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The Economics of Climatic Adaptation
Agricultural Drainage in the United States

Eric C. Edwards and Walter N. Thurman

1.1 Introduction

Climatic shocks like heat stress and drought can dramatically reduce 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, Hanemann, and Fisher 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).

Water is a key agricultural input, but its marginal product depends on local availability. In water-scarce areas, the marginal product of water is high and investments are made in irrigation. In water-abundant areas, the marginal product of water can be negative, especially at certain times of the year.[1]

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1. In irrigated areas, drainage is also used to reduce the salinization of soil that results from long-term irrigation. Irrigation increases evapotranspiration, which can effectively wick salts at deeper soil levels upward into the root zone. Drainage flushes salts from the root zone (Castellano et al. 2019).

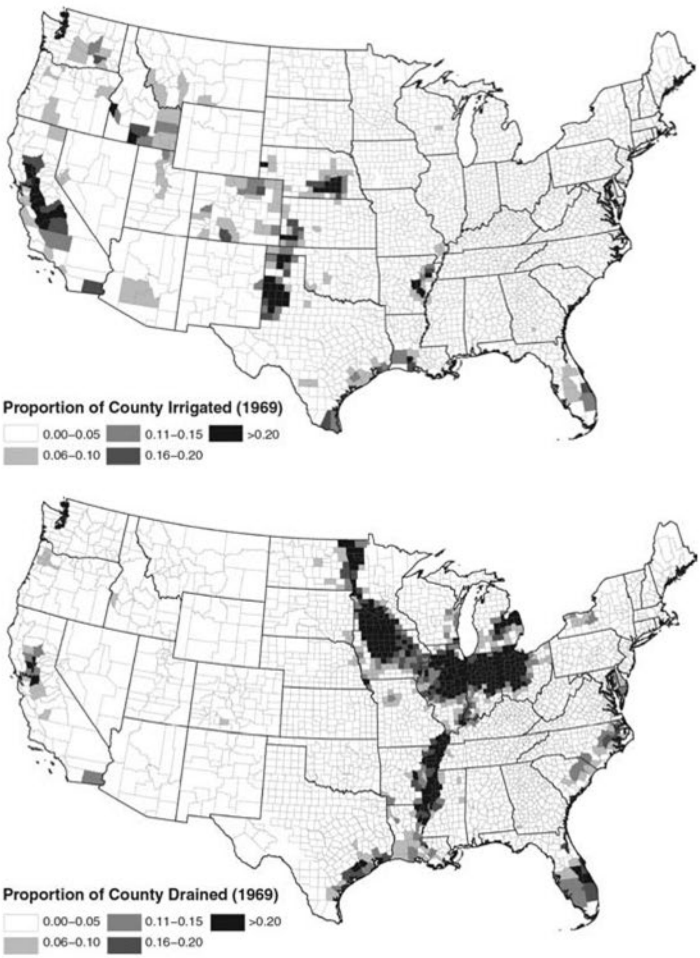


Fig. 1.1 Drainage and irrigation

Note: Percentage of county area irrigated (top) or drained (bottom) from the 1969 Census of Agriculture. Counties are scaled to 1910 borders for consistency with our later analysis.

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. Wet soils prevent field access by heavy equipment like tractors, limiting the ability of farmers to plant crops at optimal times during wet years. 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. Figure 1.1 shows the relative intensity of irrigation and drainage across the

US historically, illustrating adaptation to water scarcity in the West and excess water in the East.

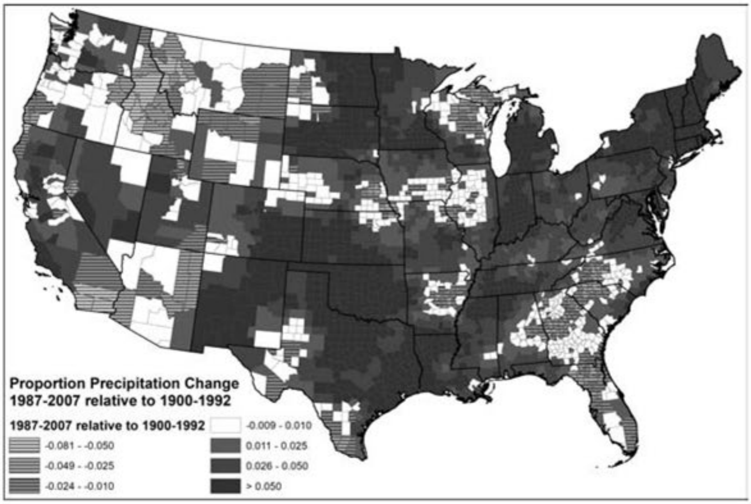
Across the US, all regions are projected to see heavier rainfall events under climate change, even those regions that see less precipitation overall (Easterling et al. 2017). The left panel of figure 1.2 shows the change in precipitation for the period 1987–2007 relative to the earlier part of the 20th century (1900–1992) and shows significant increases in precipitation for most areas east of the Mississippi. Most field crops experience no long-term damage from rainfall events if water tables fall to 6 inches below ground surface within one day and continue falling to 18 inches from ground surface within three days (Hofstrand et al. 2010). The ability of farmers to rapidly remove excess water from fields will be crucial to ensuring a secure and reliable food supply.

