The Institutional Costs of Adaptation: Agricultural Drainage in the United States

Eric C. Edwards and Walter N. Thurman*

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Abstract

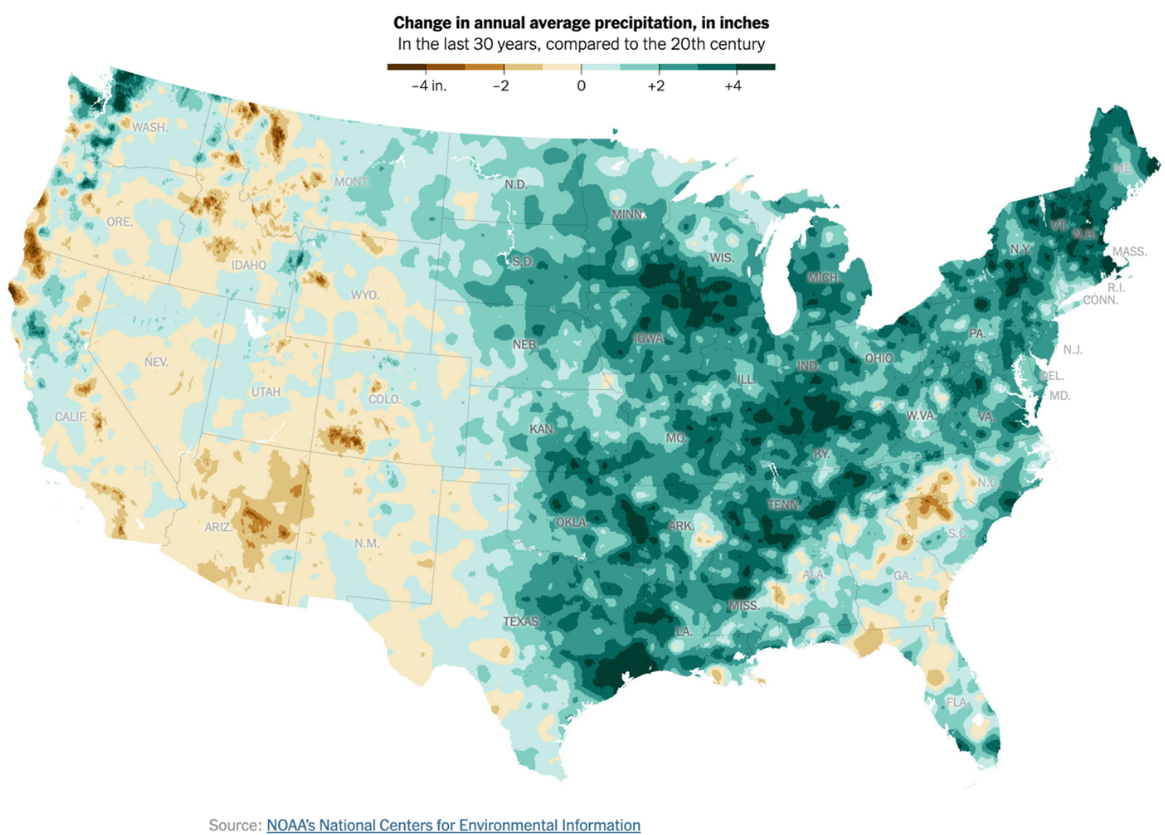
Tile drainage was first demonstrated in the United States in Upstate New York in 1835 as a method to adapt agriculture to excessive water in soils. Subsequently, innovations in coordinated drainage enterprises, engineering, and tile manufacture led to drainage over large portions of the U.S. Midwest and Southeast. Of the 215 million acres of wetlands estimated to have existed in the contiguous United States at colonization, 124 million have been drained today, 80-87% for agricultural purposes. In this paper we argue that a key institutional innovation, the drainage management district, facilitated local investment in drainage. States in our sample adopted drainage laws between 1857 and 1932, and after adoption each state saw an increase in improved agricultural land in counties with poorly drained soils relative to well-drained counties. We estimate artificial drainage increased the value of agricultural land in each of the worst-drained counties of the eastern United States by 13.5-30.3%, a total increase in these counties of $7-17B (2020 dollars). With the increasing likelihood of extreme precipitation events across the entire U.S., technical innovation in drain tile will be a key component of adaptation to climate change. Our paper points as well to the importance of institutional innovation and its associated costs.

*North Carolina State University

1 Introduction

Climatic factors like heat stress and drought play a key role in reducing agricultural yields ((Ortiz-Bobea et al., 2019). In the western United States, anthropogenic climate change is expected to increase the frequency of high temperature days and drought (Strzepek et al., 2010). Accordingly, there has been considerable focus on the role irrigation will play in adaptation (Schlenker et al., 2005; Smith and Edwards, 2021). In the eastern United States, however, projections of climate change suggest a need to adapt to more precipitation, not less (Rosenzweig et al., 2002). Figure 1 compares precipitation in the last 30 years to the 20th Century and shows significant increases in precipitation for most areas east of the Mississippi.

Figure 1: Changes in Precipitation over Last 30 Years



Across the United States, all regions are projected to see heavier rainfall events under climate change, even those regions that see less precipitation overall (Easterling et al., 2017). The ability of farmers to remove excess water from fields will be crucial to ensuring a secure and reliable food supply. 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. To address issues of excess soil moisture, water tables can be artificially lowered via within-soil flow if nearby drainage provides a pathway for water out of the plant root zone. Most field crops expereince no long-term damage from rainfall events if water tables fall to six inches below ground surface within one day and continue falling to 18 inches from ground surface within three days (Hofstrand et al., 2010).

A dramatic feature of 19th and 20th century agricultural development in the Midwest and Eastern U.S. was the application of drainage technologies to move water off of saturated lands. (See, for example, Bogue (1951) and Bogue (1963)) In fact, a significant portion of the eastern United States, including the upper Midwest, Mississippi River Basin, and eastern Coastal Plain would not be suitable for agricultural production absent such drainage. Looking forward to changing climatic conditions, agronomists, engineers and economists are discussing the technical issues associated with intensifying drainage to deal with increasing precipitation while, at the same time, protecting water quality (Castellano et al., 2019).

Missing so far from the discussion of adaptation to increased precipitation is the current state of the broad-scale drainage networks in place and the emergence of the drainage governance institutions that manage them. The physical fact of extensive tiled acreage in the Midwest is an important determinant of the costs of future adaptation that involves drainage. Understanding drainage governance can lead to an inclusive understanding of costs of climate adaptation. We conclude that the institutional costs to adapt are likely to be high, and discussion of agricultural adaptation to date has largely ignored these costs. Studying the history of drainage and empirically analyzing its effects offers lessons into how adaptation problems emerge, are solved, and at what cost.

