment. As we discuss in detail in the next section, our empirical approach sidesteps much of this heterogeneity in adoption timing and location by focusing on the effects of drainage districts and through the inclusion of county and state-by-year fixed effects.

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resemblance to its ancestor, and no longer involves clay tile.

2.2 The Economics of Drainage and Coordination

In the upper Midwest prior to 1880, unimproved wetland sold for an average of $7 per acre (ranging from $2-$12); once drained the sale price could increase by a factor of five (Prince, 2008). Farmers incurred costs in developing drainage, however. Hewes and Frandson (1952) noted in their account of Story County, Iowa after settlement that the cost of tiling there exceeded the price of drained land for several decades.[6]

As technology evolved, economic incentives to drain and fully utilize these lands emerged, with evidence of direct capitalization of land improvements into land values. Because of the cost of drainage, land with poorly drained soils was developed later. After 1880, declines in the cost of tiling drove an increase in the derived demand for its complementary input, unimproved swampland. The price of undrained swampland increased rapidly, to an average of $25 per acre (ranging from $13-$40), with drained land commanding $60-$70 per acre, a premium in the neighborhood of the cost of tiling estimated at $35 per acre (Prince, 2008).

Drainage investment, however, was generally not effective on a small scale. Drainage projects required coordination across hundreds or thousands of acres as well as new ditches, levees, and embankments on private lands (Wright, 1907; Prince, 2008). Further, common law was interpreted in many states, including Iowa and Illinois, as providing farmers the right for water outflow onto neighboring properties. The geographic scope of these benefits and costs suggested the potential for conflict and Bogue (1963) uses the diaries of a 19th century Illinois farmer, Croft Pilgrim, to illustrate:

> *Pilgrim's earliest venture in tiling disrupted the harmony of the neighborhood. No sooner was the drain completed than his neighbor Tom Mellor dammed the outlet, claiming that the tiling system was flooding his fields. Thus in 1876 began a long-drawn-out litigation, which started in the court of the local justice of the peace and moved ultimately into the district court. After a series of decisions and appeals, the case still stood on the docket at Toulon, the county seat, in 1882, and by this time had cost Croft Pilgrim several hundred dollars.*

Coordination problems among neighbors combined with large minimum scales of drainage limited private investment in drainage to large landowners. Owners of farms in Illinois ranging in size from 3,000 to 17,000 acres privately undertook tiling (and in some cases the construction of

[6] Hewes and Frandson (1952) observe that the 1860 Agricultural Census estimate of $20-$30 per acre drained is similar to estimates of average cost provided by a survey of drainage conditions in Iowa in 1903 ($25 per acre) while land was appraised by the Federal Land Bank at $35 per acre.

tile factories). For the average smallholder farm, which in the upper Midwest in 1880 was about 150 acres, the necessary scale of drainage investment exceeded farm size by one to two orders of magnitude (Prince, 2008).

While the consolidation of smallholdings by large landowners able to coordinate drainage investment offered one potential solution to the challenges of drainage, consolidation brought costs as well. Smallholders in the Midwest generally relied on family labor where agency costs were limited, and they could readily adjust effort in response to price signals. By contrast, large landowners required external labor, leading to misaligned incentives between owners and hired labor that resulted in additional monitoring costs (Allen and Lueck, 1998).

Some entrepreneurial landowners tiled their land and then converted it into smaller farming units of 80-160 acres, which were then sold or rented (Prince, 2008). These attempts at private solutions, however, were limited in area and impact. One key constraint was access to capital (Bogue, 1951). In addition, for farms already held by smallholders, the transaction costs involved in consolidation, tiling, and re-parcelization were high. For existing smallholders, who lacked consolidated ownership at the scale required to justify an individual drainage project, coordination was essential. A 1907 report to the U.S. Senate on the status of *Swamp and Overflowed Lands in the United States* by Wright (1907) described the coordination problem faced in reclaiming these lands:

> *In order to secure the necessary cooperation for efficient work in all cases and to set out the detail of procedure so as to insure uniform practice, some legal method of compulsion has been found necessary, and drainage statutes have been enacted by many of the States. All the persons interested may not agree as to the necessity for the improvement, and even if they do, when it comes to deciding what lands shall be embraced in the project, where the ditches shall be located, how the work shall be done, and particularly, what each individual landowner shall pay, differences of opinion are sure to arise. To overcome this diversified sentiment and enable the owners of swamp and overflowed lands to reclaim the same in an efficient and equitable manner, drainage laws have been found necessary.*

The initial problem facing owners of swamp lands and other poorly drained areas was one of coordination to invest in the local public good required for reclamation. Olson (1989) provides a useful framework for understanding the difficulties of solving this coordination and investment problem of collective action. Each farmer can be made better off with drainage investment, yet each also has an incentive to free-ride on the investment of others and one farmer's action can negatively affect another. Collective action in drainage requires some mechanism by which farmers agree to cooperate.

Ostrom (1990) provides insight into the settings where local groups can successfully cooperate in managing natural resources. Relevant to this work is her finding that local groups are often successful at such management, even when central governments fail. In describing her design principles of successful organizations, Ostrom suggested that the right to organize locally be recognized by the central or local government, with decisions nested in local organizations. Ultimately, it was the drainage district that provided local landowners with the tools to undertake the collective investment suggested by Olson (1989) in a form consistent with the nested structure described by Ostrom (1990).

2.3 The Drainage District

From a modern governance perspective, a drainage district is one of many examples of the special district, commonplace today and encompassing varied responsibilities that include mosquito abatement and the operation of airports, mass transit, and libraries. The U.S. Census began collecting data on special districts in 1942, but earlier forms of the special district include park districts created in the 18th century and toll road and canal corporations from the 19th century. The organizational form has been attributed to the English Statute of Sewers in 1532. The key feature of special districts is local authority that is parallel to and not subordinate to that of county and municipal governments, but is subordinate to state governments. Special districts are created by the states and wield powers delegated to them by the states.

Special districts allow landowners to retain rights to operate their properties at the scale and for the purposes that economic factors dictate, while ceding one property right "stick" to a local elected body. Drainage district laws provided sufficient legal structure to coordinate investment in drainage infrastructure through local taxing authority. In addition to facilitating public investment, eminent domain authority solved the problem of neighbors preventing drainage onto or across their land. Bogue (1951, p.180) describes "violent opposition" from neighboring landowners to drainage projects in Illinois, but under drainage district law these types of issues were resolved in the courts and generally in favor of the public good, i.e. draining land.

Arguably, irrigation districts formed later in the western United States were patterned after the drainage districts formed in the Midwest. In describing the emergence of irrigation districts, Bretsen and Hill (2006) discuss the limitations of irrigation prior to the formation of districts. Large irrigation enterprises required substantial investment and rights-of-way, requirements that were not provided without some governmental authority. Edwards (2016) discusses the formation of local groundwater management districts in Kansas after some trial and error with enabling state legislation. These districts, while limited by statute in the actions available to them, succeeded in coordinating to address externalities associated with groundwater pumping.

Although they varied in specifics, drainage districts were generally legislated to be formed via a petition from landowners residing in a specific region and then requiring some combination of signatures and a vote by the majority of land area and land owners (McCorvie and Lant, 1993). Drainage district decisions were typically made by locally elected boards. Their power was restricted to investments that met some definition of benefiting the public at large, which courts often interpreted as requiring public health benefits (Prince, 2008).

A key feature of the districts was their taxing authority and ability to issue low-interest bonds to secure cash for investment (McCrory, 1928). Similar to drainage enterprises in other locales, in Story County, Iowa "most drainage costs are individual rather than collective. The financing of the collective aspect of the county drainage enterprises has been based on taxes levied on the land included within the enterprises .... During and since the period of maximum drainage in the county, no drainage district has gone bankrupt. Rather, the drainage enterprises are considered highly remunerative investments."(Hewes and Frandson, 1952)

Consistent with the scale of private drainage observed in Illinois, drainage districts ranged in size from hundreds to thousands of acres. An in-depth account of drainage in Blue Earth County, Minnesota by Burns (1954) documented 92 districts being formed between 1898 and 1952, with the majority formed in the 1910s and 1920s. In 1920 these districts covered 99,000 acres, with 54,000 of those acres benefiting from direct drainage. The individual drainage enterprises ranged in size from 320 to 7,202 acres, with a majority in the range of 1,000 to 4,000 acres. In 1930, the average district in Blue Earth County covered 1,161 acres with 908 of the acres drained. The agricultural census shows a total of 1,836 farms drained, an average of around 20 farms per district. In Story County, Iowa there were 95 districts by 1920 draining 197,633 acres (60% of total county area), or an average size of 2,080 acres per district (Hewes and Frandson, 1952). The agricultural census shows 1,871 farms with drainage, which corresponds again to around 20 farms coordinating in each district.[7]

3 Estimating the Effect of Drainage Districts

3.1 Enabling Legislation and Identification

The formation of drainage districts required enabling legislation in each state. We construct a list of dates of passage using both modern and contemporaneous accounts (see section A1.3 in the data appendix for full details). Drainage district legislation is defined as the first enacted bill that successfully allows the petition of landowners to create a district governed by an elected body, e.g. drainage commissioners, with the power to raise funds for ditch construction activities and to condemn land (Sandretto, 1987). Table 1 shows the years of passage for drainage district laws for the 24 states in our sample.

Table 1: Year of Drainage District Legislation

State	Year	State	Year
Ohio	1859	Texas	1905
Indiana	1863	Mississippi	1906
Michigan	1869	Virginia	1906
Kansas	1879	Louisiana	1907
Illinois	1879	Florida	1907
Nebraska	1881	South Dakota	1907
Iowa	1884	North Carolina	1909
Minnesota	1887	Tennessee	1909
North Dakota	1895	New York	1909
Wisconsin	1899	Georgia	1911
Missouri	1899	South Carolina	1912
Arkansas	1904	Kentucky	1912

While 25 eastern states have drainage districts laws that meet our definition, we exclude Oklahoma due to its isolation from typical drainage geology. Most of the northeast states have a common set of drainage laws that do not involve the use of districts as discussed in Palmer (1915).

[7]While data on drainage enterprises are only available for a few select counties, the 1920 census reports that the counties we define as poorly drained and that have drainage by 1920 have on average 113,000 acres drained and 1,376 farms.

These states have little drained cropland and are excluded from the empirical analysis, as are New Hampshire and Alabama for which no records or discussion of any drainage law could be located. Adoption dates for drainage district laws vary from 1859 in Ohio to 1912 in South Carolina and Kentucky and are shown in table 1. Figure 2 shows a map of the eastern United States to help visualize the geographic timing of these laws.

We classify the 24 states into two groups based on the general characteristics of drainage articulated by Palmer (1915): "glacial swamps" and "tidewater or delta overflowed lands." Roughly following these categories we classify "Coastal Plain" states according to the definition of the Atlantic Coastal Plain in the map created by Fenneman and Johnson (1946): Virginia, North Carolina, South Carolina, Georgia, Florida, Texas, Mississippi, Louisiana, Arkansas, and Tennessee. The glacial swamps described by Palmer (1915) coincide roughly with the Midwest, and our definition of "Midwest Glaciated" includes North and South Dakota, Nebraska, Kansas, Iowa, Minnesota, Wisconsin, Illinois, Indiana, Michigan, and Ohio (see figure A4). To this list we add Kentucky and Missouri, portions of which contain glaciated regions, and New York, which adopted drainage district laws significantly later than other Midwest Glaciated states despite being the initial location of tile drainage in the U.S.

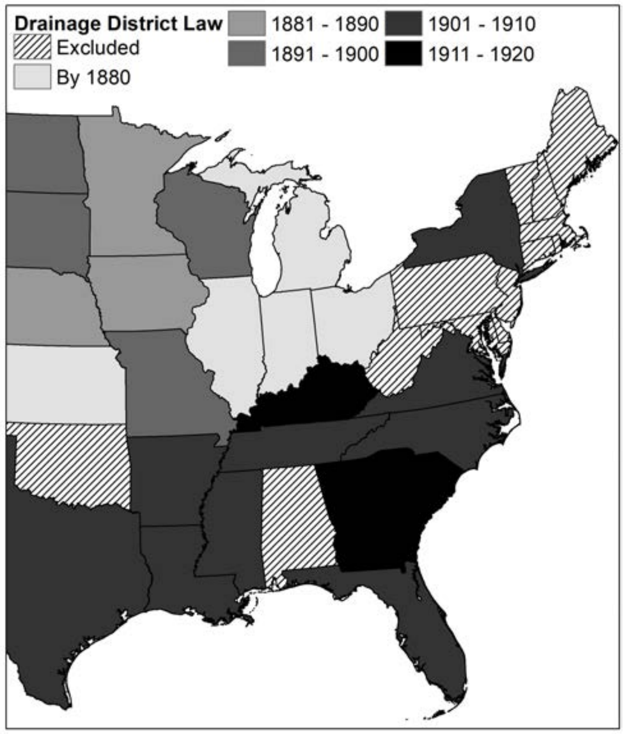
We look for evidence consistent with increases in improved farm acres and per acre land value after the date of drainage district enablement in poorly drained counties. This interpretation discretizes in time what was in each state a non-instantaneous change, as there was trial and error in arriving at ultimately effective institutions and the drainage efforts themselves (Edwards and Thurman, 2022).[8]

Our central premise is that drainage districts increase the ability of counties with high natural soil wetness to improve agricultural land via drainage districts. There is, however, heterogeneity in this effect. Counties with rougher topography do not require drainage districts because there is enough variation in elevation for farmers to drain their lands to existing streams directly without coordinating ditches.[9] At the other extreme, many Coastal Plain counties have low roughness.

[8]This strategy does not deny the importance of multi-year institutional experimentation and refinement. Instead we attempt to identify the effect of drainage legislation and assume that the magnitude of the empirical effects we find are inclusive of any subsequent changes to the legislation. Drainage development occurred over several decades following the passage of district legislation, and our empirical approach looks at long-term effects. The use of the date of drainage legislation may underestimate the effect of private drainage by putting early private drainage efforts into the pre-period.