The current location and intensity of agricultural drainage remains similar to that shown in figure 1.1 and was largely the result of the dramatic investment of 19th- and early 20th-century farmers in the Midwest and eastern US in technologies to move water off saturated lands. (See for example Bogue 1951, 1963.) In fact, a significant portion of the eastern US, including the upper Midwest, Mississippi River basin, and eastern Coastal Plain, would not be suitable for agricultural production absent such drainage. The physical fact of extensive tiled acreage in the Midwest is an important determinant of the costs of future adaptation that involves drainage.

The right panel of figure 1.2 shows a similar map for changes in average temperature. The Dakotas, Wisconsin, and northern Minnesota have already seen increased temperatures. As climate change shifts growing regions north, we expect investment in drainage to occur in currently swampy areas. Looking forward to changing climatic conditions, agronomists, engineers, and economists are discussing the technical issues associated with intensifying drainage to deal with increasing precipitation and shifting growing regions while, at the same time, addressing the environmental costs associated with drainage, including nutrient runoff and reduced wetland acreage (Castellano et al. 2019).

Historical context on drainage is needed to understand potential future climate adaptation. The locations where investments in drainage tiling, field leveling, and deswamping have been made are inherited from historic decisions—starting as early as the late 1800s. Further, adaptation is not just a technical problem about plant physiology and hydrology. It is an economic problem with a complex set of priced and unpriced costs and benefits, with important externalities and transaction costs into which historic analysis can provide key insight.

Using data from the agricultural census on improved agricultural acres and farm value spanning the period of agricultural drainage across the eastern US, we compare counties with poorly drained soils to those that



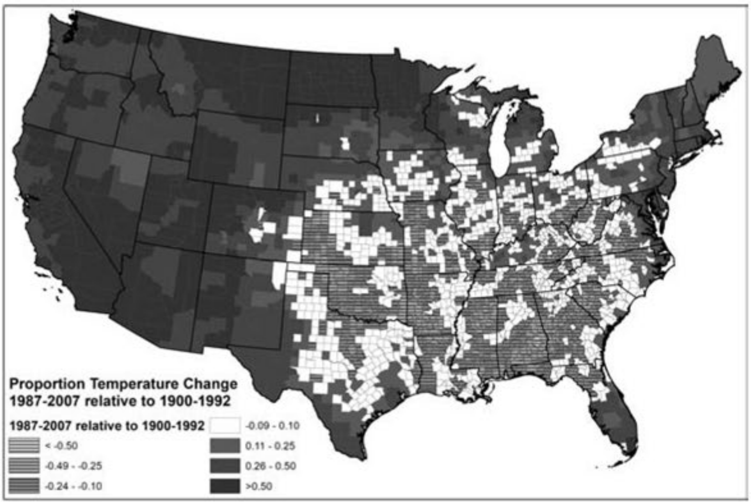


Fig. 1.2 Recent changes in temperature and precipitation

Note: Change in the average 1987–2007 precipitation (top) and temperature (bottom) relative to the 1900–1992 average using PRISM data: PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu.

were well drained within the same state. We explain how economic factors determined the timing and locations of drainage adoption and tie these factors to lessons for modern adaptation to climate change. We provide a framework for understanding benefits and costs of drainage in historical context and describe the historical performance of drainage.

Agricultural drainage in the eastern US is in many ways analogous to irrigation in the West, in that both are fixed investments in location specific assets that greatly increase agricultural production or reduce variability in production due to climatic shocks. 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 in the locations that in the past have made drainage investments, opening the possibility of new investment in drainage elsewhere. 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.

Today, agricultural drainage is perceived to have had much higher social costs than initially anticipated, both in terms of reducing the amount of wetlands and 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). New institutional innovations that coordinate over wetland protection and nutrient pollution, as well as agricultural production, can enhance the net value of such an adaptation.

1.2 Empirical Setting

1.2.1 US Drainage History

Open ditches for drainage were dug throughout the US from its founding. The earliest attempts at drainage in the Midwest, in 1818, were of this type (Prince 2008, 205). Ditches, 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. The technology that ultimately replaced open ditches 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 drainage was invisible and allowed farming above it.[2] The advent and diffusion of clay drain tile, first used in the US in Seneca County, New York, in 1835, transformed American agriculture (McCrory 1928).

The natural wetlands of the US were viewed by federal government policy as "unproductive and an economic waste" until at least 1956 (Palmer 1915; McCorvie and Lant 1993). To encourage their development via drainage,

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

Table 1.1 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).

Congress passed a series of Swamp Land Acts in 1849, 1850, and 1860 that granted wetlands to the states. The lands made available under the acts are shown in table 1.1. The acts were a first step, but the land still required investment for reclamation. The initial belief that states would simply use land sale funds to finance drainage proved incorrect because the funds raised were insufficient and because state governments were disinclined to fund these types of public works. Responsibility for the investment in reclamation passed from the states to counties, which subsequently divested the lands in the hopes that private investors would drain them (Prince 2008). 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.

1.2.2 Classifying Drained Land

The focus of our analysis is on 24 states in which deposits of soil created flat areas with relatively poor drainage. Palmer (1915) articulated two categories of such areas, "glacial swamps" and "tidewater or delta overflowed lands." We follow by segmenting states into "Coastal Plain" and "Midwest Tile" categories, as shown in figure 1.3. Coastal Plain states follow the definition of the Atlantic Coastal and Mississippi River alluvial plain in the map created by Fenneman and Johnson (1946): Virginia, North Carolina, South Carolina, Georgia, Florida, Mississippi, Louisiana, Texas, Tennessee, and Arkansas. Poor natural soil drainage in these states results from sedimentary deposits from rivers near the coast and around the Mississippi River.