A significant portion of the eastern United States has poorly drained soils that can be made substantially more productive via artificial drainage. 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 drained into Lake Erie at modern-day Toledo. Other actions were carried out at smaller scales on undulating fields in Indiana, Illinois, and Iowa that were only partially submerged. Settlers began farming higher, drier ground first and, over time, converted lower swales into additional farmland through drainage [1]

Large or fine scale, drained land was an essential input into the production of Midwestern crops—mainly oats and corn. One key barrier to the adoption of widespread drainage was the coordinated action required to finance, route, and build the large open ditches that served as outlet drains for tiled fields. It was the combination of innovations in drainage enterprises, engineering, and tile manufacture that allowed drainage to begin in earnest across the country (McCrory, 1928). Today, of 215 million acres of wetlands estimated to exist in the contiguous United States at colonization, 124 million have been drained, 80-87% for agricultural purposes (McCorvie and Lant, 1993; Tiner, 1984) [2]

The development of agricultural production on poorly drained lands can be understood in terms of the significant changes over time in underlying determinants of demand for drainage; and the spatial distribution of drained land can be understood in terms of spatial variation in these determinants. In 1880, it was estimated the drainage of unimproved wetlands increased sale value by a factor of five (Prince, 2008). Yet capturing these increased values required coordination among neighboring landowners that was initially absent.

The U.S. government passed a series of Swamp Land Acts (1849, 1850, and 1860), which allocated 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 because "piecemeal ditching" was ineffective absent open outlet channels and coordinated drainage works, which 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)" Large investment in drainage works required institutional innovation through the creation of drainage management districts.

The eventual dispersion of the Swamp Land Act lands to private landowners aligned their incentives and led to "bottom-up" institutional innovation to solve the drainage coordination problem. While drainage required coordination over areas of several square miles or more, farms in

[1] "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)"

[2] Draining vast areas of the Midwest farmland had its unintended consequences, notably 20th century algal blooms in lakes and a hypoxic Dead Zone in the Gulf of Mexico. (See, for example, Mitsch (2017)).

the wet prairie counties were smaller, around 150 acres, due to the increasing costs of monitoring labor on larger farms (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. Drainage district laws provided sufficient legal structure for collective investment in drainage through local taxing and eminent domain authority, for which we find evidence.

Using data from the agricultural census on improved agricultural acres and farm value spanning the development of agricultural drainage across the eastern United States, we compare counties with poorly drained soils to those that were well-drained within the same state. Difference-in-difference analysis reveals that after the enactment of drainage district legislation, poorly-drained counties saw relative increases in improved acres and land value. We estimate artificial drainage increased the value of agricultural land in the worst-drained counties of the eastern United States by 13.5% to 30.3%. There are 513 counties in the poorly drained category, and their combined increase in land value after the enactment of drainage district legislation sums to between $7.4B and $16.6B in 2020 dollars.

Agricultural drainage in the eastern U.S. is in many ways analogous to irrigation in the West, in that both fixed investments in location specific assets that greatly increased agricultural production. In the modern day, both have important implications for farm adaptability to a changing climate. Changing patterns of precipitation and shifting growing regions could make agricultural production less suitable on the locations that in the past have made drainage investments, opening the possibility of new investment in drainage Meyer and Keiser (2018) project increased tile drainage in the northern Midwest—North Dakota, Minnesota, Michigan, and Wisconsin—and suggest that absent drainage, losses due to climate change will be larger.

While technical innovation in drain tile was a key component of the development of drainage, our paper points as well to the importance of institutional innovation. Today, agricultural drainage is perceived to have had much higher costs than initially anticipated, both in terms of reducing the amount of wetlands in the U.S. as well as providing a more direct conduit for agricultural nutrients to make their way into rivers, lakes, and oceans. The region projected to see increases in drainage would undoubtedly include important undeveloped wetlands, such as the Prairie Pothole Region (Dahl, 2014). While will move to agriculture to reflect changing climatic conditions, new institutional innovations that coordinate over wetland protection and nutrient pollution, as well as agricultural production will enhance the net value of such an adaptation.

2 Empirical Setting

2.1 Drainage and Drain Tile

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 artificially lowered via within-soil flow if nearby drainage provides a pathway for water out of the plant root zone. Throughout the United States and from its beginnings ditches have been dug for this purpose. The construction of open ditches to remove excess standing water and lower water tables was utilized throughout the United States from its founding for this purpose. The earliest attempts at drainage in the Midwest, in 1818, were of this type (Prince, 2008, p. 205). However, these 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 regular intervals, they reduced the available land surface area and made planting and harvesting difficult. Methods for draining water while maintaining the integrity of the land surface via *underdrainage* was required for practical use.

Stone and pole underdrainage was utilized in urban settings throughout the 19th Century, but was uneconomical for general agricultural adoption. 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 in effectiveness and once implemented in a field, saw declines in effectiveness within a few years. The technology that ultimately replaced digging ditches was the laying of drain tile, an advance that transformed American agriculture. 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 drainage was invisible and allowed farming above it.[3]

[3]Modern land drainage follows the same principle, but involves the burying of perforated, corrugated, plastic tubing

It was the advent and diffusion of clay drain tile, first used in the United States in Seneca County, New York in 1835, that changed agriculture in the United States (McCrory, 1928). 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 was eventually replaced by cylindrical tile starting around 1858 (McCrory, 1928). The first tile manufacturing machine was imported in 1848 from England, with local production necessary due to the weight of tiles. 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).

The natural wetlands of the United States were viewed by Federal Government policy as "unproductive and an economic waste" from the country's formation until at least 1956 (Palmer, 1915). To encourage their development via drainage, Congress passed a series Swamp Land Acts (1849, 1850, and 1860) for reclamation. At the time, the *Congressional Globe* summarized the justification 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...These formations of swamps and periodically overflowed lands are common to almost all Territories of sufficient area to constitute a State. They are evils common to all countries, rendering, in their original condition, portions of the earth not only desolate and unsusceptible of cultivation, but fruitful promoters of disease and death. They can only be removed, or their evils gated by means of labor and money, which, when properly employed must redeem portions of the land from sterility, and make it valuable and useful, instead of the generator of disease.*
>
> -Rives et al. (1861) from (McCorvie and Lant, 1993)

The lands made available to the states under the Acts are shown in table 1. As alluded to in the the *Congressional Globe*, the Acts were a first step, and the lands still required investment for recla-

using advanced drilling and trenching machines. While still called "tile drainage," the technology bears little superficial resemblance to its ancestor, and no longer involves clay tile.

Table 1: 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)

mation. The initial belief that states would simply use land sale funds to finance drainage proved incorrect because the funds raised were insufficient and state governments were disinclined to fund these types of public works. Responsibility for the investment in reclamation passed from the states to counties, who subsequently divested the lands in the hopes that private investors would drain them (Prince, 2008). Ultimately, the task of improving drainage fell to individual landowners and was achieved over time through local investment, private and public, not federal or state support.