[9]Similarly, naturally wet areas in generally well-drained counties allow landowners to simply drain water off of

Figure 2: Map of Drainage District Law Dates



Drainage in these counties requires complex coordination beyond the district level, for instance state-level legislation to create drainage districts larger than single counties. When Wright (1907) wrote to the U.S. Senate about drainage, the Midwest had largely established drainage laws while the South had not, and he referred to this difference:

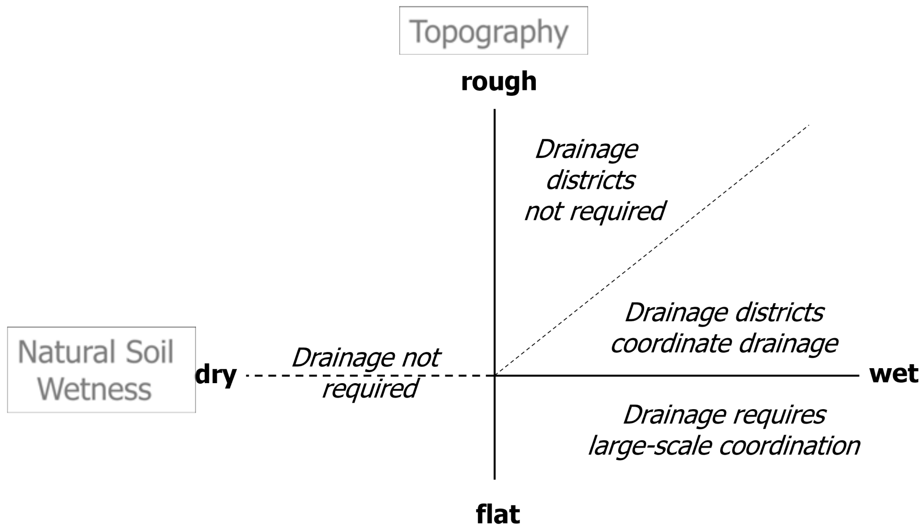
> *Throughout the United States the progress that has been made by the several States in land drainage has depended more upon the character of the drainage laws than on the geographical location of the State or the fertility of its soils. The swamps of the Yazoo Delta, Mississippi, and those of the eastern part of North Carolina are more fertile and are susceptible of producing a field crop worth much more per acre than the lands in Indiana or Illinois, yet practically all the swamps in the latter States have been drained under the provisions of wise and beneficent State drainage laws, while little or nothing has been done to drain the lands of North Carolina and Mississippi.*

It should be noted that Wright paid little heed to the differences between the drainage challenges faced in the glacial area of the Midwest and those of the alluvial outwash plains of the Southeast.

In figure 3 we provide a simple qualitative diagram to explain the relationship between natu-

naturally wet areas to better-drained areas without coordinating ditches.

Figure 3: Soil Moisture and Topography



ral soil wetness, roughness, and the efficacy of drainage districts, which we use as an identifying strategy. Where soil has moderate to low natural wetness, drainage is not required (far left). Where drainage is required, roughness determines if coordination is needed. Flat topography requires coordination across large areas of land, increasing the difficulties in coordination. In areas where topography is roughest, coordination is unnecessary. The sweet spot for the drainage district is that of intermediate roughness where coordination is needed over areas of approximately 100s to 1000s of acres. Because the Coastal Plain tends to be flatter than the Midwest, counties requiring supra-district large-scale coordination are located there. Conversely, the rougher Midwest contains the counties that benefited from drainage but don't need district coordination.[10]

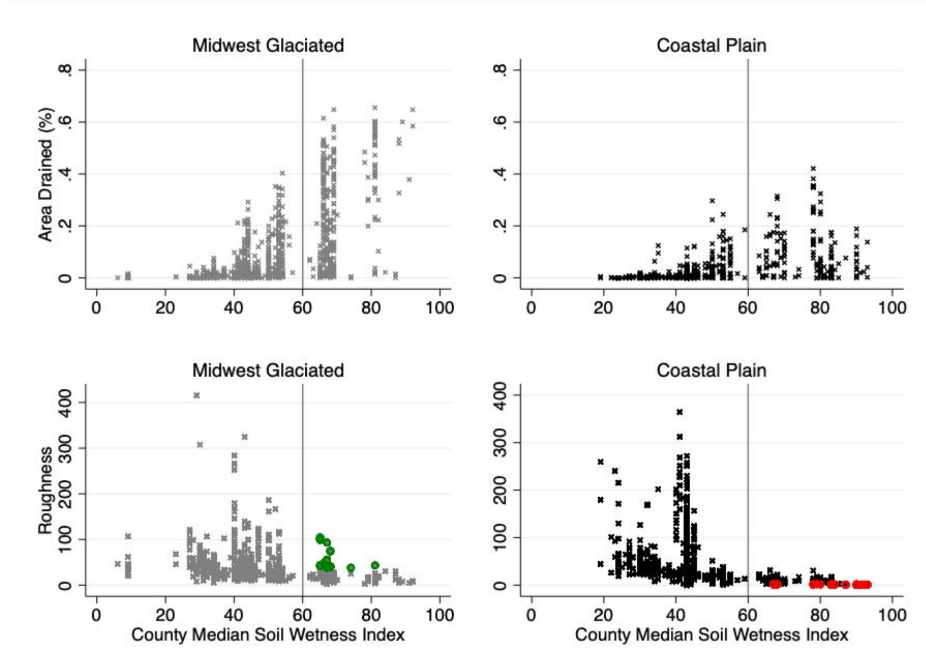
3.2 Agricultural and Geophysical Data

We construct a decadal panel spanning 119 years, from 1850 to 1969, on *Improved Acres* and *Total Farm Value* from United States Censuses of Agriculture digitized by Haines et al. (2019).[11] We focus on counties east of the 100th Meridian, generally the dividing point between the humid and

[10] There were also important differences in the institutional development of drainage between the glaciated Midwest and the Coastal Plain. While Mississippi, Florida, and Louisiana received significant federal grants via Swamp Land Acts, Alabama's grant was less than half a million acres and Virginia, North and South Carolina, Georgia, and Tennessee were not included (see table 6). These states were also later in passing drainage district legislation, faced larger coordination problems, and generally invested less in tile.

[11] After 1940 data collection is more frequent (approximately every five years) but we continue to use the censuses on the decade. See table A1, for details on the census data.

Figure 4: 1969 Drained Acres, Soil Wetness Index, and Roughness



Notes: Soil wetness index is plotted against 1969 area drained (top) and roughness, defined as the standard deviation of elevation (bottom), for counties in the 24 states in our sample. Soil wetness index is the median of 240-meter resolution pixels in each county. Green counties are those with roughness exceeding the 75th percentile while those in red are flatter than the fifth percentile.

semiarid portions of the United States. Areas east of this line can be farmed without irrigation and were generally settled or being settled during the entire panel.[12] To accommodate changes in county boundaries over time, we scale county data to 1910 county boundaries using area-weight crosswalks constructed by Ferrara et al. (2021). The USDA also conducted drainage censuses in 1920, 1930, and 1969, which recorded the number of *Drained Acres* in a county. We construct measures of *Percent of County Improved* and *Percent of County Drained* in those years by dividing by total county area.

We use the Natural Soil Wetness Index (NSWI) to represent the water content in the soil of a given county absent anthropogenic modification (Schaetzl et al., 2009). The NSWI is an ordinal measure of long-term soil wetness ranging from 0 to 99. Soils with a NSWI of around 60 are generally termed "somewhat poorly drained," while higher NSWI values represent more poorly drained up to 99, which is open water. The NSWI is derived from soil classification and slope and is not affected by drainage or irrigation.

[12]The forced removal of Indigenous groups from these states generally preceded drainage by several decades or more, starting with the Indian Removal Act of 1830.

For the early years of our study period the USDA did not collect data on drainage at the county level. Data on acreage drained were collected in 1920, 1930, and 1969. Although not usable as an outcome variable, we do use this measure to verify the relationship between NSWI and county-level drainage at the end of the sample period, as shown in the top panels of figure 4. For both the Midwest and Coastal Plain samples, the proportion of county area drained is substantially higher at NSWI levels greater than 60.

We also construct a county-level measure of roughness: the standard deviation of 40-meter grid elevation observations in a county. The relationship between roughness and wetness is shown in the bottom panels of figure 4. In both regions, wetter counties tend to be flatter. Correlation coefficients between wetness and ruggedness are negative and highly significant in both regions. But, notably, in the Midwest a number of wet counties are also rough — those shown in green are wet and exceed the 75th percentile of the overall roughness distribution and might, therefore, be predicted to implement drainage without the coordination of drainage districts. In the Coastal Plain, the counties that lie at the other extreme — wet counties that are exceedingly flat — should be less likely to benefit from, and hence less likely to form, drainage districts because effective drainage requires coordination over areas too large to manage through drainage districts. Counties flatter than the fifth percentile of those in the overall sample are plotted in red in figure 4. In figure 3, the red counties correspond to the bottom right quadrant, while the green counties correspond to the upper wedge of the top right quadrant.

3.3 Empirical Implementation

A difference-in-difference approach to estimating the effects of drainage districts suggests a dynamic panel comparison of the effects of district-enabling legislation on wetter counties with the effects on drier counties – we use a Natural Soil Wetness Index value of 60 to separate the two. Incorporating the effects of topographic relief requires an econometric modification to what would otherwise be a standard two-way fixed effects model. In our preferred model, we allow treatment status to vary by roughness by focusing on a sample that excludes the two types of counties unlikely to benefit from drainage districts: the wet and rough and the wet and exceedingly flat (green and red, respectively, in figure 4).[13]

For two outcome variables — improved acres in a county and total value of land in farms — we estimate the following two-way fixed effects model:

$$Y_{ist} = \beta_{TWFE} PostLaw_{st} \times HighNSWI_i + \lambda_i + \tau_{st} + \varepsilon_{ist} \quad (1)$$

where Y_{ist} is the outcome for county i in state s in year t, λ_i is a county fixed effect, τ_t is a state by year fixed effect, and $PostLaw$ and $HighNSWI$ are dummies indicating that a state has passed a drainage law and a county is designated as having a high NSWI, respectively.

The coefficient on $PostLaw_{st} \times HighNSWI_i$ would traditionally be interpreted as the difference-in-difference coefficient, but recent work suggests problems with this interpretation.[14] de Chaisemartin and d'Haultfoeuille (2020) and Callaway and Sant'Anna (2020) both propose alternative DiD estimators that are robust to heterogeneous treatment effects across time and/or cohorts. We use both estimators as well as the traditional TWFE approach.

Identification of the ATT associated with post-drainage legislation requires we assume that both the untreated and treated *potential* outcomes follow parallel trends, and that any shocks affecting the potential outcomes for either group are uncorrelated with treatment. Our comparison group is counties within a state that become treated, but which differ in their need for drainage. This construction reduces threats to identification to those coming from within-state shocks that differentially affect well drained and poorly drained areas differently, and occur at about the time the state implemented drainage districts.

While we present contemporaneous accounts as evidence that it was the drainage districts themselves that created the ability of poorly drained counties to increase agricultural development and production, we do not test this assumption directly because comprehensive data on district formation is not available. The discussion in section 2 provides economic rationale for the importance of drainage enabling legislation and details on the related institutional factors.

[13] We provide alternative specifications, as described in the subsequent section, to support this assumption and to control directly for roughness.

[14] Namely, β_{TWFE} potentially provides biased estimates of the ATT when different states are treated at different times and there is substantial heterogeneity in the treatment effects over time or between states (de Chaisemartin and d'Haultfoeuille, 2020; Callaway and Sant'Anna, 2020; Goodman-Bacon, 2021; Wooldridge, 2021).

4 Results

Summary statistics conditional on natural soil wetness are provided in table 2 and indicate that wetter counties behaved differently following the implementation of drainage district laws, relative to drier counties. Both sets of counties are increasing in agricultural development, with low-NSWI counties total farm value increasing from $84M to $267M and high-NSWI counties increasing from $83M to $397M.

Table 2: Conditional Summary Statistics

	Drainage Index<60		Drainage Index > 60	
Variable	Pre	Post	Pre	Post
Total value in farms (2020$ millions)	84	267	83	397
	(117)	(250)	(113)	(343)
Land value per acre (2020$)	445	1,026	437	1,391
	(986)	(2,150)	(345)	(1,010)
Proportion of county improved	0.31	0.44	0.24	0.56
	(0.21)	(0.24)	(0.22)	(0.26)
Total number of farms	1,491	2,062	1,311	2,350
	(1,202)	(1,173)	(1,121)	(1,330)
Total acres in farms	197,708	282,128	171,424	281,435
	(133,019)	(168,622)	(122,628)	(146,189)
Bushels of corn	474,627	1,162,049	579,839	2,002,959
	(622,170)	(1,628,837)	(803,687)	(2,387,208)
Bushels of wheat	101,955	252,258	121,903	378,048
	(213,206)	(498,033)	(306,374)	(591,618)
County median drainage index	44.03		71.24	
	(6.29)		(7.02)	
Median productivity index	8.51		10.80	
	(4.11)		(3.11)	
Median elevation (m)	280.40		204.25	
	(169.24)		(120.46)	
Standard deviation elevation (m)	41.92		16.54	
	(43.38)		(12.61)	

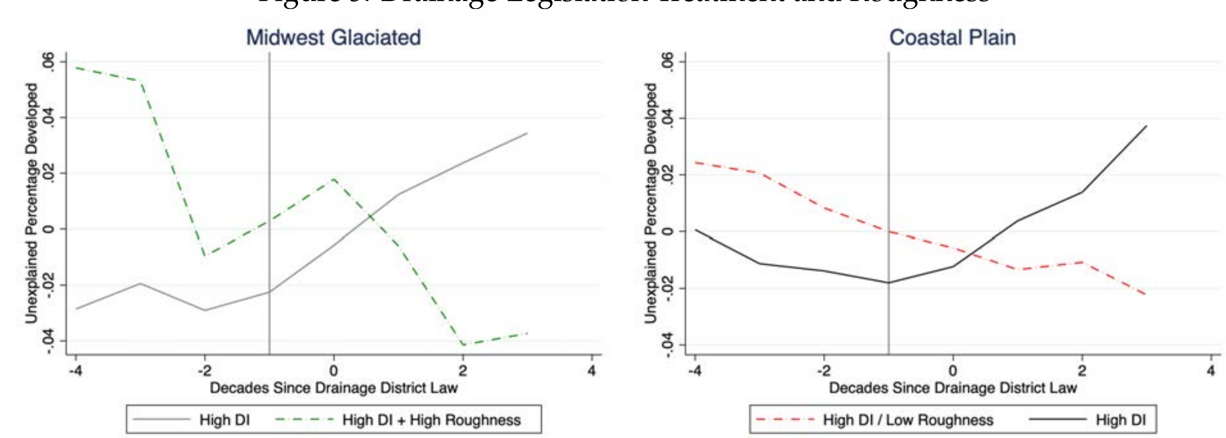
Notes: Summary statistics at county level conditional on treatment status: high drainage counties $DI > 60$ and pre/post drainage district laws. All values are the mean value of all the counties in that treatment status for the variable described on the left and for the four years before/after treatment. Standard deviations are reported in parentheses.

After the passage of drainage district legislation, the percent of county acreage improved increased by seven percentage points in low-NSWI counties and 32 percentage points in high-NSWI counties. On average, after the passage of drainage district laws high-NSWI counties have a higher percentage of total acreage in agriculture, likely because the median productivity index is significantly higher in these counties, which have more fertile soils once drained (as shown in the last row of the table). It is also worth noting that low NSWI counties are substantially rougher, as measured by the standard deviation of elevation. These summary statistics do not control for county-specific characteristics that could be related to development or changing trends in different states, which we address in the regression analysis.