The area of glacial swamps described by Palmer (1915) coincides with

Fig. 1.3 Drainage state classification

the areas subject to glaciation during the Pleistocene, where the retreating ice sheets left flat soil deposits. This area roughly coincides with the Upper Midwest, and our definition of "Midwest Tile Drainage" includes North and South Dakota, Nebraska, Iowa, Minnesota, Wisconsin, Illinois, Indiana, Michigan, and Ohio. To this list we add Kentucky, Missouri, and Kansas, portions of which share drainage similarities with these states, and New York, which was the initial location of tile drainage in the US and shares a similar geologic history.[3]

1.2.3 Public and Private Benefits and Costs

Laying tiles constituted a private investment in agricultural production, and the incentives to invest were meaningful. 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. Such 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 embank-

3. Excluded states may lack much need for agricultural drainage, or in the case of New Jersey, Maryland, and Delaware, differ from most other states in the institutions managing drainage. See Edwards and Thurman (2022) for additional discussion of drainage categorization.

ments on private lands (Wright 1907; Prince 2008). Thus, drainage incurred not only the costs of construction and maintenance, but also the contracting costs associated with collective investment and action.

Because drainage investment was generally not effective on a small scale, coordination was essential. Institutional innovation in the form of drainage districts, enabled by state law, reduced the costs of coordination by facilitating, and compelling, coordination. Although they varied in specifics, drainage districts were generally legislated to be formed via a petition from landowners residing in a region, then requiring a vote by the majority of land area and/or landowners (McCorvie and Lant 1993). District decisions were typically made by locally elected boards. Their power was restricted to investments that met some definition of public benefit, 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).

Additional benefits of drainage in the late 19th and early 20th centuries accrued due to the improved health outcomes of surrounding communities through the reduction of malarial infections.[4] Throughout the 1800s, malaria affected most of the populated regions of the US, was one of the country's leading causes of death (in 1850 45.7 of every 1,000 deaths were caused by malarial fevers), and had long-term health impacts including stunting and chronic conditions in later life (Hong 2007). The reduction of malaria was cited explicitly as the key benefit that warranted governmental intervention to create drainage legislation.

At the time of initial construction of drainage in the late 19th century, environmental costs were not well understood or relevant to farmers, but they have become important today. Of the 215 million acres of wetlands estimated to have existed in the contiguous US at colonization, 124 million have been drained, 80–87 percent for agricultural purposes. Tile systems and associated drainage canals increase the transport of nitrogen and phosphorous from inland farms to waterways, leading to environmental damage. The leading example is the Mississippi water basin and the hypoxic zone in the Gulf of Mexico.

Some benefits of drainage were also not well understood and diminished over time. Drainage increases the availability of soil nitrogen and reduces the optimal application of N-containing fertilizer. Once drained, soils sponsor greater microbial activity, which decomposes organic matter already in the soil. This releases nitrogen into inorganic forms, which are then available for uptake by crops. The initial increase in microbial decomposition of soil organic matter effectively mines the finite amount of organic matter in the soil to begin with, setting in motion a dynamic adjustment in available nitro-

4. Malaria had been linked to marshy areas through the 19th century and was definitively linked to mosquitoes near the end of the 19th century.

gen that reduces benefits in future years. Eventually a lower steady state of available N is established in the drained soil, with farmers relying more on the application of N-containing fertilizer than they did immediately after the installation of drain tile. Castellano et al. (2019) say that the time it takes for soils to reach the new post-drainage steady state in the Midwest is on the order of 15 to 30 years.

Although all 24 states in our sample (see figure 1.3) adopted similar drainage district laws, there were important differences in the development of drainage between the glaciated Midwest and the alluvial coastal plain. Drain tile was well suited for use across the glaciated regions but was not as successful on the coastal plains, where the need for additional investment in levees and pumping, as well as other challenges, limited its effectiveness. Coastal Plain states developed drainage using a combination of in-field ditching, levee systems, pump houses, and tile in select areas.

The magnitude of the drainage investment problem in the glaciated (Midwest Tile) regions is illustrated by Blue Earth County, Minnesota, and Story County, Iowa. Blue Earth County saw 92 districts form between 1898 and 1952, with around 100,000 acres in drainage districts in total in the county (Burns 1954). Districts ranged in size from 320 to 7,202 acres, with an average district consisting of around 1,200 acres and 20 farms. Similarly, in Story County there were 95 districts by 1920 with around 60 percent of the county in districts (Hewes and Frandson 1952). The districts average around 2,100 acres and 20 farms.

In the Coastal Plain states, single drainage districts require coordination over areas orders of magnitude larger than the glaciated regions, and they are larger and fewer in number. The Ross Drainage District in Arkansas is around 40,000 acres (Deaton 2016), and the Cypress Creek District in Arkansas is around 285,000 acres, the later facing decades of litigation resulting from opposition to its formation (Harrison and Kollmorgen 1948). In 1920, North Carolina had 81 districts draining 543,000 acres, making the average district size about 6,700 acres (O'Driscoll 2012). These districts were already substantially larger than those in the glaciated regions, and by 1985 drained acres had increased by an order of magnitude to 5.4M acres, but the number of districts had decreased to 53. How regional differences might continue to be important in understanding response to climate change remains an outstanding question.