2.2 The Economics of Drainage and Coordination

Laying tiles constitutes a private investment in agricultural production. Prince (2008) suggests that in the Upper Midwest prior to 1880, unimproved wetland sold for an average of $7 per acre (ranging from $2-$12), but that the sale price once drained could increase by a factor of five. In their account of drainage in Story County, Iowa, Hewes and Frandson (1952) note the cost of tiling exceeded the price of land for several decades, and offer estimates of this cost from several sources. The 1860 Agricultural Census estimate of $20-$30 per acre is similar to estimates of average cost provided by a survey of drainage conditions in Iowa in 1903 ($25 per acre) and the appraisal of the Federal Land Bank ($35 per acre).

Consistent with the direct capitalization of land improvements into land values, the fivefold increase from $7 per acre suggested by Prince is consistent with a $28 increase in land value due to tiling. After 1880, the value of unimproved 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 of $35 per acre (Prince, 2008).

Such an individual 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). Common law generally prevented individuals from engaging in drainage that led water outflows onto neighboring properties. Bogue (1963) uses the diaries of a 19th Century Illinois farmer, Croft Pilgrim, to describe just such a case:

> *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.*

The large minimum scale of drainage projects likely explains why private investment in drainage was initially conducted by large landowners. Owners of farms in Illinois from 3,000 to 17,000 acres were documented as privately undertaking tiling (and in some cases the construction of tile factories). This suggests that the scale of drainage investment exceeded by one to two orders of magnitude the size of the average smallholder farm, which was about 150 acres in 1880 (Prince, 2008).

While the consolidation of smallholdings by large landowners able to coordinate drainage investment offers one potential solution to the challenges of drainage, there were potential costs as well. Smallholders in the Midwest generally relied on family labor where agency costs were limited, and they could adjust output in response to price signals. By contrast, large landowners required external labor, leading to misaligned incentives between owners and hired labor that incurred 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 for this type of speculative venture (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 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 problem facing the owners of swamp lands and other poorly drained areas was one of coordination to invest in the local public good required for reclamation. As suggested by Wright, absent some mechanism for securing investment, there is reason to believe the public good will be under-supplied (Bergstrom et al., 1986). The result under private provision is that each individual sets their own marginal benefit of the public good equal to their marginal cost of providing it. This outcome means too little public good is provided, but no farmer is willing to unilaterally invest in additional drainage infrastructure.

Olson (1989) provides a useful framework for understanding the difficulties of solving this coordination and investment problem, which is a problem of collective action. Each farmer is better off with drainage investment, yet each also has an incentive to free-ride on the investment of others. Collective action in drainage requires some mechanism by which farmers agree to cooperate.

Ostrom (1990) provides guidance to the settings where local groups can successfully cooperate in managing natural resource problems. 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. The drainage district 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 by some 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.

Arguably, the later formation of irrigation districts in the western United States was informed by and patterned after the drainage districts formed earlier in the Midwest. Each is an application of the special district. In describing the emergence of irrigation districts in the western United States, Bretsen and Hill (2006) discuss the limitations of irrigation prior to the formation of irrigation districts. Large irrigation enterprises required substantial investment and rights-of-way, problems that were not solved 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 address groundwater management challenges, succeeded in coordinating to address externalities associated with groundwater pumping.

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) 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.

Table 2: Year of Drainage District Legislation

State	Year	State	Year
Michigan	1857	Kentucky	1912
Ohio	1859	Arkansas	1921
Iowa	1873	Louisiana	1921
Illinois	1878	Oklahoma	1921
Kansas	1879	Virginia	1924
Nebraska	1881	Georgia	1926
Minnesota	1887	Florida	1927
Indiana	1889	Missouri	1929
Wisconsin	1891	South Dakota	1929
Texas	1904	Mississippi	1930
North Dakota	1905	North Carolina	1930
South Carolina	1911	Tennessee	1932

Source: Table is adapted from McCorvie and Lant (1993) based on data from Austin (1931)

Table 2 shows the year of passage for drainage district laws for the 24 states that eventually adopt them in the eastern United States from McCorvie and Lant (1993). Although they varied somewhat in specifics, drainage districts were generally legislated to be formed via a petition from landowners in an area and typically required 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).

Another key feature of the districts was financial, with districts able 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 [we]re 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)"

The passage of drainage laws was viewed contemporaneously as a key determinant of drainage investment. When Wright (1907) wrote to the U.S. Senate about drainage, the Midwest had largely established drainage laws while the south had not (refer to table 2 for the dates):

> *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.*

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 as having 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 those acres drained. The agricultural census shows a total of 1,836 farms drained, suggesting 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. While data on drainage enterprises is only available for a few select counties,the 1920 census reports that for the counties we define as poorly drained and that have drainage by 1920, they have on average 113,000 acres drained and 1,376 farms.

The problem of drainage, and the opportunity its solution afforded, was recognized early on. Authors of the 1849, 1850, and 1960 federal Swamp Land Acts attempted to accelerate settlement of poorly drained lands by moving responsibility for drainage to the states. At the time, however, the application of drain tile technology had not yet begun, the transportation infrastructure to move farm inputs and crop outputs was poorly developed, and institutions that ultimately proved successful – notably, drainage districts – were yet to be devised.

Like investment in agricultural production generally, the development of drainage was shaped by the fertility and climate of each county as well as changes in input and output prices. For instance, the panic of 1873 and subsequent fall in farm prices would have reduced demand for drainage, while emerging transportation networks would have 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 through the inclusion of county and state-by-year fixed effects. This allows the empirical work to focus on the effect of drainage districts. While private enterprises existed, the available accounts suggest this private drainage occurred on farms of the size of drainage districts or larger. As the experience of Blue County, Minnesota suggests, drainage development occurred over several decades following the passage of district legislation, and our empirical approach looks at long-term effects. Still, we acknowledge that 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.

There were also important differences in the development of drainage between the Midwest and South. While Mississippi, Florida, and Louisiana received significant grants from the 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 1). These states, with the exception of South Carolina, were also late in passing drainage district legislation (see table 2).