4.1 Flatness and Coordination

Our identification strategy can be cast in terms of parallel pre-treatment trends in treated and untreated counties. To systematically drop observations for which this assumption does not hold, we begin by finding the residuals of regressions including all counties in our 24 sample states, controlling only for county and state by year fixed effects. In figure 5 we plot the means of groups of counties standardized to the timing of state-level drainage district legislation and relative to counties with NSWI< 60. The left plot contains counties in the Midwest with NSWI>60 (gray) and those with NSWI>60 and very high roughness (green). The right plot shows counties in the Coastal Plain with NSWI>60 (black) and those with NSWI>60 and very low roughness (red).

Figure 5: Drainage Legislation Treatment and Roughness



These figures show how topography in the Midwest and the Coastal Plain affect drainage district outcomes. The gray and black lines show significant increases in developed agricultural land after the passage of a drainage district law relative to counties with soil moisture index below 60, the expected treatment effect. The green and red lines show that the roughest and smoothest counties do not follow the same trends. Because we are focused on estimating the ATT of counties that benefit from drainage district legislation, we drop these 65 counties from the main empirical estimates.[15] The remaining counties appear to follow similar pre-treatment trends and post-treatment increases, justifying our decision to pool both sets of counties in out preferred specifications.

4.2 Drainage District Treatment

Using this modified sample we implement the difference-in-difference methodology from equation 1. Event study estimates can be used to provide evidence that the necessary parallel trends assumptions are now likely to hold. Our data include 13 observations per county, one every 10 years, and we report a window that includes three pre-periods (30 years) and four post-periods (40 years), with period "0" defined as the first year in which treatment begins.

Figure 6 presents the results of the event study estimates using the estimator proposed by de Chaisemartin and d'Haultfoeuille (2020) and includes county fixed effects and state-specific non-parametric trends.[16] The left panel shows the event study for improved acres and the right for farm value.[17] All coefficients are relative to the difference between treated and untreated parcels (NSWI>60) in the period just prior to treatment, which is normalized to 0 (i.e. within a state the estimator compares high NSWI counties to others).

The coefficients for periods $t-1$ through $t-3$ are the pre-trends. None of the coefficients are statistically different from 0. Although the per acre farm value figure shows an upward trend in point estimates from period t-2 to t-1 (which would be consistent with anticipation of drainage in land markets), this change is not statistically distinguishable from 0. From period $t=0$ onward in the improved farmland measure and $t=1$ onward in the land value measure, there is a statistically significant difference in counties with high NSWI relative to others.

The main estimates for the effect of drainage on percent of a county improved and agricultural value are presented in Table 3. Panel A reports estimates from de Chaisemartin and d'Haultfoeuille (2020)'s method, Panel B reports estimates using the Callaway and Sant'Anna (2020) estimator, and Panel C reports estimators from the classic TWFE estimator.[18] Panel A in-

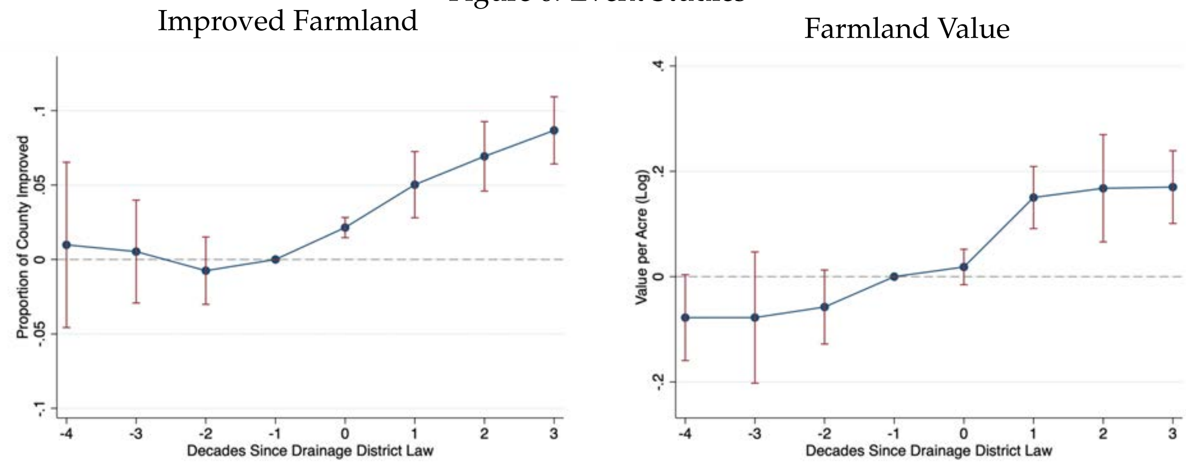
[15] A regression including these dropped samples showing that in a TWFE model the treatment effect on the roughness outliers is different from the other counties is shown in table A5.

[16] Implemented with the `did_multiplegt` package in Stata.

[17] Individual event study figures for Midwest Glaciated and Coastal Plain samples separately are shown in figure A6

[18] Panel A estimates are derived using with the `did_multiplegt` package in Stata. Panel B estimates are derived using the `csdid` package in Stata.

Figure 6: Event Studies



Notes: This figure depicts event study estimates using the estimator developed by de Chaisemartin and d'Haultfoeuille (2020), implemented with the `did_multiplegt` package in Stata. The model corresponds to the specification in columns 3-6 of Panel A of Table 3, which includes parcel fixed effects and state-by-year fixed effects. The difference between treated and untreated groups is normalized to zero in period $t-1$, the final period before treatment. Period 0 denotes the first period in which a drainage district law exists. The sample includes counties in 14 Midwest states and 10 Coastal Plain states. Treatment is $DI > 60$ after drainage law passage, excluding counties with roughness higher than the 75th percentile or less than the fifth percentile.

cludes state-specific non-parametric trends and Panel C includes state-by-year fixed effects, but Panel B includes only year fixed effects.[19]

Columns (1) and (2) report the results for the 24 states with drainage district laws shown in figure 2. Columns (3)-(6) report separate results for Midwest Glaciated and Coastal Plain regions. Coefficients from column 1 show that following the implementation of drainage districts, a county with a natural soil wetness index greater than 60 saw a 4.4 to 5.8 percentage point increase in the area of the county with improved agricultural land and a 12.4 to 21.3 percent increase in land value per acre.[20] Midwest coefficient estimates are generally larger than those from the Coastal Plain for percentage improved. While the estimates in panels A and C are generally statistically significant at the 10% level or higher, this is true of only some of the estimates in panel B. Overall, the results provide solid evidence that the passage of drainage district legislation was followed by an increase in improved farmland acres and value per acre in counties with naturally wet soils relative to those with better drained soils.

[19] The Callaway and Sant'Anna (2020) estimator does not have an option for including group-varying time effects.

[20] Land value calculations come from coefficients ranging from 0.117-0.193 in the log-level regression, corresponding to a $e^{\beta}-1$ proportionate increase.

Table 3: Agricultural Development after Drainage District Legislation

	(1)	(2)	(3)	(4)	(5)	(6)
	All States in Sample		Midwest Glaciated		Coastal Plain	
	Prop. Impr.	\$/ac (log)	Prop. Impr.	\$/ac (log)	Prop. Impr.	\$/ac (log)
Panel A:						
	de Chaisemartin & D'Haultfoeuille (2020)					
Post Dist. Law	0.054***	0.117***	0.066***	0.106**	0.029**	0.141**
	(0.009)	(0.031)	(0.008)	(0.049)	(0.012)	(0.066)
Panel B:						
	Callaway & Sant'Anna (2020)					
Post Dist. Law	0.044*	0.139***	0.035	0.124*	0.022	0.094
	(0.009)	(0.031)	(0.008)	(0.049)	(0.012)	(0.066)
Panel C:						
	Two-Way Fixed Effects					
Post Dist. Law	0.058***	0.193***	0.074***	0.156***	0.034*	0.249***
	(0.009)	(0.031)	(0.008)	(0.049)	(0.012)	(0.066)
Observations	14,042	14,476	7,409	7,531	6,633	6,945
R^2 (TWFE)	0.908	0.909	0.911	0.911	0.843	0.849

Notes: This table presents difference-in-difference estimates for the effect of drainage district adoption on high drainage index counties relative to others based on the model in Equation 1 using several estimators. Panel A uses the estimator proposed by de Chaisemartin and d'Haultfoeuille (2020) and implemented with the `did_multiplegt` Stata package with four leads and four lags of treatment. Panel B uses the estimator proposed by Callaway and Sant'Anna (2020) and implemented with the `csdid` package in Stata. Panel C presents traditional TWFE estimates obtained via OLS. Panels A and C include state-by-year fixed effects, whereas Panel B uses pooled year fixed effects due to limitations of the `csdid` package. Standard errors are clustered by county and reported in parentheses; statistical significance is indicated by $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

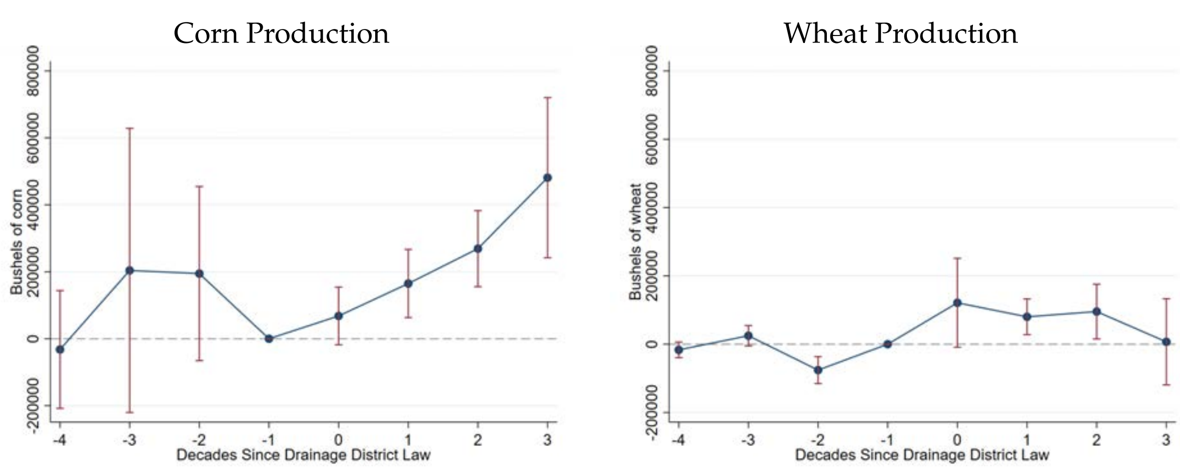
4.2.1 Crop Choice

We can also apply our empirical strategy to crop-specific production data. Our sample period spans several eras of agricultural production and market development, and our broad geographic scope spans a wide diversity of crops. We examine wheat and corn as keystone crops: wheat as a versatile crop with winter varieties potentially tolerating several weeks of waterlogging with small yield losses (Cavers and Heard, 2001); and corn as a high-value crop with a growing export market throughout our sample period benefiting from the highly fertile soils on drained lands. Today, in the Corn Belt states of Iowa, Illinois, Indiana, Minnesota, and Ohio, 57% of corn production occurs in counties with high natural soil wetness. By examining the same regression as specified in equation 1, but with bushels as the dependent variable, we can test whether the farmland created by drainage was more favorable to corn production.

The export market in corn increased dramatically from 1850 to 1900 (see Fornari (1976) for a discussion of U.S. exports of wheat and corn since 1850). Acreage in specific crops is not recorded in the agricultural census until 1880, but bushels of wheat and corn are recorded starting in 1860. From 1860 to 1900, corn production in the 24 states in our sample sample increased by 238%, from 723 million to 2.45 billion bushels. Analysis in this section allows us to link drainage to the increased production of corn in the U.S. without establishing the direction of causality.

Event studies shown in figure 7 for the entire sample suggest a relative increase in corn production in high NSWI counties over the four decades post drainage district law passage. Wheat production shows an initial increase, smaller in magnitude, that disappears by the end of the treatment period. Region-specific event study plots, shown in figure A7, reveal similar patterns in both the Coastal Plain and Midwest. The magnitude of the treatment effect on Midwest counties (in bushels) was about three times larger than in Coastal Plain counties. Coefficient estimates corresponding to the event study figures for the entire sample shown in panel A of table A6 suggest a 246,000 bushel increase in corn and 77,000 bushel increase in wheat post treatment across all 24 states, although statistical significance and point estimates across estimators appear much less consistent than our estimates for improved farmland and value per acre. In sum, we find evidence that district coordination of drainage favored corn production relative to wheat.

Figure 7: Wheat and Corn Production Event Studies



Notes: This figure depicts event study estimates using the estimator developed by de Chaisemartin and d'Haultfoeuille (2020), implemented with the `did_multiplegt` package in Stata. The model corresponds to the specification in columns 1 and 2 of Panel A of Table A6, which includes parcel fixed effects and state-by-year fixed effects. The difference between treated and untreated groups is normalized to zero in period $t-1$, the final period before treatment. Period 0 denotes the first period in which parcels are exposed to treatment. The sample includes counties in 14 Midwest states and 10 Coastal Plain states. Treatment is NSWI>60 after drainage law passage, excluding counties with high roughness (Roughness = fourth quartile) and roughness less than fifth percentile.

4.3 The Value of Drainage Districts

The results in table 3 provide evidence that the passage of drainage district legislation increased the amount of improved farmland in counties with high natural soil wetness as well as the per acre value of farmland.[21] To interpret the economic magnitude of these results, we perform a back-of-the-envelope calculation to estimate the total value of these changes to counties with different degrees of natural soil wetness. We begin by running a regression similar to the model in equation 1 but with the treatment variable *HighNSWI* replaced by bins of natural soil wetness to allow for more heterogeneity in the treatment effect. The results of running a TWFE model in this way are shown in table 4, which provides coefficient estimates relative to a control group of counties with NSWI<50. Looking at columns (2) and (3), the coefficient estimate for the counties with NSWI between 50 and 60 is not statistically different from 0 for either outcome measure. For all groups with NSWI>60, the proportion of county improved and value per acre coefficient estimates are positive and significant. Further, for both outcome measures, the size of the effect increases with natural soil wetness.