Drainage districts provided local landowners with the tools to undertake collective investment suggested by Olson (1965) in a form consistent with the nested structure described by Ostrom (1990). 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.[5]

1.2.4 Trial and Error

The historic drainage experience suggests trial and error will play a large role in future climate adaptation (more generally see Ridley 2020). Institutions needed 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. The historical record offers several examples of drainage failures—projects deemed ex ante to be profitable, but ex post proven to be not. Two large-scale examples come from physiographically distinct areas—the marshy region of central Wisconsin and Lake Mattamuskeet in the coastal plain of North Carolina.

Prince (1995) develops the chronology for Wisconsin. Beginning around 1900, soon after the period of drainage district formation and successful drainage in nearby Midwestern states, Wisconsin marsh lands were organized into drainage districts. The attempts to improve agricultural land through drainage followed by several decades the economically successful efforts in Iowa and Illinois, but they failed in central Wisconsin. By the 1930s, lands that had been drained largely reverted to public ownership and became recreational havens. In a section titled "A Chronicle of Repeated Failure," Prince places Wisconsin in the context of a global history of land reclamation and drainage:

> Most accounts of changing geographies of marshlands have happy endings. The reclamation of the Dutch polders, the draining of the English fenlands and Somerset levels, the draining of the wet prairies in Ohio, Indiana, Illinois, and Iowa were success stories. The marshland chronicle of central Wisconsin is unusual in that it records a succession of short-lived unsuccessful economic ventures. (page 17)

Another example of project failure and reversion of drained land to its prior state is Lake Mattamuskeet, the largest natural lake in North Carolina. The shallow freshwater bay near the Atlantic coast drains into the Pamlico Sound. In many ways, the 19th- and 20th-century history of the lake parallels that of central Wisconsin.

By the mid-19th century, the fertility of the area surrounding Lake Mattamuskeet suggested that draining the several-foot-deep lake could create thousands of acres of productive land. Partial draining of the lake took place as early as 1837. Larger-scale draining took place in the early 20th

5. 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. 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.

century (see Forrest 1999). Private investors fully drained the lake in 1916 by dredging 130 miles of canals and building water control dams and a large coal-fired pumping station. Soon afterward the investing firm failed, due in part to low commodity prices, and the pumping station was abandoned. The lake refilled. Twice more between 1916 and 1926, the lake was drained but then abandoned and allowed to refill. The privately owned lake eventually was sold to the federal government in 1934 to become the Lake Mattamuskeet Wildlife Refuge.

Just as Prince (1995) casts the history of central Wisconsin as a series of failed attempts to claim partially submerged land for agriculture, Lake Mattamuskeet followed a similar trajectory. In both cases, the land ultimately reverted to its initial state and the primary land use became recreation, hunting, and fishing. The similar timing of drainage efforts in Wisconsin and North Carolina suggests that drainage was not simply a technology waiting for discovery and then application to different landforms; it was also a product of the state of knowledge about drainage and land use at certain times, conditions in agricultural markets at those times, and possibly a contagion of ideas deemed at the time to be suitable and promising by investors.

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.

1.3 Data and Empirical Strategy

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, Fishback, and Rhode (2019).[6] We focus on counties east of the 100th meridian, generally the dividing point between the humid and semiarid portions of the US. Areas east of this line can be farmed without irrigation and were generally settled or being settled during the entire panel.[7] We scale county data to 1910 county boundaries using area-weight crosswalks constructed by Ferrara, Testa, and Zhou (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

6. After 1920 Improved Acres is not provided as a standalone variable. We construct this measure using other available variables after 1920 (see Edwards and Smith 2018 for details).

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

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 investment in drainage or irrigation.[8]

Using a 240-meter cell resolution raster, we extract the median DI value for each county. We then categorize poorly drained counties in two ways. First, we create a variable *High DI* (poor natural drainage), for counties with a median DI greater than 60. Second, within each state we can separate median DI into *DI Quartile*, and then can compare outcomes from Q4 (poorly drained) to Q1 (well-drained). Figure 1.4 shows the original drainage index raster (top left) as well as our two measures (bottom panels).

The figure also shows a measure of land productivity, the Soil Productivity Index (PI), developed by Schaetzl, Krist Jr., and Miller (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 generally do not include PI as a control, although our results are not driven by its inclusion or exclusion.[9] A comparison of the top panels of figure 1.4 demonstrates that lands with a high drainage index value are more productive once drained, on average, than low DI land.

Figure 1.5 shows the relationship between median DI and the observed percent of a county drained in 1969 by quartile. The DI=60 cutoff is shown on each plot. The two measures of poor drainage are highly correlated. There are no *High DI* counties in Q1 while most counties in Q4 are classified as *High DI*. The *DI Quartile* measure ensures a more balanced comparison within each state. Within poorly drained states, however, the comparison may be between counties that are, in absolute terms, all poorly drained.

Finally, we collect USDA Agricultural Census data from 2017 on land

8. 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).

9. "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, Krist Jr., and Miller 2012).