3 Data & Empirical Strategy

3.1 Data

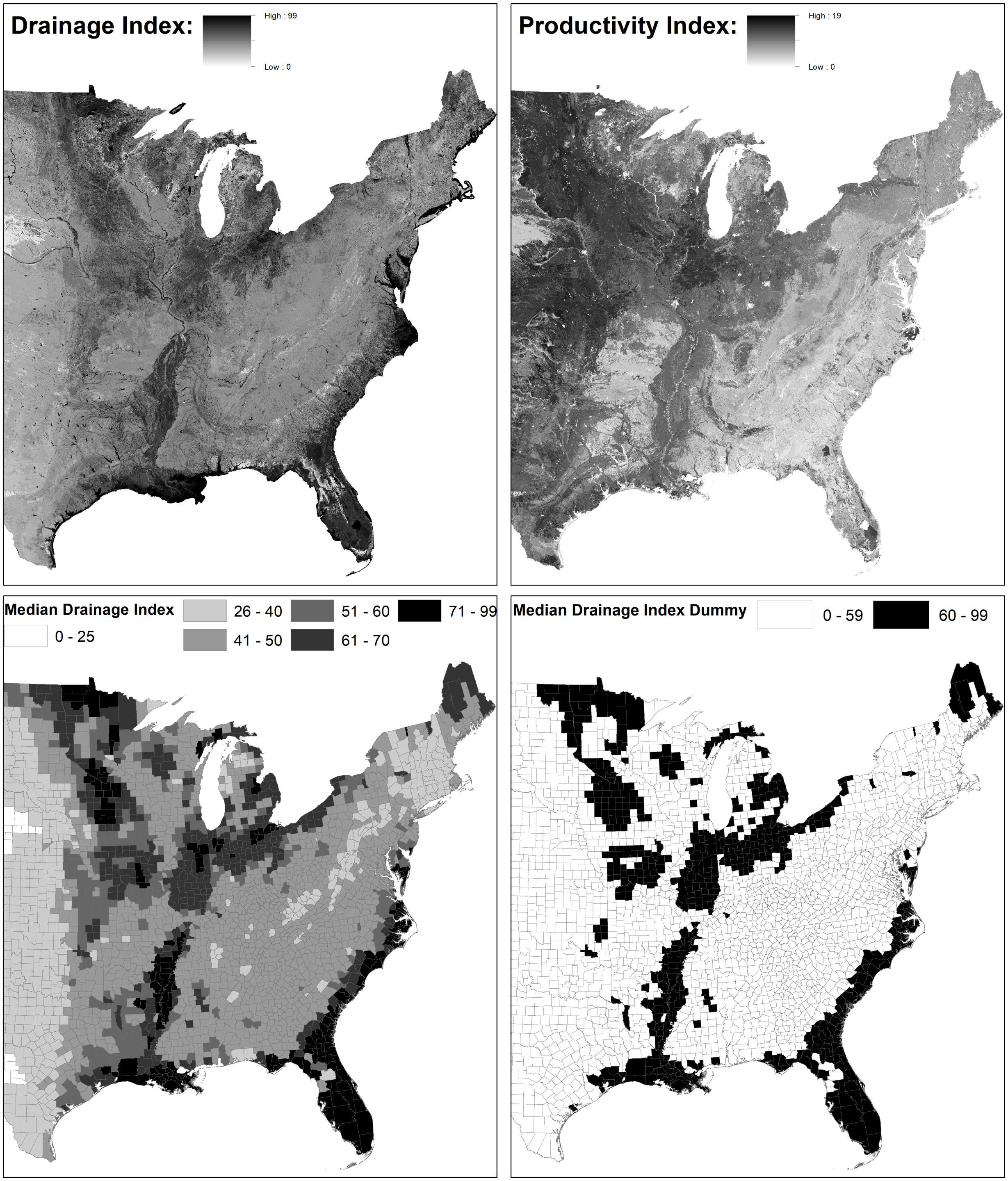
We construct a 109-year panel from 1850-1969 on *Improved Acres* and *Total Farm Value* from United States Censuses of Agriculture collected once per decade and digitized by Haines et al. (2019). We focus on counties east of the 100th Meridian, generally the dividing point between the humid and semiarid 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. 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 by dividing by total county area.

We use a Soil Drainage Index (DI) to represent the natural wetness of soil in a given county (Schaetzl et al., 2009). The DI is an ordinal measure of long-term soil wetness ranging from 0 to 99. Soils with a DI of around 60 are generally termed "somewhat poorly drained," while higher DI values represent more poorly drained up to 99, open water. The DI is derived from the soil classification and slope and so is not affected by drainage or irrigation.[4] Using a 240 meter cell resolution raster, we extract the median DI value for each county. We can then construct a variable to represent high DI (poor natural drainage), for counties with a median DI greater than 60. Figure 3 shows the relationship between median DI and the observed percent of a county drained in each of 1920, 1930, and 1969. As can be seen, the DI=60 cutoff represents a natural break in the data. Figure 4 reveals that counties with *DI High* tend to have more area drained.

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. Because soil PI is correlated with DI, and PI is also potentially affected by practices like drainage, we include specifications with and without PI to ensure results are not driven by its

[4] A soil's taxonomic classification is not initially affected by on-farm investments like irrigation or artificial drainage and so the DI does not change unless these investments change the classification of the soil in the long-run. 'Instead, the DI reflects the soil's *natural* wetness condition. Each soil *series* has, in theory, its own unique DI." (Schaetzl et al., 2009)"

Figure 2: Drainage Index

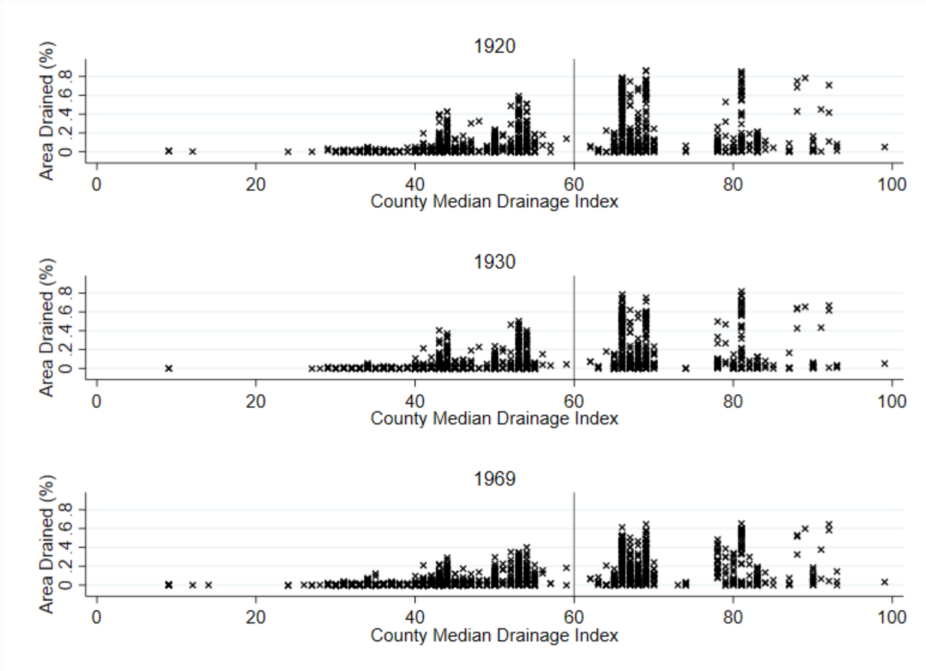


Notes: The top panels show the Drainage Index and Productivity Index rasters used to create county-level measures. The bottom panels show the median drainage index for each county east of the 100th Meridian and the constructed variable *High Drainage* which is counties with median drainage index greater than 60.

inclusion or exclusion. [5]

[5]"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

Figure 3: Drainage 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.