Table 4: Binned Soil Wetness Index Results

	(1) Prop. Farmland	(2) Prop. Improved	(3) Value per Acre (log)
Post x NSWI[50-60]	0.047	-0.01	0.041
	(0.096)	(0.010)	(0.046)
Post x NSWI[60-70]	0.044	0.047***	0.182***
	(0.041)	(0.014)	(0.055)
Post x NSWI[70-80]	0.081**	0.070**	0.215*
	(0.037)	(0.027)	(0.107)
Post x NSWI[>80]	0.096	0.071**	0.270***
	(0.057)	(0.028)	(0.041)
Obs	14,053	14,042	14,035
R^2	0.388	0.908	0.89

Notes: This table presents difference-in-difference estimates for the effect of drainage district adoption on high drainage index counties relative to others based on the model in Equation 1 but with the treatment variable *HighNSWI* replaced by bins representing: $50 \geq NSWI < 60$, $60 \geq NSWI < 70$, $70 \geq NSWI < 80$, and $80 \geq NSWI$. Regressions exclude smooth and rough counties as described in figure 5 and control for county and state-by-year fixed effects. Standard errors are clustered by county and reported in parentheses; statistical significance is indicated by $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

To estimate the change in the total land value of a county implied by the estimated treatment

[21] For robustness we include table A7 without county FE that shows the relationship between fixed county characteristics — elevation, roughness, NSWI, and productivity index — and outcomes variables.

effects, assumptions must be made on whether the drainage improvements were on the intensive or extensive margin. The value per acre measure is per *farm acre*, of which improved acres are a subset. Drainage law passage may have induced the draining of new farmland, a change on the extensive margin, or the conversion of existing farmland into the "improved" category, a change on the intensive margin. In reality, we expect drainage laws affected both margins. Column (1) of table 4 shows the same regression run with a different outcome measure: the proportion of a county in farmland. These results are mostly not statistically different from zero, meaning we are unable to reject the null hypothesis that there was no change on the extensive margin.

The point estimates on farmland, however, are similar enough to those on improved acres that we cannot reject the hypothesis that they are the same, meaning it is possible that the entire increase in improved acres was caused by an extensive adjustment in farmland acres. Because we know a fully extensive or intensive adjustment represents the extreme outcomes, we proceed with a dual analysis to bound our cost estimates.

Panel A of table 5 summarizes the characteristics of counties in the sample in each NSWI bin for the observation immediately prior to drainage law passage.[22] As one would expect, high NSWI counties tend to have lower per acre land values, less land in agriculture, and of the land in agriculture, fewer improved acres. We can use the coefficients in columns (2) and (3) of table 4 to find the increase in the value of agricultural land in these counties as a result of drainage. Panel B of table 5 assumes the total amount of farmland has not changed, and that all new drainage has occurred on existing farms — an intensification — and so the value of drainage district legislation is calculated by taking the coefficient for each bin (β) from (3) and multiplying $e^{\beta} - 1$ by the total amount of farmland. Panel C assumes the other extreme, that total farmland is increased by the full amount of the estimated increase in improved acres. This extensive margin effect is found by adding existing improved acres to the product of the coefficient from (2) and total county area. This total area of farmland is then multiplied by $e^{\beta} - 1$ to arrive at a per county value increase.

We find that counties with an NSWI between 60 and 70 saw a 20-21% increase in agricultural land value, bounded below by the assumption that the estimated land value increases were applicable to the same farmland base as prior to drainage legislation, and above by adding the

[22]Our coefficient estimates are based on counties that do not fall into the high-roughness or low-roughness categories and these counties are also excluded from this analysis.

Table 5: Back-of-Envelope Value Calculation

	NSWI[50-60]	NSWI[60-70]	NSWI[70-80]	NSWI[>80]
Panel A: Measures Decade Prior to Drainage Law				
Counties	271	307	54	90
Average county size (acres)	411,351	388,710	564,985	505,710
Farmland (acres)	254,193	238,608	157,399	201,835
Improved farmland (acres)	185,931	183,083	92,657	144,127
Value (2020$, per acre)	1,330	832	834	523
Panel B: Drainage improvements made only to existing farmland (intensive margin)				
per county				
ΔFarmland value (per acre) from (3)	-	166	200	162
ΔTotal value (2020$, millions)	-	39.6	31.5	32.7
aggregate				
ΔTotal value (2020$, millions)	-	12,163	1,699	2,945
Percentage increase	-	20%	24%	31%
Panel C: Drainage improvements only create new farmland (extensive margin)				
per county				
ΔFarmland (acres) from (2)	-	18,269	39,549	35,905
Total farmland (acres)	254,193	256,877	196,948	237,740
ΔFarmland value (per acre) from (3)	-	166	200	162
ΔTotal value (2020$, millions)	-	42.7	39.4	38.5
aggregate				
ΔTotal value (2020$, millions)	-	13,095	2,126	3,468
Percentage increase	-	21%	30%	37%

estimated increase in improved acres to the total farmland base. The relative magnitude of the increase in county value is increasing with higher NSWI bins, and we estimate a 24-30% value increase for counties with NSWI between 70 and 80, and a 31-37% increase for counties with NSWI>80. Multiplying the per county average value increase by the number of counties in each bin allows us to arrive at an aggregate estimate. By the intensive margin approach we arrive at an aggregate increase of $16.8B, while the extensive margin approach yields $18.7B.

5 How Technology and Institutions Evolved

Our empirical analysis attributes large increases in farmland value to drainage districts and the investments in drainage they induced. We consider here the evolution of the technology and the local institutions that led to these effects, as well as the earlier failure of top-down federal and state drainage efforts.

5.1 Drain Tile

John Johnston is credited as the Father of Tile Drainage in America. Born in Scotland in 1791, he farmed, married, and emigrated to America at the age of 30. He arrived in New York City in 1821 and purchased 112 acres overlooking Seneca Lake in upstate New York. Around 1835, Johnston began installing underground ceramic drain tile, manufactured locally using a semi-cylindrical form that Johnston imported from Scotland. The drained areas saw dramatic increases in yields.[23]

Following Johnston's innovation came several decades of public debate over the merits of subsurface drainage —- in agricultural society meetings, in writings and speeches by academics, and in popular farming publications such as *The Rural New Yorker*. Part of the long period of discussion and adoption had to do with the heterogeneity of soil types and hydrology. Part of it must also have been that the opportunistic draining of farmland was hardly a controlled experiment to assess the merits of a new technology. Further, intrinsically variable yields across farms and crop years made the contribution of drain tile difficult to measure, at least for lands that weren't so saturated to begin with that drainage allowed cultivation in the first place. [24]

Ultimately Johnston's tile idea gained traction. In 1859 Henry D. French wrote in his book *Farm Drainage*: "[n]o system of drainage can be made sufficiently cheap and efficient for general adoption, with other materials than drain tiles (French, 1859)." The flat tile method used by Johnston was eventually replaced by cylindrical tile starting around 1858 (McCrory, 1928). Local production was dictated by the costs of transporting the heavy tiles and the first tile manufacturing machine was imported in 1848 from England. Production quickly spread with 66 tile factories established in the United States from 1850-59, 234 from 1860-69, and 840 from 1870-79 (McCrory, 1928).

A caveat to the John Johnston story concerns what he did not contribute. Given the subsequent importance of large-area coordination of drainage schemes, especially in the Midwest, one

[23]Johnston did not invent subsurface tile drainage and knew it as it was practiced in Scotland. But in America in 1821, the advisability of drainage was debated and appropriate ways to implement it were in flux. (See, for example, Weaver (1964, pp. 38-45)

[24]Innovation in tile, its application, and its manufacture follows well the narrative in Ridley (2020) where technology advances through tinkering by many individuals in applied settings, rather than being created in laboratories or research centers and then disseminated broadly to applications.

might expect Johnson and his neighbors to have been wrestling with the same issues: flooding of neighbors' lands and free rider problems complicating the construction of ditch networks. We are aware of no such accounts. Article, chapter, and book-length treatments of Johnston's role in the adoption of subsurface drainage talk exclusively of the back-and-forth debate over the agronomic and economic efficacy of drain tile, and not on external effects or public goods problems arising from transactions costs. A plausible explanation for this dog that did not bark comes from the fact that Seneca County, the home of John Johnston's farm, is both wet and rugged. Seneca is one of the more than 500 modern counties in the Eastern United States with wet soils, and among those counties it lies in the top one percentile for roughness (see figure A2).[25]

The logic of our empirical approach applies here. Seneca's wetness implies high value to drainage and its roughness implies that coordination problems are minimal because areas with greater relief provide more drainage outlets, creeks and rivers, on or near farms. Further, the water drained by Johnston's tile was readily routed into Seneca lake, the western boundary of his farm.[26] In other words, the area where John Johnston chose to farm requires drainage, but does not require extensive coordination among neighbors. Johnston and others were incentivized to drain and tinker with drain tile without having to simultaneously solve the coordination problems that blocked wide-spread drainage in the flatter wet counties, notably those in the Midwest.[27]

One might ask if Johnston's decision to farm in a wet and rugged area reflected great foresight that his innovation to come would be lower cost absent the coordination problems posed in flatter wet areas. Or possibly he chose to settle where he did because the terrain was similar to the Scottish Southern Uplands where he grew up. Or possibly there were 50 other John Johnstons who settled in wet, but flatter, parts of the Eastern United States in the 1830s, each experimenting with drainage methods but stymied by the requirement that they solve both technological puzzles and a wholly different set of collective action problems. We don't know which, if any, of these

[25]That Seneca is unusually wet and rough can be seen in Figure 6; it is the light green vertical shape in eastern upstate New York. The bulk of counties in the state are shown there as being unlikely candidates for agricultural drainage —- all but seven have wetness index values less than 60. Correspondingly, in the modern day there is little agricultural drainage in New York counties, Seneca being the leader with 14% of county area in drainage. Seneca is the fifth roughest of the 516 counties east of the 100th meridian with natural wetness index values over 60.

[26]See Weaver (1964, p. 302) for remarks prepared by Johnston's grandson for the 100th anniversary of his grandfather's innovation: "The tiles were used to conduct the water towards the lake for some distance, draining the adjacent field." (From The Geneva Daily Times, October 1935.)

[27]For comparison, Seneca has a Natural Soil Wetness Index (NSWI) value of 66 and a roughness value of 22.9. Champaign County in Illinois has a NSWI value of 81 and a roughness index value of 9.9. By 1969, Champaign had 58% of its area drained, the third largest percentage among Illinois counties.

conjectures explain Johnston's central role in the history of drainage. We do know that Seneca County, the Cradle of Drainage in America, is almost uniquely wet and rugged.

5.2 Federal and State Wetland Policies

Roughly coincident with the development of drain tile were federal efforts to address the "unproductive and an economic waste" stemming from wetlands in the federal domain. (See Palmer (1915).) To encourage development and drainage Congress allocated substantial swampland to the states through a series Swamp Land Acts (1849, 1850, and 1860). In 1861, after the last of the Acts was passed, the *Congressional Globe* (Rives et al., 1861) summarized their justification and method as follows:

> *The passage of this bill and the donation of these scraps of land, injurious as they exist, to the States, and utterly valueless to this Government, is but the beginning of the work of reclamation; the State Legislatures must follow, appropriate money, and redeem them from the water—and the sooner the better for the health of the people and the prosperity of the country.*

The lands made available to the states under the Acts are shown in table 6. The first of the Acts gave 9.5 million acres of federal land to Louisiana—28% of its combined land and water area. The clear federal impetus for the legislation was to regulate the annual spring flooding of the Mississippi River. There also was substantial support in the state for draining swamplands that lay more permanently under water.

After passage of the 1849 Act, the Louisiana legislature divided the state into districts and established a statewide board that sold swampland in each district, prioritized drainage projects, and put selected projects out for bid. The highest priority projects invariably were repairing and constructing levees to protect farmland in the Southern Mississippi River Alluvial Valley. The Louisiana system may seem unexceptional from a 21st century perspective, but Vileisis (1999, p.79) notes that "at the time such division of lands and establishment of additional governance was revolutionary," requiring "citizens to accept a whole new vision of the proper role of state government."

The first Swampland Act in 1849 was followed in 1850 by similar legislation granting over 50 million acres to 12 widely scattered states, and a third Act in 1860 for two more states.[28] In

[28]The 50 million acres granted in the Act of 1850 represented one of the largest single transfers of land out of the

Table 6: Swamp Land Acts

Year	State	Acres
1849	Louisiana	9,493,456
1850	Alabama	441,289
	Arkansas	7,686,575
	California	2,192,875
	Florida	20,325,013
	Illinois	1,460,184
	Indiana	1,259,231
	Iowa	1,196,392
	Michigan	5,680,310
	Mississippi	3,347,860
	Missouri	3,432,481
	Ohio	26,372
	Wisconsin	3,360,786
1860	Minnesota	4,706,503
	Oregon	286,108
TOTAL		84,895,415

Source: Fretwell (1996)

each case, states were left to devise their own means of drainage and improvement and their methods varied. Even neighboring states differed in their approaches. While Indiana managed its 1.3 million acres at the state level, Illinois distributed its 1.5 million acres directly to counties.

Ultimately, the Swampland Acts were unsuccessful at taming the Mississippi – both initially and following the disruption of the Civil War – and unsuccessful at inducing much drainage.[29] Despite this failure, the methods employed by the state to dispose of and manage lands would prove to be important forerunners of the ultimately more successful institutional innovation of drainage districts.

5.3 Institutional Evolution Leading to Drainage Districts — A Case Study of Illinois

While the period of drainage technology development and debate over its agronomic merits was roughly between 1835 and 1865, the body of law that codified drainage districts and their ditch law equivalents (see Ohio) developed between 1855 and 1912. Relatively early in this process, and

public domain in the history of the United States and taken together the Swamp Land Acts represented the second largest aggregate land grant by the federal government to states (behind land for common schools of 77.6M acres) (Huston, 1983).

[29]See Vileisis, 1997, chapter 5. Failure at the state level to control Mississippi flooding was recognized institutionally by the 1879 creation of the multi-state, federally overseen Mississippi River Commission.

early in terms of its own settlement, was Illinois in 1879. The legal evolution prior to the 1879 law in the state that became the leading corn producer for much of the 20th century provides a case study of the coordination problems that inhibited drainage investment prior to drainage districts.

5.3.1 Two drainage problems and two types of districts

The earliest settlement in Illinois occurred along the Wabash, Ohio, and Mississippi rivers – the western and southeastern borders of the state, created in 1818. Excellent flood plain soil was available to be tilled once the bottom lands were cleared of timber. Prairie land, away from the rivers, was of little initial interest due to the difficulty in breaking prairie sod and the often flooded soils (Illinois Tax Commission, 1941, p. 2). The difficulties of sod busting were reduced significantly by the invention and mass production of the self-scouring steel plow in the 1830s, usually credited to John Deere, an Illinois blacksmith. With the technical means to more easily cultivate, and as the bottom lands filled with settlers, attention turned to prairie lands and the challenges of drainage.

Managing excess water on agricultural lands in Illinois and elsewhere in the Midwest posed two problems: "sub-soil drainage and open ditches in some parts of the state and flood and high-water protection in others." (Illinois Tax Commission, 1941, p. 2) Just as there are two drainage problems, Illinois law since 1879 has recognized two closely related types of drainage district: levee districts and tile-and-ditch districts.