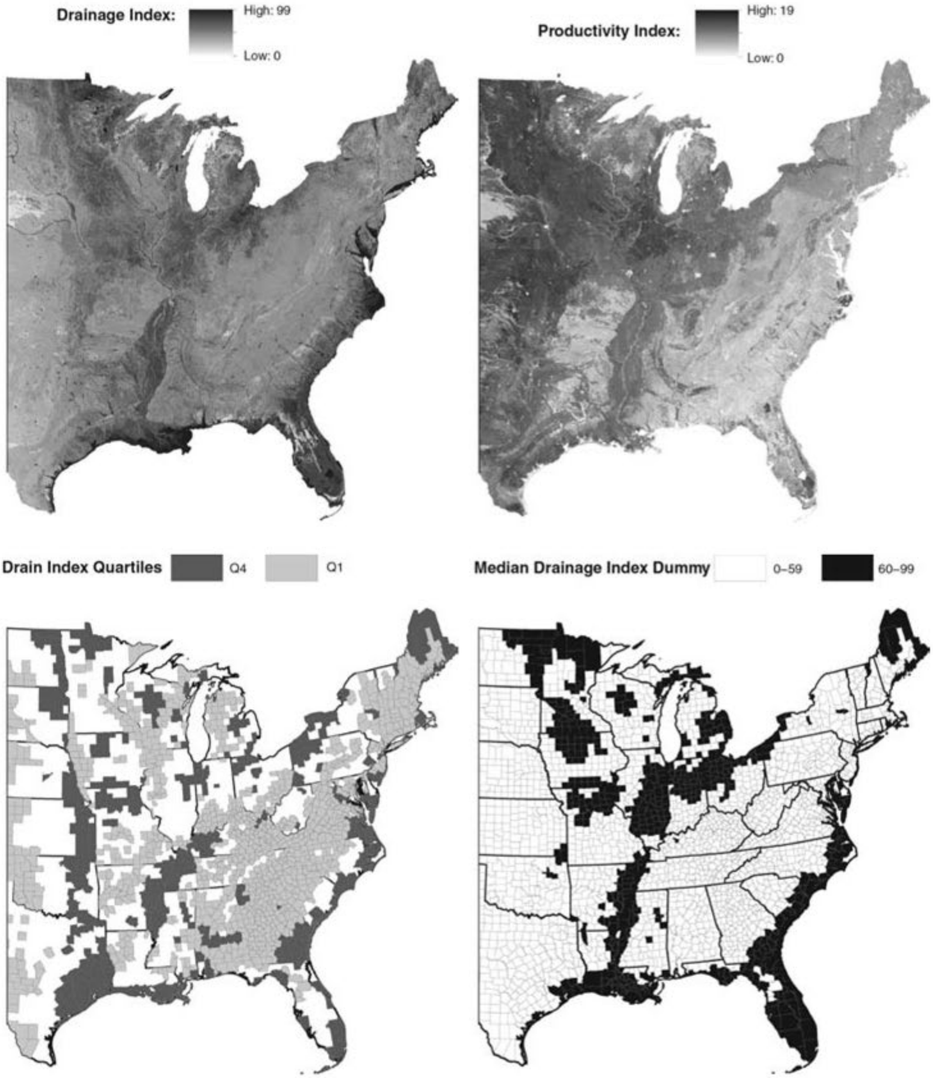


Fig. 1.4 Measures of poorly drained lands and productivity

Note: The top panels show the Drainage Index and Productivity Index rasters used to create county-level measures. The bottom left panel shows the *High Drainage* variable, which is the counties with median drainage index greater than 60. The bottom right panel shows the best and worst drained quartile of counties in each state.

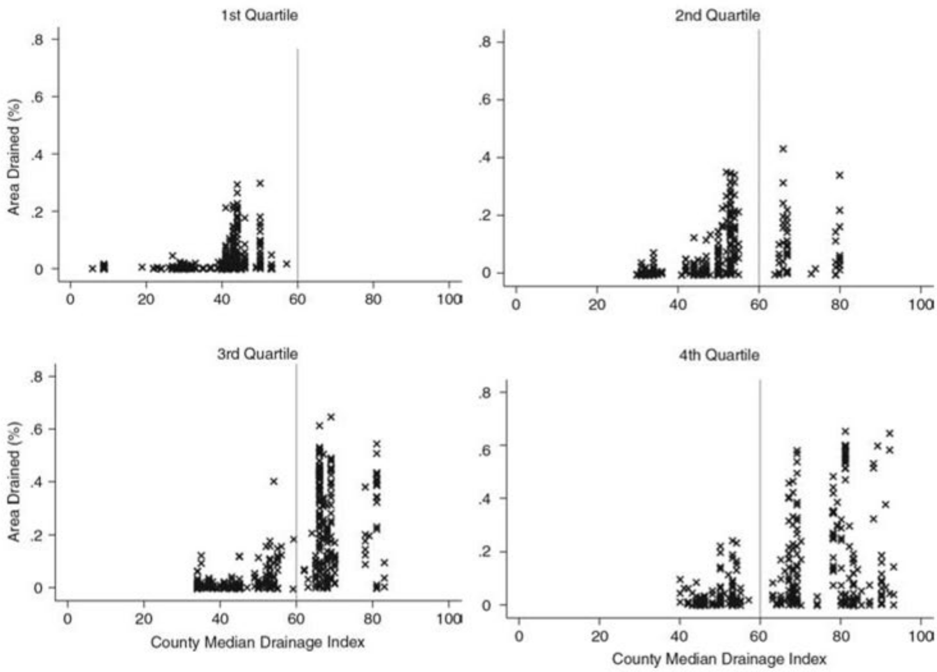


Fig. 1.5 Drainage index and drainage

Note: This figure depicts, for each county in our sample, the relationship between the median drainage index and the percent of county area drained in 1969, separating the data into state-specific drainage quartiles.

production practices from the National Agricultural Statistics Service Quick Stats. These data provide area (in acres) drained by artificial ditches and area drained by tile as two separate categories. To get total drainage acres we add these together.