3.2 Empirical Strategy and Identification

Our empirical work examines the importance of drainage districts to county-level farm drainage. To identify the effect of drainage districts we rely on a list of key dates, varying by state, of the passage of district enabling legislation. The list comes from McCorvie and Lant (1993), who cite the earlier source of the Fifteenth Census of the United States Austin (1931). Adoption dates for drainage district law vary in the Midwest from 1857 (Michigan) to 1889 (Indiana). Outside the Midwest, but still east of the 100th meridian and in our sample of states, adoption dates range from 1911 (South Carolina) to 1932 (Tennessee).

We find evidence consistent with substantial responses of improved farm acres in poorly drained counties to drainage district enablement, starting when a law is passed and persisting for several decades afterward. This interpretation rests on the McCorvie and Lant chronology to accurately identify dates of changes in the abilities of land owners to coordinate at the scales re-

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) quired for effective land drainage. It also discretizes what was in each state a non-instantaneous change–the history of drainage law reveals substantial trial and error in arriving at ultimately effective institutions. 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 has been exercised in identifying the date in which viable drainage legislation was passed in each state. We find the dates provided by McCorvie and Lant (1993) the most consistent source for the passage of the first effective piece of drainage legislation–for instance, they provide 1878 for the effective date for Illinois.

Our empirical work relies on Census data on improved agricultural lands, recorded at the county level every ten years. The empirical challenge presented by this approach is to distinguish between decades in a county during which there were not drainage districts from decades during which there were. This strategy does not deny the importance of multi-year institutional experimentation and refinement. Instead we attempt to identify the availability of drainage legislation and assume that the magnitude of the empirical effects we find are inclusive of any subsequent changes to drainage legislation. In this sense, the empirical strategy does not distinguish over time between different causes of continued drainage development.

We use a difference-in-difference approach to estimate county-level improved acres and total agricultural value after state implementation of drainage districts. Within each state, outcomes of counties with a high DI index are compared to others before and after drainage law implementation. The typical approach for recovering difference-in-difference estimates of average treatment effects (ATT) would be to use a two-way fixed effects estimator (TWFE) of the form:

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

where Y_{ist} is the outcome for county i in state s in year t, λ_i is a vector of county fixed effects, τ_t is a vector of state by year fixed effects, and $PostLaw$ and $HighDI$ are dummies indicating a state as passed a drainage law and a county is designated as having a high DI, respectively.

The coefficient on $PostLaw_{st} \times HighDI_i$ would traditionally be interpreted as the difference-in-difference coefficient, but recent work suggests problems with this interpretation. 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). This bias arises because β_{TWFE} is a weighted average of all comparisons of "switchers" to "non-switchers" that appear in the data, which includes: i) comparisons of switchers to never-treated counties, ii) comparisons of early switchers to non-yet-treated counties, and iii) comparisons of late switchers to already-treated counties (Goodman-Bacon, 2021). The third comparison, where already-treated counties act as a control group for late-treated counties, can lead to negative weights in the weighted average represented by β_{TWFE}, resulting in a downward bias or even a negative coefficient when all underlying ATTs are in fact positive (de Chaisemartin and d'Haultfoeuille, 2020).[6]

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

[6] These problems are more likely to arise as treatment effects become more heterogenous either across time or between treatment cohorts. See de Chaisemartin and d'Haultfoeuille (2020) and Callaway and Sant'Anna (2020) for additional details.

both the untreated and treated *potential* outcomes for the treated and untreated groups 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. The parallel trends assumptions is explored via an examination of trends in an event study during the pre-treatment period.

While there is reason to believe it was the drainage districts themselves that created the ability of poorly drained counties to increase agricultural development and production, there is no way to test this assumption directly. The discussion in section 2 provides economic rationale for the importance of drainage legislation and detail on the related institutional factors.

4 Results

4.1 Agricultural Development and the Drainage Index

In this section we examine the contribution of drainage to agricultural production in the United States east of the 100th Meridian. Conditional summary statistics provided in table 3 indicate that high- and low-drainage counties behaved differently following the implementation of drainage district laws. Both sets of counties are increasing in agricultural development over time but well-drained counties are more developed prior to the passage of drainage district laws: the low-DI counties have average total farm value of $133M versus $107M in the high DI counties with 29% of the county with improved agricultural land versus 22% for high-DI counties.

After the passage of drainage district legislation, farm values increase by $151M in low-DI counties and over $326M in high-DI counties. The percent of county acreage improved increased by 10 percentage points in low-DI counties and 28 percentage points in high-DI counties. On average, after the passage of drainage district laws high-DI counties have a higher percentage of total acreage in agriculture, likely because the mean productivity index is significantly higher in these counties, which have more fertile soils once drained (as shown in the last row of the table). These summary statistics do not control for county-specific characteristics that could be related to

Table 3: Conditional Summary Statistics

Variable	Drainage Index<60 Pre	Drainage Index<60 Post	Drainage Index >60 Pre	Drainage Index >60 Post
Total Value in Farms (2020$ millions)	132.75	283.76	106.58	433.28
	(174.79)	(260.00)	(153.04)	(408.16)
Pct. of County Improved	0.29	0.39	0.22	0.50
	(0.20)	(0.24)	(0.22)	(0.27)
Total Farms	1,669	1,777	1,380	2,003
	(1,358)	(1,096)	(1,493)	(1,259)
Total Acres in Farms	202,257	288,167	162,324	279,917
	(138,779)	(190,034)	(133,031)	(166,578)
Median Drainage Index	43.84		72.47	
	(6.24)		(7.83)	
Median Productivity Index	8.09		10.16	
	(3.93)		(3.42)	

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 all years in that status. Standard deviations are reported in parentheses.