Levee districts addressed the challenges of protecting river bottoms from floods. They constructed protective levees along rivers and open ditches to carry water from inland areas denied their usual outlet to the river by the levees. Because much of the land protected by levees sits near river level, modern levee districts operate pumping plants to keep groundwater levels low enough for farming. (See, for example, the 2022 annual report of the Sny Island Levee Drainage District.)

Tile and open ditch districts were organized to drain open prairie land. Leaving the installation of tile to individual land owners, tile-and-ditch districts typically build outlet ditches used in common by multiple landowners and coordinate the interconnection of private drain tile systems. Tile-and-ditch districts are initially capital intensive when ditches are dug and eminent domain exercised. Most become inactive after ditch construction.[30]

[30] Both types of districts have powers of eminent domain, used to site drainage canals and construct levees. Both types

While the two types of districts are treated very similarly under Illinois law, and both types were authorized in the same year, the evolution of Illinois drainage law that led to their creation in 1879 seems mainly to have been driven by flood control.

5.3.2 Drainage before district authorization in 1879

Various legal means were used to effect drainage and flood control before districts were authorized in Illinois in 1879. Two were important forerunners to modern drainage districts: action under common law and legislatively-created charter companies.

As to common law, drainage rights lay in the public domain before the potential value of farm drainage and flood protection warranted their invention and allocation.[31] As land and rights to drain became more valuable, two alternative common law rules were adopted by different states. Illinois, unlike Indiana, Minnesota, and Missouri, adopted a "dominant heritage" rule, giving rights of drainage to upstream property owners. While this rule would seem to break the Coasean logjam by a clear definition of rights, it turned out to be insufficient. The dominant heritage rule insisted that upstream land owners could drain water onto downstream neighbors only through "natural" channels. The right to build new ditches and drain into them, or to block such drainage, remained unspecified.

The second challenge difficult to address through the common law was that of organizing collective action (see Illinois Tax Commission (1941, p. 41).) In the early and mid- 19th century, common law drainage rights were supplemented under the first two Illinois state constitutions (of 1818 and 1848) by giving the legislature authority to grant charters to private parties. Powers granted to charters were various and foreshadowed those ultimately held by districts. In attempts to induce drainage and flood protection, chartered companies were given lands, money, and taxing authority, and sometimes claims to future property tax revenue (see Illinois Tax Commission (1941, p. 41)).[32] While charter companies achieved some success in getting levees built

of districts can finance drainage projects through the issuance of bonds, often surrendered to contractors in exchange for construction work. Differences in the types of operations of the two districts result in different capital intensities, different time profiles of investment, and different assessment burdens.

[31]See Smurr, 1909, page 2 on the state of drainage law in the first half of the 19th century and Barzell, more generally, on how transactions costs determine the extent of property rights definition.

[32]Examples of companies chartered for drainage include the City Bank of Cairo, an 1818 attempt to establish the town of Cairo at the southern tip of the state and protect it from flooding, and the American Bottom Improvement Board, chartered in 1851 and 1853 to control flooding along an area of the flood plain of the Mississippi River, north of Cairo

and ditches dug, an 1869 Illinois Supreme Court opinion held that they violated the state constitution on grounds of taxing residents, and supposed drainage beneficiaries, without their political representation.[33].

The definitive district-authorizing law comprised two bills, the Drainage and Levee Act and the Farm Drainage Act, which were passed by the Illinois legislature in 1879, sixty years after the first legislative authorization of a charter company. Before their passage, a prototype act authorizing districts was passed in 1871 at the urging of levee interests in the Sny Island area. But in 1876 districts under this legislation, like charter companies before them, were found to be constitutionally defective. The situation was remedied by an amendment to the Illinois constitution in 1878, followed the next year by the two district authorization acts. [34]

5.3.3 Drainage District Formation after 1879

In earlier sections, we measure the effects on drainage and farm value made possible, state by state, by the authorization of drainage districts. In every state, those outcomes coincided with the decades-long process of drainage district creation and the carrying out of their investment plans. In Illinois this process is reflected in the top panel of figure 8 based on data from a 1941 Illinois Tax Commission monograph displaying acreage in districts created as a result of the 1879 district authorization (see table A8 for number of districts as well as acreage).

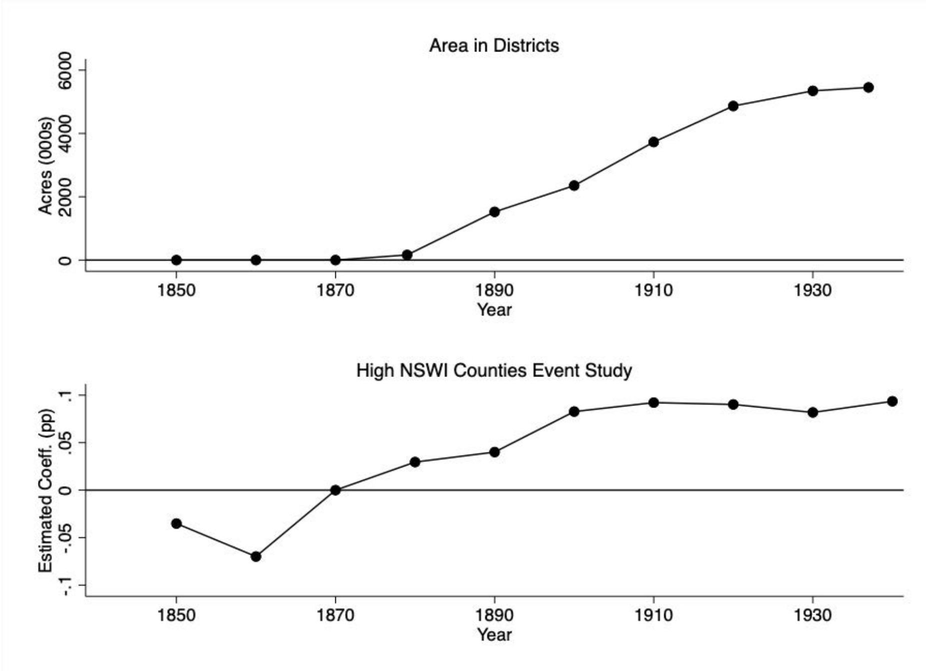
The bottom panel of figure A8 shows the corresponding event study constructed as are our

and opposite St. Louis. An 1840 charter, the Kaskaskia Navigation Company, was given authority to straighten the Kaskaskia River at the southern boundary of the Great American Bottom and to charge tolls to boats moving on the river.

[33]Early charter companies were formed in the southern part of the state, where flood control was imperative. An historically significant charter was the St. Clair and Monroe Levee and Drainage Company, authorized in two acts of the General Assembly (in 1859 and 1865) to build a levee along a 20-mile stretch of the Mississippi just south of St. Louis. After the levee was built and property owners assessed, a group of residents protested their assessments. In the 1869 decision Harwar v. St. Clair the Illinois Supreme Court found that the taxation authority granted to the charter company violated the Illinois constitution on grounds of taxation without representation. In its decision, the Court offered that drainage entities would be constitutional if legislation were passed requiring drainage commissioners to be elected by the population of a county (see Illinois Tax Commission (1941, pp.44-45))

[34]It is noteworthy that the case that ultimately determined the unconstitutionality of the prototype act (the Drainage and Levee Act of 1871) and set the stage for the two 1879 Acts was initiated, once again, by landowner complaints about assessments; this time levied by districts instead of charter companies. The constitutional test case concerned the Sny Island Drainage District, an effort to control flooding along the Mississippi River. It was Sny Island district members who pushed for passage of the 1879 Acts: "Through the efforts of C.N. Clark, a landowner and one of the leading men in the district, pressure was exerted for the passage of the constitutional amendment of 1878 and the New Drainage and Levee Act of 1879. (Illinois Tax Commission, 1941, p. 18)" The first district to be authorized under the 1879 legislation was the reconstituted Sny Island Levee Drainage District. Sixty years later, the Illinois Tax Commission commented on its subsequent success: "Once the district commenced operations under a satisfactory and enforceable law, their difficulties seem to have consisted mostly of minor ones.(Illinois Tax Commission, 1941, p. 18)"

Figure 8: Illinois Drainage Districts



Notes: Top panel source is Illinois Tax Commission (1941).

aggregate results shown in figure 6 but estimated over a panel of only Illinois counties. A comparison of the two demonstrates broad agreement between our empirical estimate of the effects of drainage district legislation and the data on acres in districts in Illinois (for which we lack data in other states). The top panel shows the total acres in districts for all counties in Illinois, which should largely represent drained acres in high NSWI counties, but will include some undrained areas and acres in low-NSWI counties. The bottom panel estimates the relative effect on improved acreage of being in a high-NSWI county in Illinois relative to the last pre-district observation, 1870, in a low-NWSI county. While we do not observe drained acres directly, we infer that in high-NSWI counties, many of the new acres are attributable to drainage. Prior to 1870, increases in improved acreage in high-NSWI counties occurred due to development without drainage and drainage development absent districts. In Illinois, the period of experimentation with drainage prior to 1879 is seen in the uptick in district acres from 1860 to 1870.

6 Conclusion

In this paper we study the historical record of farm drainage in the eastern half of the United States and estimate the role played by coordinating governance institutions. After federal and state actions to stimulate drainage failed, locally initiated drainage districts spurred investment over millions of acres. States in our sample adopted district-enabling drainage laws between 1859 and 1912, and after adoption each state saw an increase in improved agricultural land and land values, comparing counties with naturally wet soils to those with lower soil wetness. Of the 215 million acres of wetlands estimated to have existed in the contiguous United States at colonization, 124 million have been drained. (Although not considered at the time drainage was implemented, drainage has resulted in large environmental costs due to habitat destruction and degraded water quality, see Edwards and Thurman (2022) for additional discussion). Today, the Corn Belt states Minnesota, Iowa, Indiana, Illinois, and Ohio produce over 50% of their corn in counties with high natural wetness. More broadly, naturally wet counties in our sample comprise around 19% of total US agricultural land value and produce 38% of corn value. We estimate that district induced drainage increased the value of agricultural land in these counties by 20-37%, or $16.-18.7 billion in 2020 dollars.

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A1 Data Appendix

A1.1 Agricultural Census Data

We construct a panel data set consisting of 2,235 US counties with 13 observations (one per decade) in the 24 states described in section A1.3 from 1850 to 1969. These data are digitized by Haines et al. (2019). Data from the United States Census of Agriculture is used to look at farmland acres, improved acres, and total farm value per acre. The monetary measures are adjusted to constant 2020 dollars for inflation using the CPI. Because our economic data span a significant portion of the 20th century, we adopt 1910 counties as our observations, reweighting data from later years to fit these borders based on the crosswalks provided by Ferrara et al. (2021).

Table A1: Census Variables Through Time

FINAL DATASET VARIABLE	NAME	DESCRIPTION	NAME	DESCRIPTION
	1850	**1850 Description**	**1860**	**1860 Description**
Total acres in farms	ACIMP	Improved Acres in Farms	ACIMP	Improved Acres in Farms
	ACUNIMP	Unimproved acres in farms	ACUNIMP	Unimproved acres in farms
Total value of farm: land, buildings, equipment, livestock	FARMVAL	Cash value of farms	FARMVAL	Cash value of farms
		**no distinction between farm value and improvements		**no distinction between farm value and improvements
Number of improved acres in farms	ACIMP	Improved acres in farms	ACIMP	Improved acres in farms
Number of bu. of corn produced	CORN	Number of bu. of Indian corn produced, 1849	CORN	Number of bu. of Indian corn produced, 1859
Number of bu. of wheat produced	WHEAT	Number of bu. of wheat produced, 1849	WHEAT	Number of bu. of wheat produced, 1859
	1870	**1870 Description**	**1880**	**1880 Description**
Total acres in farms	ACIMP	Number of improved acres farmland	ACRES	Number of acres in farms
	ACUNIOTH	Number of unimproved acres farms		
Total value of farm: land, buildings, equipment, livestock	FARMVAL	Present cash value of farm	FARMVAL	Value of farmland/improvements
		**no distinction between farm value and improvements		**no distinction between farm value and improvements
Number of improved acres in farms	ACIMP	Number of improved acres farmland	ACIMP	Number of improved acres farmland
Number of bu. of corn produced	CORN	Number of bu. of Indian corn produced, 1869	CORN	Number of bu. of Indian corn produced, 1879
Number of bu. of wheat produced	SWHEAT	Number of bu. of spring wheat produced, 1869		
	WWHEAT	Number of bu. of winter wheat produced, 1870	WHEAT	Number of bu. of wheat produced, 1879
	1890	**1890 Description**	**1900**	**1900 Description**
Total acres in farms	FARMSIZE	Average farm size (acres)	ACFARM	Total acres of farmland
	FARMS2	Total number of farms, 1890		
Total value of farm: land, buildings, equipment, livestock	FARMVAL	Value of farmland/improvements	FARMVAL	Value of farmland/improvements (excluding buildings)
		**no distinction between farm value and improvements	FARMBUI	Value of farm buildings
Number of improved acres in farms	ACIMP	Number of improved acres in farms	ACIMP	Number of improved acres farmland
Number of bu. of corn produced	CORN	Number of bu. of Indian corn produced, 1890	corn	Number of bu. of Indian corn produced, 1899
Number of bu. of wheat produced	WHEAT	Number of bu. of wheat produced, 1890	wheat	Number of bu. of wheat produced, 1899
	1910	**1910 Description**	**1920**	**1920 Description**
Total acres in farms	FARMLAND2	Total acres in farms, 1910	VAR487	All land in farms (acres), 1920
Total value of farm: land, buildings, equipment, livestock	FARMVAL	Value of farmland/improvements (excluding buildings)	VAR23	Value of farmland/improvements (excluding buildings)
	FARMBUI	Value of farm buildings, 1910	VAR24	Value of farm buildings, 1920 (dollars)
Number of improved acres in farms	IMPAC	Number of improved acres in farms, 1910	VAR19	Number of improved acres in farms, 1920
Number of bu. of corn produced	CORN	Corn bu. 1909	VAR148	Corn (bu.), 1919
Number of bu. of wheat produced	WHEAT	Wheat bu. 1909	VAR152	Wheat (bu.), 1919