1.4 Results

In this section we examine the contribution of drainage to agricultural production in the US east of the 100th meridian. Conditional summary statistics are provided in table 1.2. This table offers a comparison of area with high potential need for drainage relative to others in 1880 and 1920.

We begin by examining outcomes across states in our two groups, Midwest Tile and Coastal Plain, 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—state by year and county fixed effects—and then group counties in each state by drainage index quartile.

Table 1.2 **Conditional summary statistics**

	Drainage Index < 60		Drainage Index > 60	
Variable	1880	1920	1880	1920
Total Value in Farms (2020$ millions)	103.68	265.91	124.02	413.22
	(149.00)	(277.84)	(144.60)	(403.80)
Farm Value per Acre (2020$)	448	1,054	496	1,708
	(844)	(1,714)	(405)	(6,284)
Pct. of County Improved	0.34	0.45	0.36	0.51
	(0.23)	(0.22)	(0.29)	(0.30)
Total Farms	1,717	2,405	1,705	2,410
	(1,202)	(1,343)	(1,300)	(1,510)
Total Acres in Farms	225,923	279,310	207,490	263,111
	(127,343)	(157,627)	(129,705)	(149,661)
Median Drainage Index	43.65		72.32	
	(6.38)		(7.75)	
Median Productivity Index	8.29		10.25	
	(3.96)		(3.41)	

Note: Summary statistics conditional on high/low drainage index (DI > 60) for 1880 and 1920. All values are the mean value of all the counties in that treatment status for the variable described on the left. Standard deviations are reported in parentheses.

We exclude Q2 and Q3 and then plot the yearly mean for each quartile group. Comparing the best- and worst-drained quartiles shows the changing trends over time.

The Midwest Tile states generally drained land via small districts, on the order of around 1,000 acres with around 20 farms. Coastal Plain districts were orders of magnitude larger and thus required more coordination. Because the transaction and overall costs of forming and draining larger areas are higher, we expect the Midwest Tile states to begin draining first. The top panels of figure 1.6 show how the percentage of a county in improved acres changes over time for Q1 and Q4 counties. After controlling for state by year and county specific variation, counties in Q4 see less improved agricultural land than counties in Q4, in both the Midwest Tile states (left) and Coastal Plain states (right). By 1900 in the Midwest Tile states, Q4 counties have as much improved land as Q1 counties, which we attribute to the rapid rollout of drain tile. In contrast, Coastal Plain states do not see success in drainage, bringing high-DI counties to parity in improved acres until 1940.

The bottom panels use the same approach with agricultural land value per acre as the variable of interest. Midwest Tile states see Q4 land values initially far below Q1 counties, but increase as buyers and sellers begin to anticipate drainage success. By 1880—a time when tile was being successfully deployed and land buyers could reasonably be assured that drainage could successfully improve their poorly drained lands—Q4 and Q1 counties

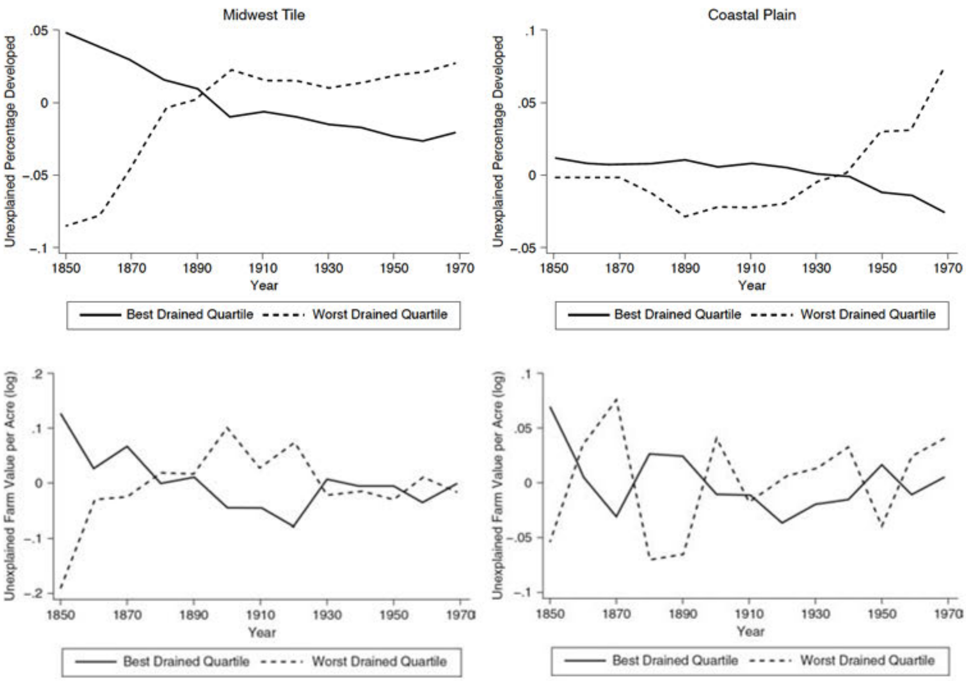


Fig. 1.6 Drainage quartile comparisons

Note: 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 (top panels) and total farm value (bottom panels) for counties in the Midwest (left panels) and Coastal Plain (right panels). Outcomes are bifurcated by drainage index quartile, Q4 relative to Q1.

have similar per acre land values. Thus capital markets appear to anticipate on-the-ground improvements. The story is much less clear for Coastal Tile states, with fluctuations in the relative prices of land in Q1 and Q4 counties. We attribute some of this to the uncertainty surrounding drainage in these states. Land markets may have alternatingly anticipated successful and unsuccessful drainage over time, while on-the-ground implementation ultimately took longer.