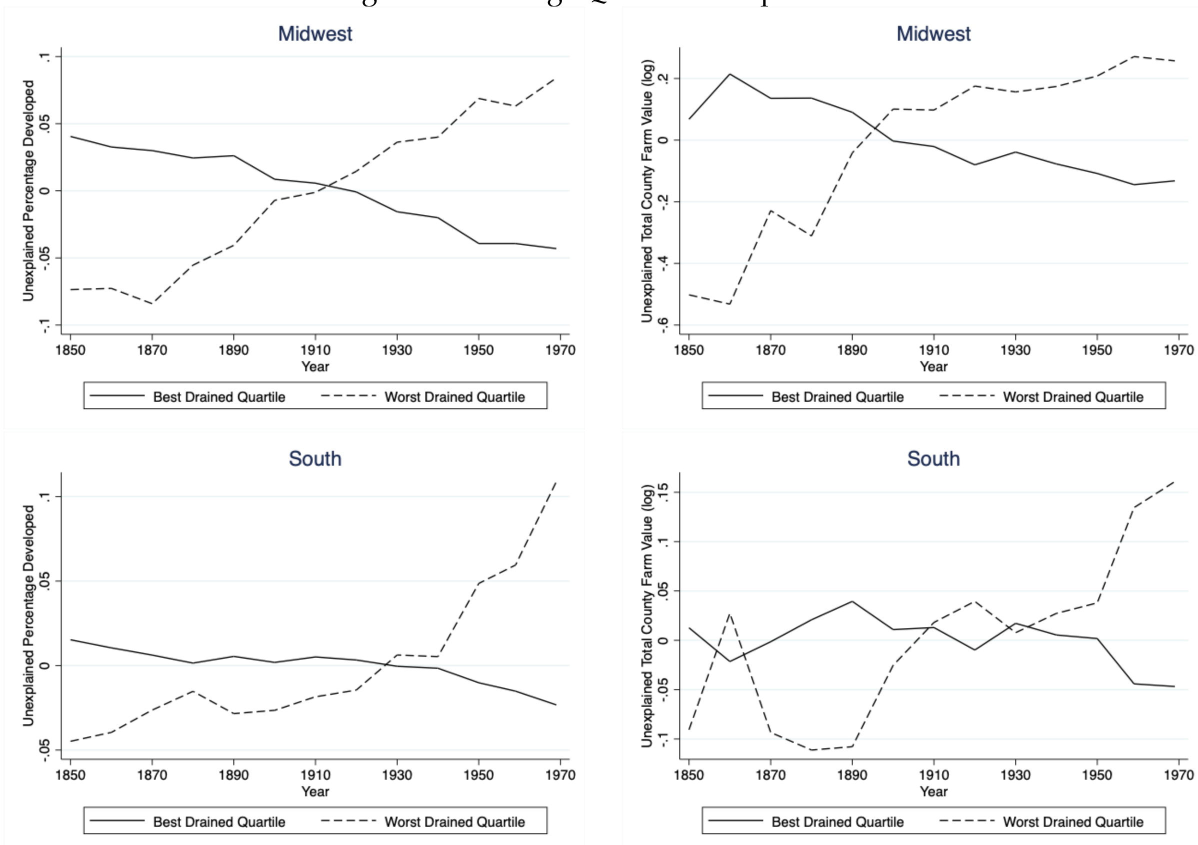
development or changing trends in different states, which we address in the regression analysis.

We begin by examining outcomes across select states in the Midwest and South to provide a comparison of counties likely to be treated with drainage, relative to others. We regress two variables, percentage of a county with improved agricultural land and total county farm value (logged) on a flexible set of controls and then group counties in each state by the quartiles of drainage index. We exclude the second and third quartiles and then plot the yearly mean for each geography-quartile group. Comparing the best- and worst-drained quartiles shows the changing trends over time.

In the Midwest, as shown in table 2, drainage district laws were generally passed between 1860 and 1890, suggesting the development of drainage and related increases in improved acres and farmland value in the subsequent decades. The top panels of figure 4 show the catch-up of the worst-drained quartile for improved acres (left) and total value (right). By 1920 the percentage of a county improved is the same and eventually goes higher for poorly drained counties. Similarly, once drained, the value per acre of the worst drained quartiles, which are generally nutrient rich, exceeds those of the best drained quartiles by 1900. Thus the land value outcomes appear to anticipate drainage implementation to some extent. [7]

[7] Similar figures for farm value per acre and crop value are shown in appendix figureA1

Figure 4: Drainage Quartile Comparisons



Notes: This figure depicts the unexplained variation, the residuals of a regression on county fixed effects and state-by-year fixed-effects, of percentage of county improved (left panels) and total farm value (right panels) for counties in the Midwest (top panels) and South (bottom panels). Midwest states are Illinois, Ohio, Iowa, Michigan, Minnesota, Indiana, and Wisconsin. South states are Georgia, Arkansas, Virginia, Missouri, North Carolina, Mississippi, and Tennessee.

A similar catch-up occurs, but much later, in the South. As shown in table 2, states in the South generally passed drainage district laws between 1910 and 1930. The percentage improved in the worst drained counties in the South exceeds the level of the best drained counties by 1930. Again, land markets appear to anticipate the implementation of drainage by about 20 years, with per-acre land value estimates of best- and worst-drained quartiles similar by 1910.

4.2 Drainage Impact Estimation

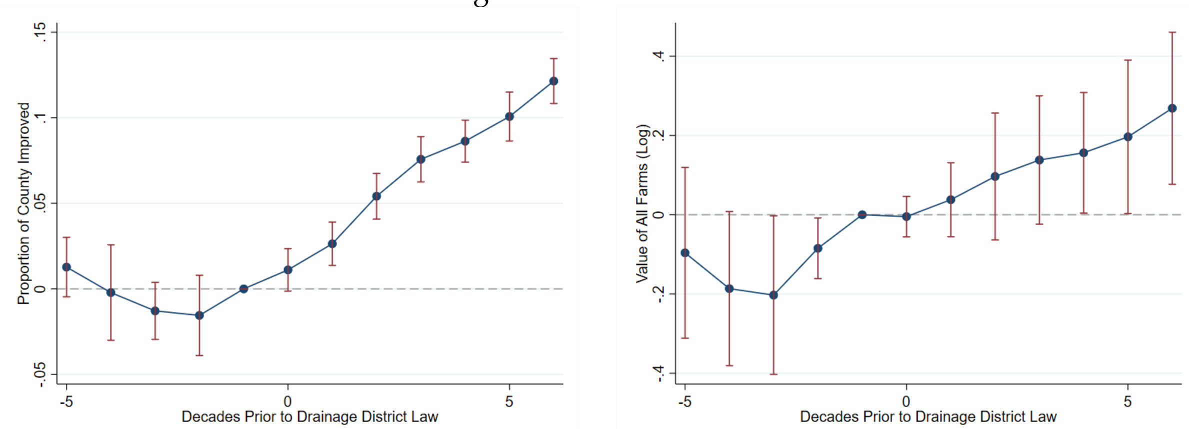
Next, we turn to the difference-in-difference methodology from equation 1. Event study estimates can be used to provide evidence that the necessary parallel trends assumptions are likely to hold in this setting. Our data includes 13 observations, one per 10 years, and we report a window that includes 5 periods (50 years) prior to treatment and 7 periods (70 years) after treatment, with period "0" defined as the first year in which treatment begins.

Figure 5 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.[8] The left panel shows the event study for improved acres and the right panel for total county farm value. All coefficients are relative to the difference between treated and untreated parcels in the period just prior to treatment, which is normalized to 0 (i.e. within a state the estimator compares high drainage index counties to others).

The figure shows no evidence of a pre-trend for the improved acres event study: the coefficients for periods $t-2$ through $t-5$ are near zero and statistically insignificant. From period $t-3$ to $t-1$ in the farm value event study there appears to be an increase, which would be consistent with anticipation of drainage in land markets.