Table A2: Census Variables Continued

FINAL DATASET VARIABLE	NAME	DESCRIPTION	NAME	DESCRIPTION
	1930	**1930 Description**	**1940**	**1940 Description**
Total acres in farms	VAR8	All land in farms, acres, 1930	VAR2512	All land in farms, acres, 1940
Total value of farm: land, buildings, equipment, livestock	VAR120	Value of land & buildings, total, $, 1930	VAR29	Value of farm (land & buildings), $,1940
Number of improved acres in farms	(+) VAR13	Total crop land harvested, acres, 1929	(+) VAR10	Total crop land harvested, acres, 1939
	(+) VAR14	Total crop land with crop failure, acres, 1929	(+) VAR12	Total crop land with crop failure, acres, 1939
	(+) VAR15	Total crop land idle or in fallow, acres, 1929	(+) VAR14	Total crop land idle or in fallow, acres, 1939
	(+) VAR17	Plowable pasture, acres, 1929	(+) VAR16	Plowable pasture, acres, 1939
Number of bu. of corn produced	VAR238	Corn harvested for grain, bushels, 1929	VAR267	Corn harvested for grain, bu., 1939
Number of bu. of wheat produced	VAR246	Wheat threshed, total, bushels, 1929	VAR310	Wheat for grain, bu. (calculated), 1939
	1950	**1950 Description**	**1959**	**1959 Description**
Total acres in farms	VAR8	Land in farms, acres, 1950	VAR5	Land in farms, acres, 1959
Total value of farm: land, buildings, equipment, livestock	(*)VAR10	Value of land & buildings, average per farm, $, 1950	(*) VAR1	Farms, number, 1959
	(*) VAR1	Farms, number, 1950	(*) VAR7	Average value of land & buildings per farm, $, 1959
Number of improved acres in farms	(+) ITEM006	Harvested cropland in farms (acres), 1949	(+) VAR11	Cropland harvested, acres, 1959
	(+) ITEM009	Cropland w/ all failed crops in farms (acres), 1949	(+) VAR22	Cropland used only for pasture, acres, 1959
	(+) ITEM011	Cropland in cult. summer fallow in farms (acres), 1949	(+) VAR24	Cropland not harvested & not pastured, acres, 1959
	(+) ITEM012	Cropland idle in farms (acres), 1949	(+) VAR44	Improved pasture, acres, 1959
	(+) ITEM018	Other improved pasture & rangeland in farms (acres),1949		
Number of bu. of corn produced	VAR449	Corn harvested for grain, bushels, 1949	VAR878	Corn harvested for grain, bu., 1959
Number of bu. of wheat produced	VAR485	All wheat threshed or combined, bushels, 1949	VAR916	Wheat, bu., 1959
	1969	**1969 Description**		
Total acres in farms	ITEM01002	Land in farms (acres), 1969		
Total value of farm: land, buildings, equipment, livestock	(*) ITEM01001	Farms (number), 1969		
	(*) ITEM01007	Value of land and buildings:Average per farm ($), 1969		
Number of improved acres in farms	(+) ITEM01026	Cropland, all crops failed (acres), 1969		
	(+) ITEM01028	Cropland in cultivated summer fallow (acres), 1969		
	(+) ITEM01030	Cropland idle (acres), 1969		
	(+) ITEM01038	Harvested cropland (acres), 1969		
	(+) ITEM01065	Improved pasture & rangeland (acres), 1969		
Number of bu. of corn produced	ITEM401	Production: field corn for grain or seed (bu.), 1969		
Number of bu. of wheat produced	ITEM10015	Production: wheat (bu.), 1969		

A1.2 Geological and Geographic Variables

We use the Natural Soil Wetness Index (NSWI) to represent the water content in the soil of a given county absent anthropognic modification (Schaetzl et al., 2009). The name of this index has been changed to the Soil Drainage Index (DI) but we use the older name to avoid confusion between naturally poor drainage (NSWI) and artificial drainage. The NSWI is an ordinal measure of long-term soil wetness ranging from 0 to 99. Soils with a NSWI of around 60 are generally termed "somewhat poorly drained," while higher NSWI values represent more poorly drained up to 99, which is open water. The NSWI is derived from soil classification and slope and so is not affected by drainage or irrigation. A soil's taxonomic classification is not initially affected by on-farm investments like irrigation or artificial drainage and so the NSWI does not change unless these investments change the classification of the soil in the long-run. 'Instead, the NSWI reflects the soil's *natural* wetness condition. Each soil *series* has, in theory, its own unique NSWI." (Schaetzl et al., 2009)"

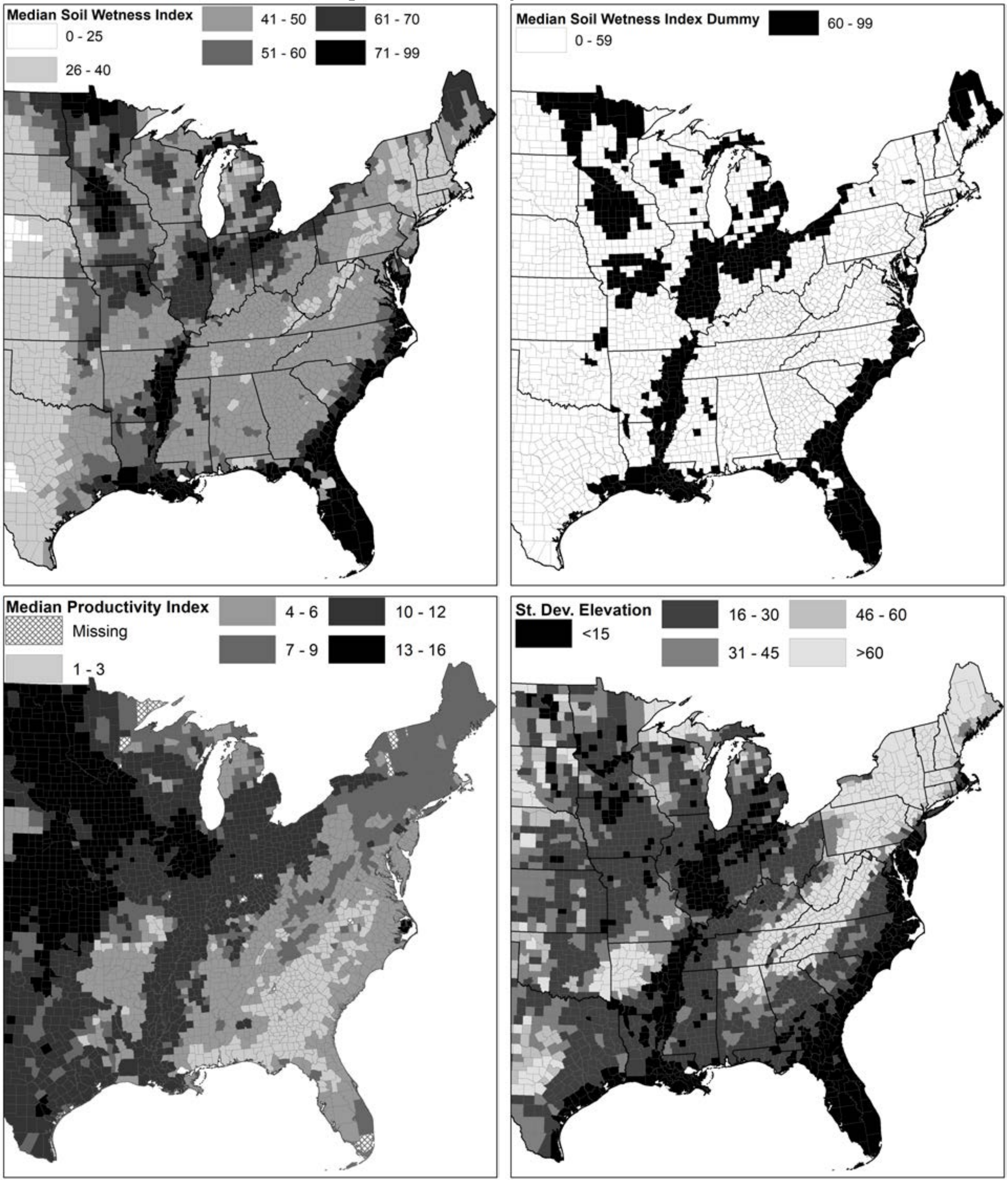
We also construct a measure of roughness, the standard deviation of elevation for each county. Maps of county PI and roughness measures are shown in figure A1. The relationship between roughness and Soil Wetness Index is shown in the top panels of figure 4. In these panels we highlight two sets of counties that roughly correspond to the categories in figure 3: in the Midwest those with NSWI>60 and roughness greater than 38.5 (75th percentile) are shown in green; in the Coastal Plain counties with NSWI>60 and roughness below 2.6 are plotted in red. The bottom panels of figure 4 show the relationship between proportion of total county area drained and NSWI.[35] A map of the different categories of counties is shown in figure A2.

To control for soil quality in cross-sectional regressions, we use the Soil Productivity Index (PI) developed by Schaetzl et al. (2012). The PI is an ordinal measure of how advantageous the soil is to crop production based on soil taxonomy. The index ranges from 0 to 19, with 19 being the most productive.[36]

[35] Similar figures comparing drained acreage from 1920, 1930, ad 1969 are shown in figure A3.

[36] "Soil productivity can be easily and rapidly amended by human activities. Thus, no index of productivity can accurately assess current soil productivity where soils have had a long history of cropping, erosion, and/or additions of soil amendments. Particularly, irrigation and drainage practices impact soil fertility/productivity and, therefore, any index of productivity is only an estimate; it is always affected by land-use practices, both current and those in the past. Thus, we focus on natural native soil productivity, as expressed in a soil's taxonomic classification and recognize that such an estimate is, at best, a good starting point." (Schaetzl et al., 2012)

Figure A1: County Land Features



Notes: The top panels show the median drainage index for each county east of the 100th Meridian and the constructed variable *High Drainage* which is counties with median drainage index greater than 60. The bottom panels show the county-level measures of soil productivity and the standard deviation of elevation, a measure of flatness.

Figure A2: Natural Soil Wetness Index and Roughness Heterogeneity

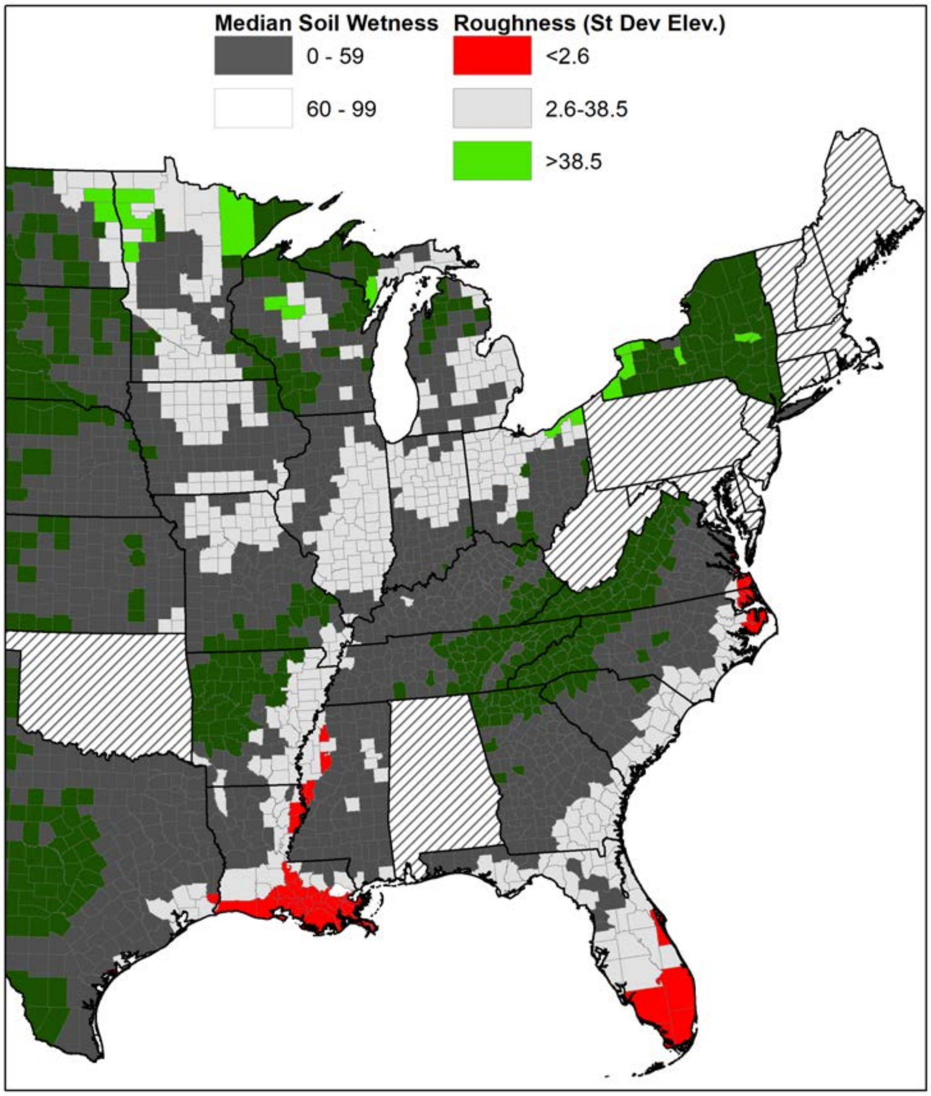
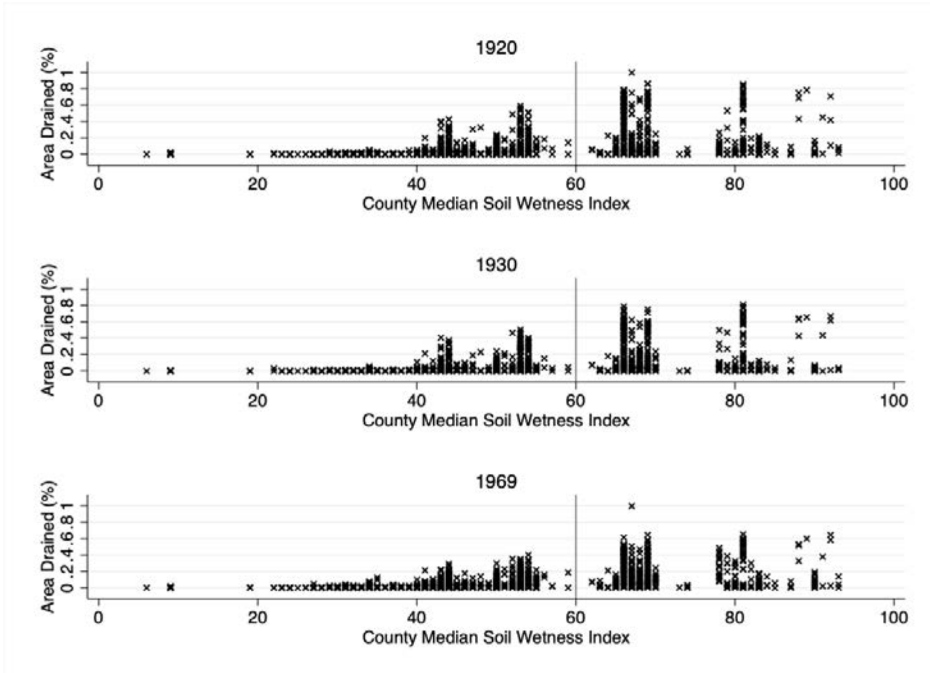


Figure A3: Natural Soil Wetness Index and Drainage



Notes: This figure depicts, for each county in our sample, the relationship between the median drainage index extracted from each county shape and the percent of county area drained for each of 1920, 1930, and 1969.