We perform a similar analysis using our alternative measure of *High DI*, and these results are shown in figure 1.7. The results are quite similar to figure 1.6, with *High DI* counties having improved acreage levels similar to low DI counties by 1900 for Midwest Tile states, and around 1940 for Coastal Plain states. The per acre land value trends, shown in the bottom panels, are clearer using the *High DI* measure. For Midwest Tile states, per acre land value for high- and low-DI counties is equal by around 1890, and by about 1900 for Coastal Plain states.

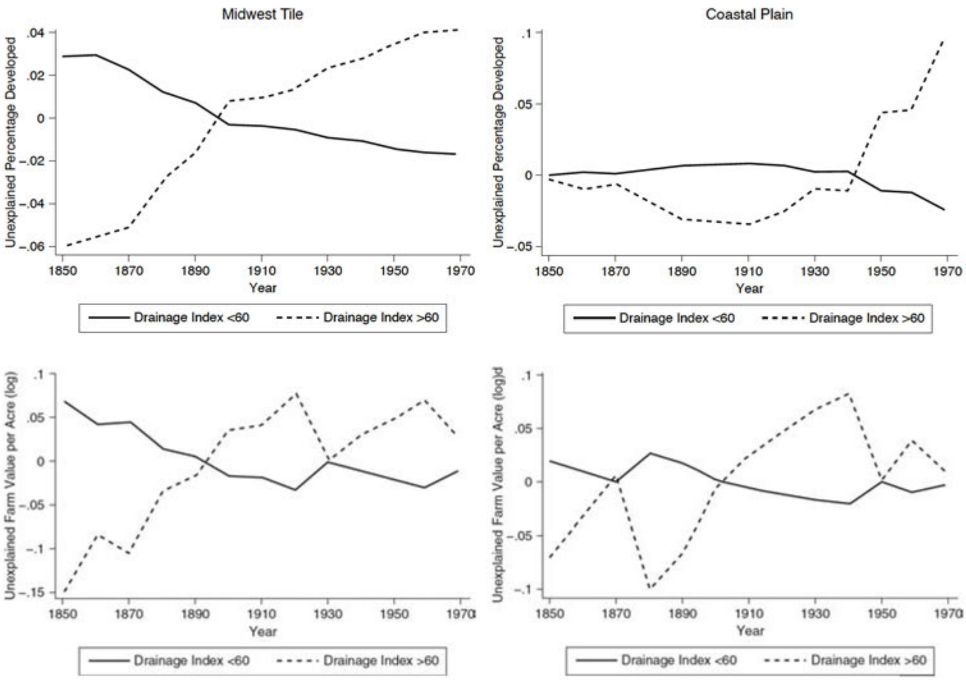


Fig. 1.7 Drainage index comparisons

Note: 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 (top panels) and total farm value (bottom panels) for counties in the Midwest (left panels) and Coastal Plain (right panels). Outcomes are bifurcated by drainage index.

1.5 Lessons for Future Adaptation

Our historical analysis offers insight into the real barriers associated with institutional change for drainage. A key conclusion of our work is that institutional development to solve drainage coordination problems, including trial and error and legislative revision, took time. 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 as in 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. Hewes and Frandson (1952) discuss the evolution in Iowa:

> Within Story County, the pattern of small, discontinuous wet tracts intermingled with well drained land is the general rule except in the northeastern one-half of Lafayette Township, where the one extensive continuous poorly-drained prairie portion of the county is found. Although as an

> early settler put it, 'only the higher laying lands could be broken, wet prairie land was necessarily included in most prairie farms.' The wet areas, if used at all, served for pasture or wild hay, or for open range grazing into the 1880's.

Projected increases in temperature and precipitation suggest that Midwestern agriculture will shift north, likely leaving behind some of the previously dominant Corn Belt.[10] The sequence of 19th-century American settlement revealed the important coincidence of wet and fertile soils in the Midwest and the resulting importance of land drainage technology. More extensive agricultural development in northern areas like North Dakota, Minnesota, Michigan, and Wisconsin will similarly incentivize land drainage (Meyer and Keiser 2018). It is useful to consider what can be learned from the settlement of the Corn Belt (read Drainage Belt) and how the context of investment in drainage is and will be different from what it was historically.

From a strictly agricultural perspective, the opportunity to drain wet land and increase its productivity is a welcome aid to climate adaptation. Opportunities to drain and improve soil productivity are likely to be broadly similar to those taken advantage of by earlier generations of farmers. Further, drainage technology, like virtually all agricultural technology, has dramatically improved. Terra-cotta tile is no longer the foundation of drainage, having long since been replaced by corrugated PVC pipe, installed with modern trenching machinery. Market incentives can be expected to lead to extensive investment in drainage of wet, but productive, farmland. Institutions such as the drainage district are well suited to coordinate communities of farmers with related interests in drainage.