From period $t = 0$ onward, there is a statistically significant (and increasing) difference in percentage of county improved between the counties we expect to see the most change from the adoption of drainage districts relative to others. While the land value trend after $t = 0$

Figure 5: 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 column 1 of Panel A of Table 4, 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 main estimates for the effect of drainage on percent of a county improved and agricultural value are presented in Table 4. 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.[9] Panel A in-

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

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

cludes state-specific non-parametric trends and Panel C includes state-by-year fixed effects, but Panel B includes only year fixed effects.[10]

Table 4: Ag Development after Drainage District Law

	(1)	(2)	(3)	(4)	(5)	(6)
	ALL COUNTIES		MIDWEST		SOUTH	
	% Impr.	Ag Value (log)	% Impr.	Ag Value (log)	% Impr.	Ag Value (log)
Panel A:						
	de Chaisemartin & D'Haultfoeuille (2020)					
Post Drain	0.068***	0.127*	0.091	0.243**	0.074***	0.093
	(0.005)	(0.069)	(0.007)	(0.115)	(0.025)	(0.098)
Panel B:						
	Callaway & Sant'Anna (2020)					
Post Drain	0.157***	0.147	0.116***	0.011	0.089**	0.00
	(0.034)	(0.286)	(0.027)	(0.187)	(0.041)	(0.137)
Panel C:						
	Two-Way Fixed Effects					
Post Drain	0.092***	0.265***	0.125***	0.530***	0.108**	0.226
	(0.019)	(0.092)	(0.031)	(0.120)	(0.031)	(0.141)
Counties	2,949	2,951	621	621	726	727
R^2 (TWFE)	0.882	0.882	0.867	0.88	0.798	0.904

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 five 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 * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Columns (1) and (2) report the results for all counties with drainage district laws in table 2. Columns (3)-(6) report results for subregions as described in figure 4. The coefficient estimates are fairly consistent across all three estimators and across the three geographic groups. Column 1 suggests that following the implementation of drainage districts, a poorly drained county (median drainage index greater than 60) will see a 6.8 to 15.7 percentage point increase in the area of the county with improved agricultural land. As observed in figure 5 the full effect of drainage law passage occurs after 50 years before leveling off.

While coefficient estimates of percentage of county acres improved are statistically significant across all three estimators in column (1), the farm value changes are less robust (column (2)). One explanation for this is that the land markets anticipated changes in drainage, meaning some of

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

the effect of drainage on land value occurs i=during what we define as the pre-period. Results for counties in the Midwest and South are consistent with these results as well, with improved acreage results highly statistically significant across all specifications. Farm value results in the South show no statistical significance. Although agricultural drainage did increase the improved acres in southern counties, this change does not appear to translate into the statistical results for land value.

While noting that the farm value results are less statistically significant, we can use the coefficients in column 2 to find the increase in the value of agricultural land in these counties as a result of drainage. Coefficient estimates range from 13.5 percent to a 30.3 percent increases [11]. Using the mean county land value for pre-treatment high-DI counties of $106.58M from table 3, we can calculate a rough estimate that relative to low-DI counties, drainage increased their value by $14.4-32.3M. There are 513 counties in the high-DI category, suggesting that drainage added $7.38-16.57B to U.S. agricultural land value in 2020 dollars.

5 Lessons for Future Adaptation

Our historical analysis offers key insight into the real barriers associated with institutional change. A key conclusion of our work is that institutional development to solve drainage coordination problems, including trial and error and legislative revision, took time. Even when a solution was legally enabled, in this case drainage management districts, their formation still took time once authorized.

The problem of adaptation via drainage was not known in advance and was discovered over time through the development process. The particular circumstances of time and place a la Hayek (1945) played an important role in adaptation. It took time for local agents to discover and learn the areas that needed to be drained, what technology to apply, and to coordinate on a solution. Historian Joseph Otto discusses such development in Iowa (Maulsby, 2019):

> *Iowa wasn't settled east to west, but from the bottoms up to the top of the state's many river valleys. Atop the river valleys were the flat, glaciated prairies of north-central and northwestern Iowa. These were settled and farmed starting in the 1870s and 1880s – several decades after*

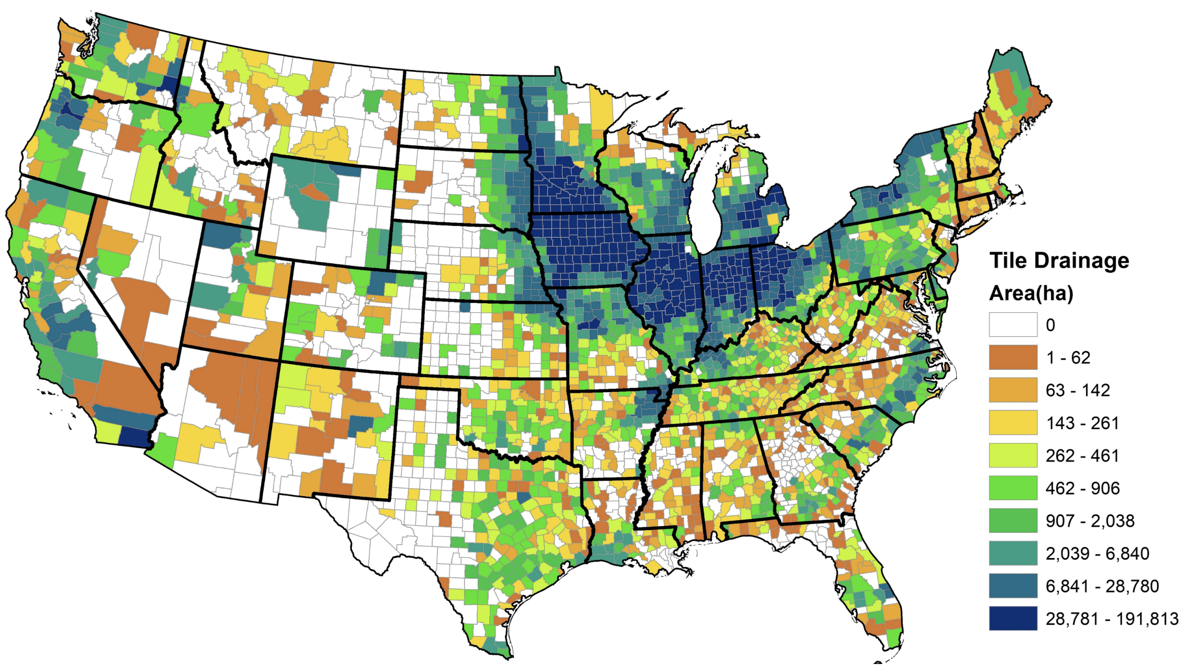
[11] These calculations come from coefficients in a log-level regression corresponding to a $e^{\beta} - 1$ percent increase.

farming started along the Mississippi."