A1.3 Drainage District Legislation

First drainage district legislation data are collected by the authors from various sources. Drainage district legislation is considered to be the first bill that successfully allows the petition of landowners to create a district governed by some elected body, e.g. drainage commissioners (see (Sandretto, 1987)). For example, from the Illinois Department of Archives:

> *"The Illinois Constitution of 1870 authorized the General Assembly to pass laws giving landowners drainage rights, including the use of adjoining land for ditching purposes. As a result, a comprehensive drainage law was passed in 1871. The law set up legal procedures for local citizens to petition the county courts for drainage works, assessing and collecting the costs of the drainage construction from the owners of the lands to be benefited by the work, and compensating the owners of land which would be entered for ditching purposes. ... The 1871 law was found unconstitutional; as a result the Illinois Constitution was amended, making drainage commissioners the heads of corporate drainage districts and giving these districts constitutional authority to levy property taxes. Two separate and coequal Illinois drainage laws were passed in 1879. One, the 'Levee Law,' repeated the procedures of the 1871 law, with added procedures for legal appeal by landowners dissatisfied with their assessments; the second, the 'Drainage District Law,' made the township highway commissioners the township drainage district commissioners. ... [T]he responsibilities of drainage commissioners have largely remained unchanged since 1871." [Illinois Secretary of State, 2022.]*

As this paragraph demonstrates for Illinois, considerable discretion must be exercised in identifying the date in which viable drainage legislation was passed. For Illinois, based on this passage we find the 1879 law best met our previously discussed criteria for drainage district legislation.

There are 25 states with similar drainage district legislation east of the 100th Meridian. We drop Oklahoma (drainage law date 1908) from the analysis due to its isolation from typical drainage geology.

Drainage law passage dates for the remaining 24 states are obtained from the following sources:

- Ohio (1859) (McCorvie and Lant, 1993)
- Indiana (1863) (Vermillion, 2011)
- Michigan (1869) (Quackenbush, 1973)
- Kansas 1879 (McCorvie and Lant, 1993)
- Illinois (1879) (Herget, 1978)
- Nebraska (1881) (Fischer et al., 1970)
- Iowa (1884) (Sherman, 1924)
- Minnesota (1887) (Palmer, 1915)
- Wisconsin (1899) (Prince, 1995; Graham, 1919)
- Missouri (1899) (Olson et al., 2016)
- Arkansas (1904) — however, issues existed and 1917 was the year of effective legislation for the creation of the Ross Drainage District (Deaton, 2016)
- Texas (1905) (Smith, 1952)
- Louisiana 1907, both (Gagliano, 1973) and (Okey, 1914) reference this year although Palmer (1915) discussed 1906 and 1910
- North Carolina 1909 (O'Driscoll, 2012)
- South Carolina (1912) (Eason, 1918)

- Palmer (1915) provides the sole source for dates of effective legislation in nine states: North Dakota (1895), Virginia (1906), Mississippi (1906), Florida (1907), South Dakota (1907), Tennessee (1909), New York (1909), Georgia (1911), Kentucky (1912).

Palmer (1915) discusses drainage district laws of Connecticut (1861), Delaware (1901), Maryland (1858), Pennsylvania(1863), West Virginia (1860), New Jersey (1878), Maine (1903), Massachusetts (1902), Rhode Island (1896), and Vermont (1906) as being different from the drainage laws in states with higher levels of agricultural production, essentially providing existing public agencies the right of eminent domain for drainage but not creating districts or empowering landowners to petition for district creation. These states are excluded from our analysis.

A2 Results Appendix

Figure A4: Geographical Classification

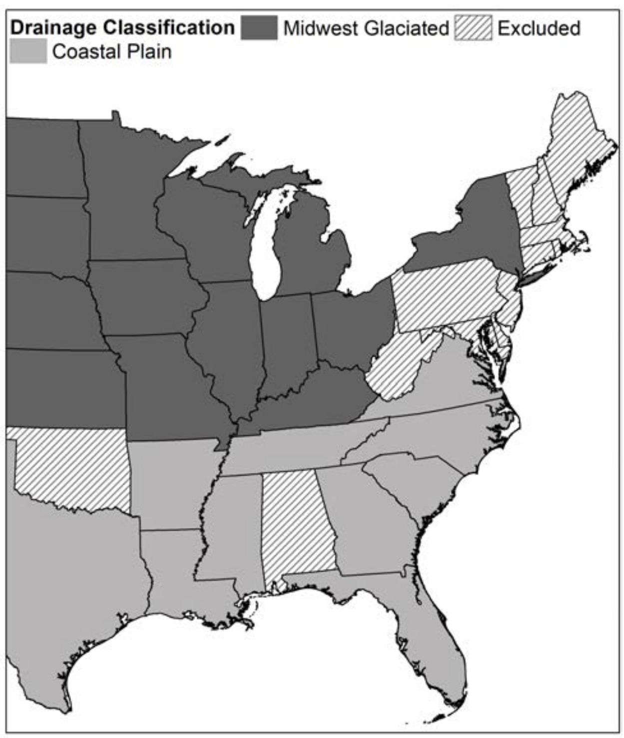
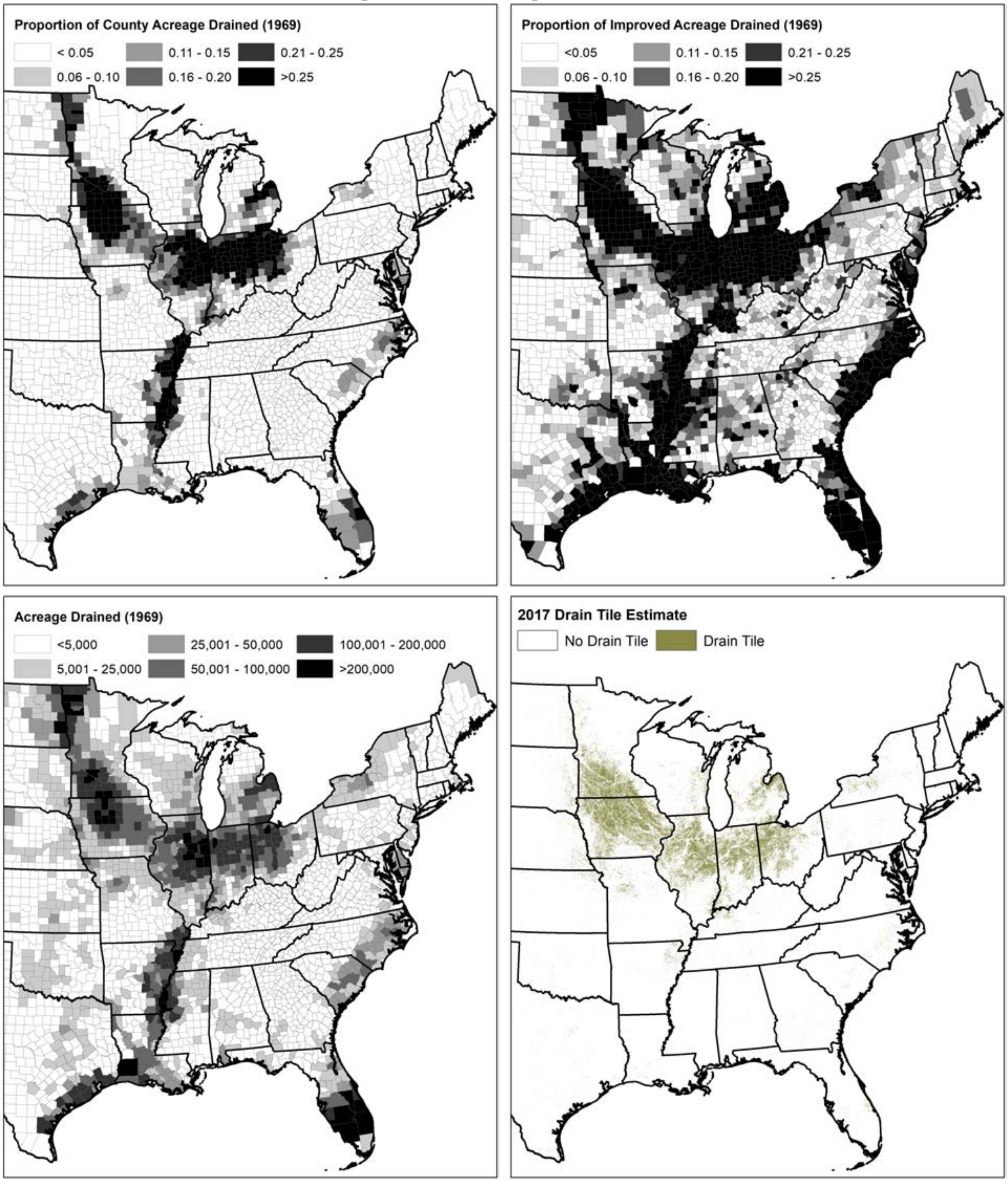


Figure A5: Drainage Outcomes



Notes: The state of drainage as of 1969 by percentage of county area, percentage of improved area, and total acres. The figure also shows the estimated area of tile drainage in 2017, which although not available from the 1969 census data, provides an estimate of historic drain tile locations. When compared to the maps of drainage index and topography from figure A1, it is clear that drainage index and actual area drained are closely related. Comparison to the right panel of figure 1 shows the tile drainage has been primarily a phenomenon linked to glaciated flat lands.

Table A3: Conditional Summary Statistics: Midwest Tile

	Drainage Index<60		Drainage Index>60	
Variable	Pre	Post	Pre	Post
Total value in farms (2020$ millions)	131	330	114	444
	(161)	(275)	(139)	(352)
Land value per acre (2020$)	692	1,181	544	1,486
	(1,482)	(1,942)	(370)	(930)
Proportion of County Improved	0.37	0.53	0.32	0.63
	(0.26)	(0.24)	(0.25)	(0.22)
Total number of farms	1,651	1,971	1,430	2,294
	(1,307)	(986)	(1,180)	(1,015)
Total acres in farms	195,838	302,582	174,528	298,576
	(140,157)	(166,907)	(126,399)	(143,940)
Bushels of Corn	674,718	1,601,079	841,917	2,341,304
	(863,780)	(1,905,892)	(990,700)	(2,508,220)
Bushels of Wheat	194,361	371,610	216,247	459,511
	(302,013)	(591,277)	(386,466)	(625,085)
County Median Drainage Index	44.65		69.72	
	(6.96)		(5.99)	
Median productivity index	10.85		11.94	
	(3.33)		(1.87)	
Median elevation (m)	320.48		260.12	
	(130.19)		(80.02)	
Standard deviation elevation (m)	34.39		19.20	
	(27.87)		(13.04)	

Notes: Summary statistics conditional on treatment status: high drainage counties $DI > 60$ and pre/post drainage district laws. All values are the mean value of all the counties in that treatment status for the variable described on the left and for the four years before/after treatment. Standard deviations are reported in parentheses.

Table A4: Conditional Summary Statistics: Coastal Plain

Variable	Drainage Index<60 Pre	Drainage Index<60 Post	Drainage Index>60 Pre	Drainage Index>60 Post
Total value in farms (2020$ millions)	54	161	44	185
	(59)	(150)	(44)	(192)
Land value per acre (2020$)	285	765	305	960
	(344)	(2,439)	(253)	(1,222)
Proportion of County Improved	0.26	0.30	0.14	0.25
	(0.15)	(0.15)	(0.11)	(0.17)
Total number of farms	1,387	2,216	1,162	2,604
	(1,116)	(1,420)	(1,026)	(2,244)
Total acres in farms	198,915	247,811	167,572	204,176
	(128,207)	(165,912)	(117,790)	(130,559)
Bushels of Corn	345,475	425,495	254,659	477,991
	(336,119)	(380,204)	(198,253)	(434,117)
Bushels of Wheat	42,311	52,023	4,844	10,883
	(82,887)	(116,919)	(19,368)	(42,825)
County Median Drainage Index	43.30		75.85	
	(5.31)		(7.87)	
Median productivity index	5.76		7.33	
	(3.12)		(3.54)	
Median elevation (m)	233.15		34.44	
	(195.71)		(28.79)	
Standard deviation elevation (m)	50.79		8.48	
	(55.12)		(6.24)	

Notes: Summary statistics conditional on treatment status: high drainage counties $DI > 60$ and pre/post drainage district laws. All values are the mean value of all the counties in that treatment status for the variable described on the left and for the four years before/after treatment. Standard deviations are reported in parentheses.