Different now from then—beyond technology—are the perceived external effects of draining land. There are two main categories: loss of wetland ecosystems (and wildlife habitat) and off-farm transport of nutrients. With respect to wildlife, for example, the benefits from seasonal habitat for migratory ducks extend well beyond the borders of individual farms. But especially far reaching are the effects of nutrient runoff, abetted by the drainage systems put in place over the past 150 years. Nitrogen transported from Midwestern farms—all in the Mississippi watershed—collect in the Gulf of Mexico, creating a hypoxic dead zone (see Dale et al. 2010). External effects in both categories extend beyond the boundaries of farms as well as existing drainage districts, or any districts devised to deal with agricultural production.

There are both regulatory and market approaches to incorporating off-site effects into the calculations of farmers investing in drainage. Direct regu-

10. Changes in climate will not make North Dakota agronomically identical to Illinois because day lengths still will differ. See Olmstead and Rhode (2011) on adoption of wheat varieties from similar latitudes.

lation of land use, including drain tile installation, is a natural regulatory suggestion. Private mechanisms are available as well. Conservation easements placed on farms restrict future development and specify management methods, including drainage measures, that promote wildlife habitat and other off-site environmental benefits. Parker and Thurman (2019) discuss how private land trusts serve to aggregate public demands for environmental goods and incentivize their provision through the easement mechanism. Government policy plays a significant role in this private provision by granting substantial tax benefits to landowners who restrict their rights with easements (see Parker and Thurman 2018).

The path of human ingenuity to adapt to changing conditions is impossible to predict. We can say, though, that both institutional and technical innovation will play important roles. We argue here and elsewhere (Edwards and Thurman 2022) that institutional innovation in the form of drainage districts was vital to 19th-century agricultural development. Further institutional innovation will be key if we are to effectively discover and account for the full spectrum of benefits and costs to future adaptation. Technological innovation will continue to play an important role. Castellano et al. (2019) discuss and promote advanced drainage technologies that allow improvements in agricultural value at lower external cost.

Finally, in addition to the land use changes likely to result from Corn Belt agriculture moving north, important broad scale changes are likely to result in lands left behind—lands now less suitable to the types of agriculture relied on in the past. Much of this land is already drained, and the future private and public benefits from its use will be conditioned by the existing network of drain tile and ditches.

Figure 1.8 looks at the changes in agricultural drainage made over the last 50 years, from the last year in our data analysis, 1969, to 2017. Intensive investment in drainage continued to be made in Minnesota, Iowa, Illinois, the Dakotas, and Michigan. 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). Meyer and Keiser (2018) project that under climate change, states in the northern Midwest—the eastern Dakotas and northern areas of Minnesota, Michigan, and Wisconsin—will see additional drainage development, continuing the trends that have emerged over the last 50 years.

In contrast, the Coastal Plains states have seen relative declines in the amount of drainage. Florida, Texas, Louisiana, South Carolina, and Mississippi all have numerous counties where share of drainage has decreased by more than 2.5 percentage points. This distinct difference between glaciated and plain areas suggests the importance of understanding the history of the challenges facing drainage enterprises. The costs and benefits of future adaptation via drainage are likely to be heterogeneous across space. Where coordination among large numbers of landowners is needed, transaction

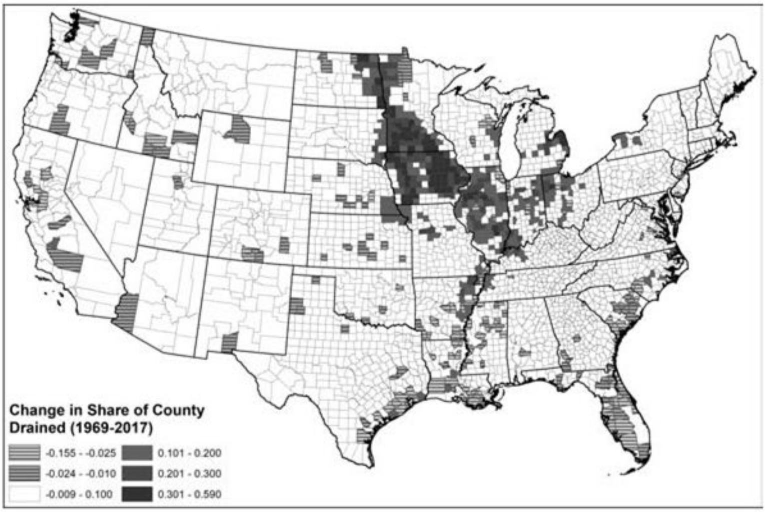


Fig. 1.8 Change in drainage

costs create challenges to adaptation that cannot be assumed away or solved ex ante.

While we can learn about how to solve drainage coordination problems of adjacent landowners from historical experience, 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. 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, Brevé, and Gilliam 1994), and degradation of soil quality (Castellano et al. 2019). New institutional innovations that address these impacts as well as agricultural production will need to emerge.

1.6 Conclusion

In this paper, we document and analyze how local drainage enterprises invested in tile drainage, ditches, and drainage works. After federal and state funding for these projects failed to materialize, drainage management districts formed to locally finance drainage investment over wetlands spanning thousands to hundreds of thousands of acres. Of the 215 million acres of wetlands estimated to have existed in the contiguous US at colonization, today 124 million have been drained.

While modern drain tile is no longer baked clay, 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. Once installed, drainage eliminates the inverted "U" relationship between precipitation and land values, making areas with excess precipitation more profitable to farm. For the eastern US, drainage is perhaps the most important climatic adaptation, despite its low profile, perhaps as a result of being buried out of sight.

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