The drainage experience suggests trial and error will play a large role in adaptation. Institutions needed to time to adapt and evolve and property rights were refined over time through case law (see Tovar (2020)). Successes and failures were not obvious prior to investment. In North Carolina, the drainage of Lake Mattamuskeet, the largest freshwater lake in North Carolina, was begun around 1915 and the failure of the ambitious farming scheme based on draining the lake was not realized until the late 1920s.

Changing patterns of precipitation and shifting growing regions could make agricultural production less suitable in locations that in the past made drainage investments, opening the possibility of new investment in drainage. As seen in figure 6, intensive investment in drainage has been made in southern Minnesota, Iowa, Illinois, Indiana, northwestern Ohio, and southern Michigan. Meyer and Keiser (2018) project increased tile drainage in the northern Midwest—the eastern Dakotas and northern areas of Minnesota, Michigan, and Wisconsin. This region includes important undeveloped wetlands, such as the Prairie Pothole Region, where the use of agricultural subsurface drainage systems continues to increase (Tangen and Wiltermuth, 2018).

Figure 6: Tile Drainage Area (2017, in hectares)



Source: Valayamkunnath et al. (2020)

While technical innovation in drain tile was a key component of the development of drainage, our paper points as well to the importance of institutional innovation. Today, agricultural drainage is perceived to have had high external costs due to the reduction in wetland acreage (McCorvie and Lant, 1993), an increase in water pollution and sedimentation (Skaggs et al., 1994), and degradation of soil quality (Castellano et al., 2019).

The institutional costs of future adaptation are likely to be large and they can't be assumed away or solved ex ante. While we can learn about how to solve drainage coordination problems of adjacent landowners from the historical experience we investigate, the coordination problems involved in adapting to climate change will be different. One important difference is that third-party interests in nutrient runoff and wetland protection should, and will, influence the drainage solutions that groups of landowners will select as they adapt. New institutional innovations that address these impacts as well as agricultural production, will need to emerge.

6 Conclusion

While modern "drain tile" is no longer baked clay as was used starting in New York in 1835–today the tiles are perforated plastic tubing–much original drain tile is still in place, representing an important long-term investment in agricultural adaptation. Meyer and Keiser (2018) suggest that this adaptation was related to climate, with the probability of adopting tile drainage increasing with precipitation. One installed, drainage eliminates the inverted "U" relationship between precipitation and land values, making areas with excess precipitation more profitable to farm.

In this paper we demonstrate how local drainage enterprises invested in tile drainage and drainage works. After federal and state funding for these projects failed to materialize, drainage management districts formed to locally financed drainage investment over tens of thousands of acres of wetlands. Of the 215 million acres of wetlands estimated to have existed in the contiguous United States at colonization, today 124 million have been drained. States in our sample adopted drainage laws via legislation between 1857 and 1932, and after adoption each state saw an increase in improved agricultural land in counties with poorly drained soils relative to well-drained counties. We estimate artificial drainage increased the value of agricultural land in each of the worst-drained counties of the eastern United States by 13.5-30.3%, a total increase across all poorly-drained counties of $7-17B (2020 dollars).

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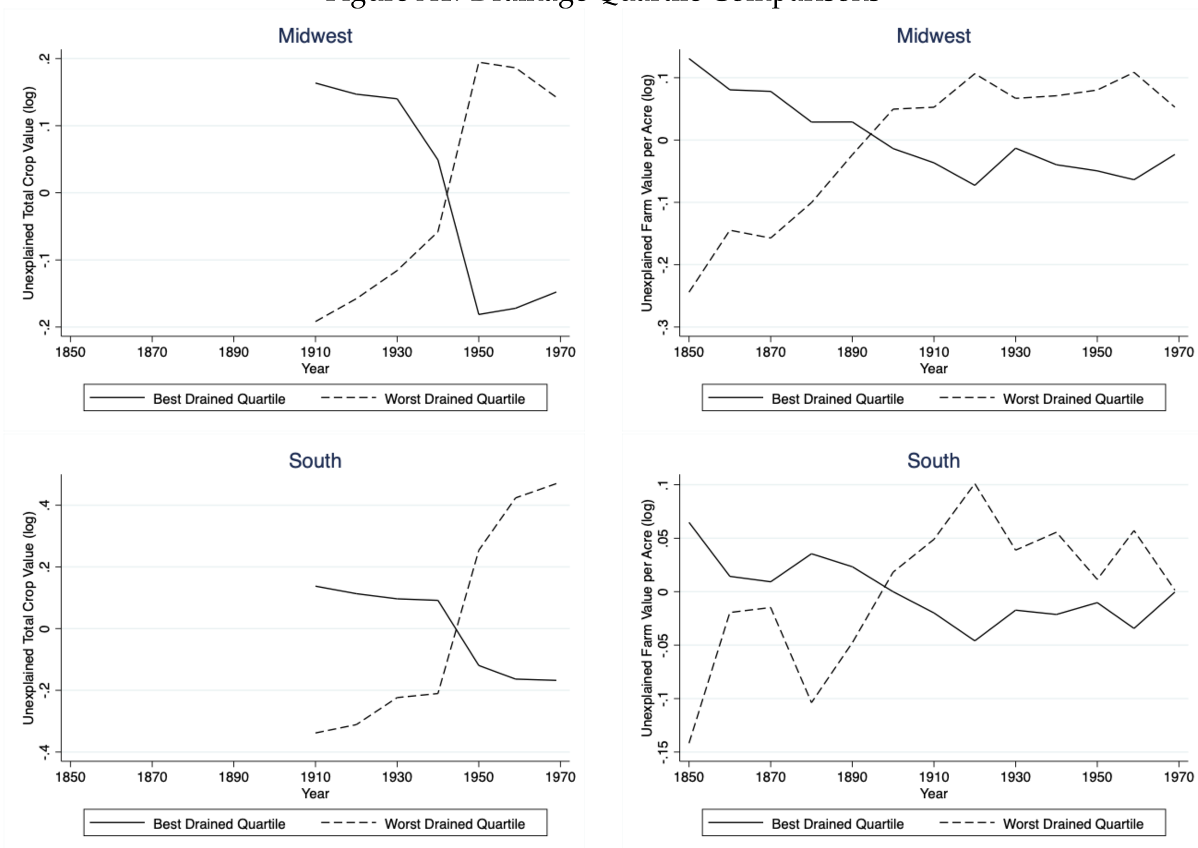
Appendix

Figure A1: Drainage Quartile Comparisons



Notes: This figure depicts the unexplained variation, the residuals of a regression on county fixed effects and state-by-year fixed-effects, on logged crop values (left panels) and log farm value per acre (right panels) for counties in the Midwest (top panels) and South (bottom panels). Midwest states are Illinois, Ohio, Iowa, Michigan, Minnesota, Indiana, and Wisconsin. South states are Georgia, Arkansas, Virginia, Missouri, North Carolina, Mississippi, and Tennessee.