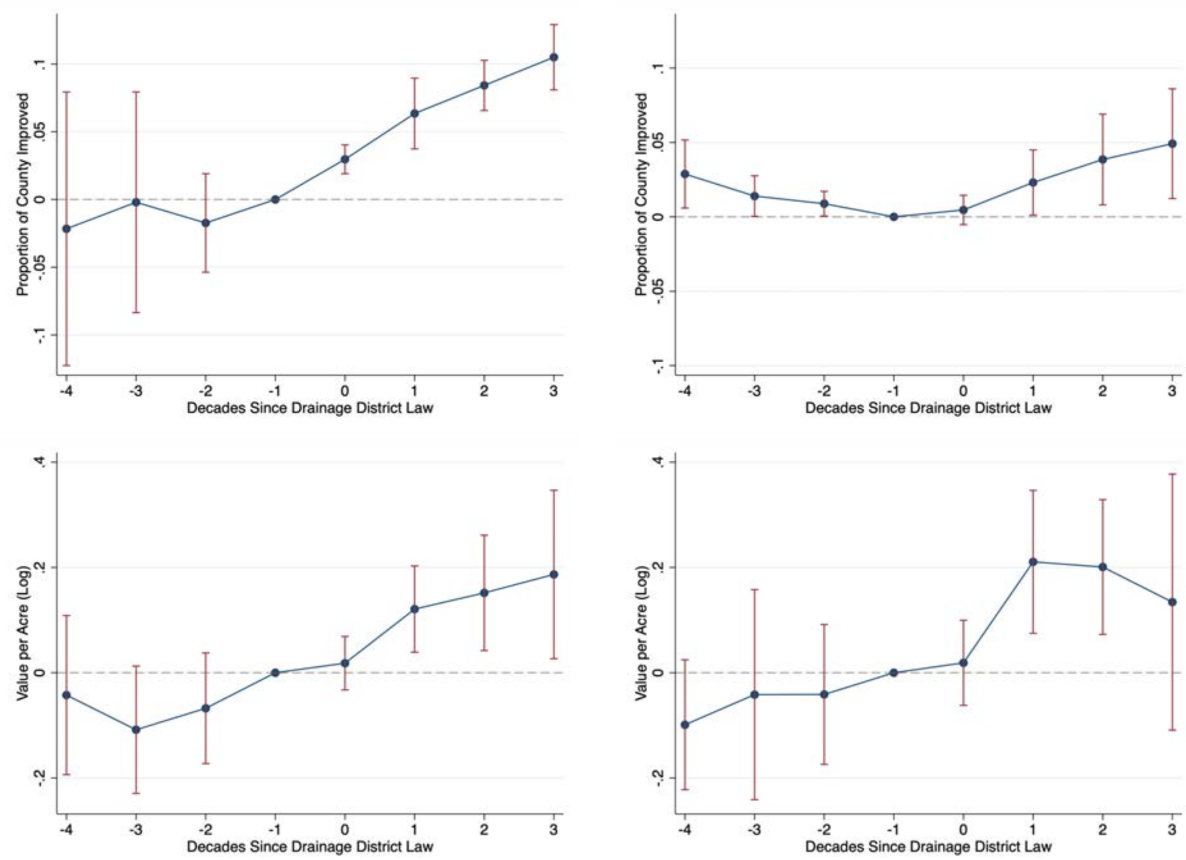
Table A5: Treatment Effect Heterogeneity

	All States in Sample		Midwest Tile		Coastal Plain	
	Prop. Impr.	$/ac (log)	Prop. Impr.	$/ac (log)	Prop. Impr.	$/ac (log)
Baseline	0.058***	0.196***	0.074***	0.156***	0.034*	0.257***
	(0.011)	(0.043)	(0.013)	(0.047)	(0.016)	(0.074)
High Roughness	-0.023	-0.105*	-0.02	-0.113*		
	(0.022)	(0.061)	(0.021)	(0.060)		
Low Roughness	-0.01	-0.039			-0.018	-0.02
	(0.019)	(0.165)			(0.022)	(0.168)
Obs	14,476	14,466	7,531	7,533	6,945	6,933
R^2	0.909	0.889	0.911	0.904	0.849	0.843

Notes: This table presents difference-in-difference estimates for the effect of drainage district adoption on high soil wetness index counties ($NSWI > 60$) relative to others, with counties spilt into three exclusive categories: those with low roughness (standard deviation of elevation meters less than 2.6), high roughness (standard deviation of elevation in the top quartile of all counties); and all remaining counties with $NSWI > 60$. All specifications include state-by-year and county fixed effects. Standard errors are clustered by county and reported in parentheses; statistical significance is indicated by $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. Coefficient comparisons show statistical differences at the 1% significance level for comparison of high roughness to baseline counties; comparisons are statistically significant for low roughness relative to baseline counties at the 5% level for proportion improved but not for value per acre.

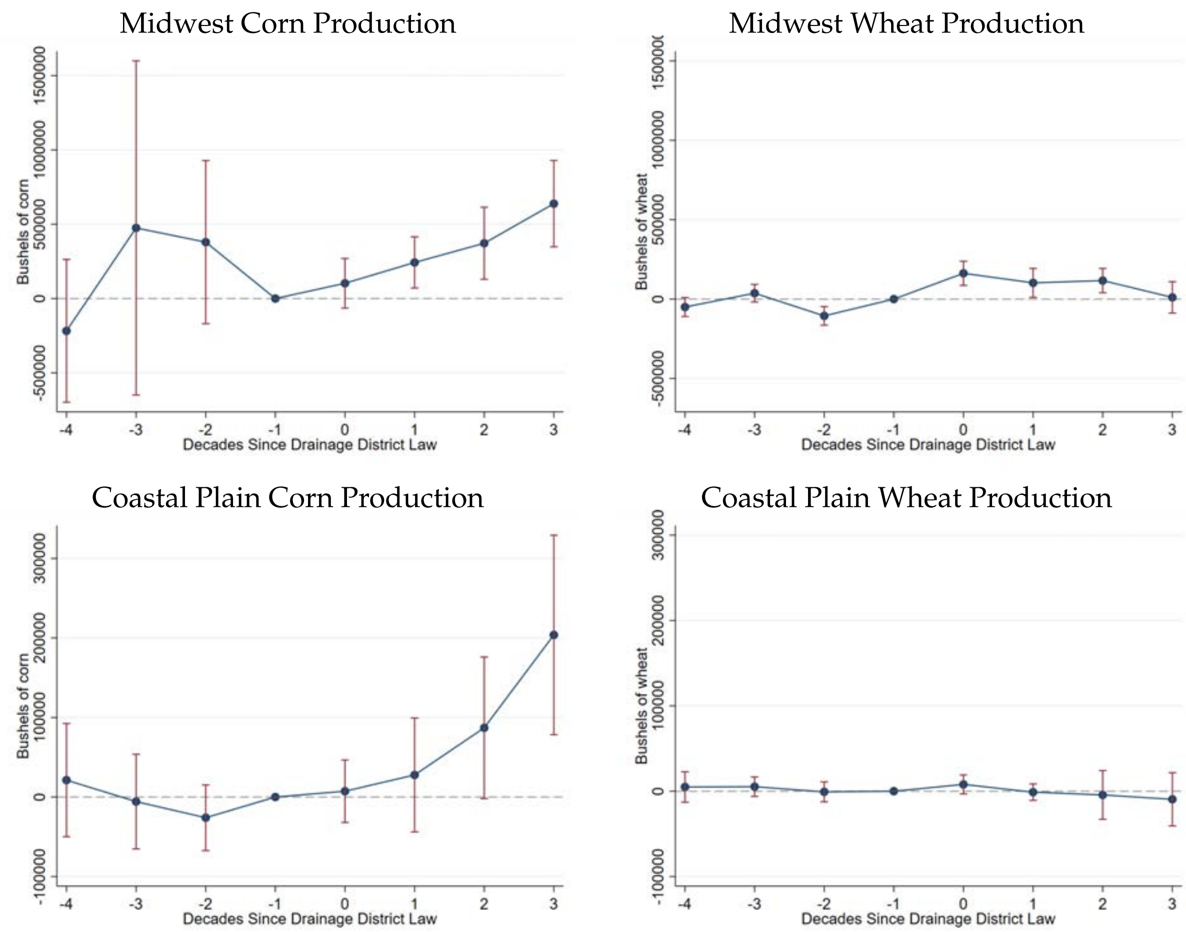
Figure A6: Event Studies by Region

Midwest Glaciated | Coastal Plain



Notes: This figure depicts event study estimates using the estimator developed by de Chaisemartin and d'Haultfoeuille (2020), implemented with the `did_multiplegt` package in Stata. The model corresponds to the specification in columns 3-6 of Panel A of Table 3, which includes county fixed effects and state-by-year fixed effects. The difference between treated and untreated groups is normalized to zero in period $t-1$, the final period before treatment. Period 0 denotes the first period in which parcels are exposed to treatment. The sample includes counties in 14 Midwest states and 10 Coastal Plain states. Treatment is DI¿60 after drainage law passage, excluding counties with high roughness (Roughness = fourth quartile). Counties with roughness less than fifth percentile are excluded.

Figure A7: Wheat and Corn Production Event Studies by Region



Notes: This figure depicts event study estimates using the estimator developed by de Chaisemartin and d'Haultfoeuille (2020), implemented with the `did_multiplegt` package in Stata. The model corresponds to the specification in columns 3-6 of Panel A of Table 3, which includes county fixed effects and state-by-year fixed effects. The difference between treated and untreated groups is normalized to zero in period $t-1$, the final period before treatment. Period 0 denotes the first period in which parcels are exposed to treatment. The sample includes counties in 14 Midwest states (top) and 10 Coastal Plain states (bottom). Treatment is NSWI¿60 after drainage law passage, excluding counties with high roughness (Roughness = fourth quartile). Counties with roughness less than fifth percentile are excluded. Note y-axes have different scale sin top and bottom panels.

Table A6: Crop Production after Drainage District Law

	(1)	(2)	(3)	(4)	(5)	(6)
	All States in Sample		Midwest Glaciated		Coastal Plain	
	Corn (bu)	Wheat (bu)	Corn (bu)	Wheat (bu)	Corn (bu)	Wheat (bu)
Panel A:						
			de Chaisemartin & D'Haultfoeuille (2020)			
Post Drain. Dist. Law	245,941***	76,963**	339,395***	97,792**	81,436**	-519
	(50,728)	(32,090)	(98,307)	(35,563)	(38,595)	(8,696)
Panel B:						
			Callaway & Sant'Anna (2020)			
Post Drain. Dist. Law	206,237	51,267	207,675	53,944	91,187***	-9,654
	(148,028)	(46,249)	(257,309)	(62,760)	(31,096)	(15,148)
Panel C:						
			Two-Way Fixed Effects			
Post Drain. Dist. Law	100,925	69,482*	88,119	105,068*	116,039**	157
	(124,392)	(35,489)	(229,678)	(50,969)	(44,890)	(5,177)
Observations	14,042	14,476	7,409	7,531	6,633	6,945
R$2̂$ (TWFE)	0.908	0.909	0.911	0.911	0.843	0.849

Notes: This table presents difference-in-difference estimates for the effect of drainage district adoption on high drainage index counties relative to others based on the model in Equation 1 using several estimators. Panel A uses the estimator proposed by de Chaisemartin and d'Haultfoeuille (2020) and implemented with the `did_multiplegt` Stata package with four leads and four lags of treatment. Panel B uses the estimator proposed by Callaway and Sant'Anna (2020) and implemented with the `csdid` package in Stata. Panel C presents traditional TWFE estimates obtained via OLS. Panels A and C include state-by-year fixed effects, whereas Panel B uses pooled year fixed effects due to limitations of the `csdid` package. Standard errors are clustered by county and reported in parentheses; statistical significance is indicated by $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table A7: Regression Results without County Fixed Effects

	(1) Pct. Impr.	(2) Pct. Impr.	(3) Pct. Impr.	(4) \$/ac (log)	(5) \$/ac (log)	(6) \$/ac (log)
Panel A: All States in Sample						
Post Dist. Law (High NSWI)	0.056***	0.057***	0.064***	0.169***	0.168***	0.175**
	(0.013)	(0.012)	(0.021)	(0.045)	(0.048)	(0.073)
Productivity Index		0.032***	0.033***		0.067***	0.066***
		(0.004)	(0.004)		(0.014)	(0.014)
Elevation (m x 10^{-3})		-0.193**	-0.193**		-0.925***	-0.925***
		(0.074)	(0.072)		(0.193)	(0.193)
Roughness (m x 10^{-3})		-0.307	-0.265		-0.603	0.268
		(0.291)	(0.269)		(0.900)	(0.961)
Post Dist. Law x Roughness (m x 10^{-3})			-0.179			-1.371**
			(0.186)			(0.599)
High NSWI x Roughness (m x 10^{-3})			4.074***			-1.79
			(1.414)			(5.020)
Post x High NSWI x Roughness (m x 10^{-3})			-0.887			-2.212
			(0.790)			(2.906)
Obs.	14,476	14,406	14,406	14,466	14,396	14,396
R^2	0.493	0.610	0.616	0.530	0.598	0.599
Panel B: Midwest Glaciated						
Post Dist. Law (High NSWI)	0.067***	0.058***	0.092***	0.165***	0.134***	0.238***
	(0.019)	(0.014)	(0.029)	(0.032)	(0.037)	(0.051)
Productivity Index		0.043***	0.042***		0.054*	0.054*
		(0.006)	(0.006)		(0.027)	(0.027)
Elevation (m x 10^{-3})		-0.467***	-0.464***		-1.792***	-1.789***
		(0.120)	(0.120)		(0.339)	(0.339)
Roughness (m x 10^{-3})		-0.706	-0.479		-3.051	-1.963
		(0.420)	(0.469)		(2.657)	(2.947)
Post Dist. Law x Roughness (m x 10^{-3})			-0.397			-1.649
			(0.303)			(1.389)
High NSWI x Roughness (m x 10^{-3})			2.104			3.781
			(1.217)			(2.485)
Post x High NSWI x Roughness (m x 10^{-3})			-1.865*			-5.838**
			(1.050)			(2.056)
Obs.	7,531	7,499	7,499	7,533	7,501	7,501
R^2	0.463	0.686	0.688	0.5	0.63	0.631
Panel C: Coastal Plain						
Post Dist. Law (High NSWI)	0.025	0.024	0.012	0.205**	0.199**	0.039
	(0.018)	(0.018)	(0.028)	(0.081)	(0.081)	(0.103)
Productivity Index		0.017***	0.017***		0.061***	0.059***
		(0.003)	(0.003)		(0.011)	(0.011)
Elevation (m x 10^{-3})		-0.085	-0.085		-0.617*	-0.615*
		(0.051)	(0.050)		(0.278)	(0.281)
Roughness (m x 10^{-3})		-0.378	-0.372		-0.227	0.386
		(0.313)	(0.253)		(0.591)	(0.739)
Post Dist. Law x Roughness (m x 10^{-3})			-0.026			-0.855
			(0.186)			(0.621)
High NSWI x Roughness (m x 10^{-3})			1.462			-42.362**
			(2.986)			(15.175)
Post x High NSWI x Roughness (m x 10^{-3})			1.416			16.763*
			(1.741)			(8.923)
Obs.	6,945	6,907	6,907	6,933	6,895	6,895
R^2	0.284	0.352	0.353	0.447	0.490	0.500

Notes: This table presents difference-in-difference estimates for the effect of drainage district adoption on high NSWI counties ($NSWI > 60$) relative to others. These regressions include all counties, including those with high and low roughness. All specifications include state-by-year and state fixed effects. Standard errors are clustered by state and reported in parentheses; statistical significance is indicated by $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table A8: Number of Drainage Districts and Acreage

Year	Number	Acreage
1879	205	163,000
1890	322	1,522,900
1900	594	2,353,700
1910	1,059	3,728,700
1920	1,324	4,867,100
1930	1,526	5,346,100
1937	1,541	5,454,000

Notes: Number of drainage districts of both types, levee and tile-and-ditch. Note the immediate response after 1879 and also the long trajectory of district formation. Source: Table 1 from Illinois Tax Commission (1941)

A3 Poem Appendix

From L.H. Bailey, founding Dean of Agriculture at Cornell University, serving from 1903 to 1913:

"Tile Drain"

Far under the ground
as men pass by
unseen and alone
I silently lie.

When the plow-team tramps
on the full crunching earth
I feel the hard thrust
of the first harvest birth;
but the plow man thinks not
that I lie down below
and tireless prepare for the harvest to grow.

Calm and content
I secretly lie
and carry my work
as men pass by.

Dedicated "to Prof. Fippin who likes tile drains."

From E.R. Jones, first Chair of the Department of Agricultural Engineering in the College of Agriculture at the University of Wisconsin (Madison), serving from 1918 to 1936:

Untitled

John Johnston, he of Scottish birth
Brought tiling to the west
While Johnston tiled
His neighbors smiled
But he smiled last and best.

Both poems cited in Weaver (1964).