The Appalachian Coalfield in Historical Context

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Abstract The Appalachian coalfield occurs within the eastern United States (US). This mountainous landscape is formed from natural dissection of sedimentary geologic strata with interbedded seams of coal and serves as headwaters for multiple rivers. The region's natural ecosystems, with a primary vegetation of mostly deciduous forest, are among the non-tropical world's most biodiverse. After first humans arrived more than 10,000 years ago, the first Europeans came to Appalachia as fur trappers and traders; agriculturalists and merchants came soon after. The region's diverse forests and rich mineral resources supported economic development as settlements expanded and populations grew. Coal mining began in the mid-1700s to supply commercial and residential users. Large-scale timber harvesting and coal mining stimulated railroad expansion in the mid-1800s, which improved transportation linkages to more populated areas and further increased coal demand. The American nation's industrial development increased usage of iron and steel, further expanding coal demands. Coal was essential to American electrification during the twentieth century. With numerous and thick coal seams accessible by both surface and underground mines, Appalachia was the US's primary coal-producing region from the 1800s through the 1970s. Appalachian coal mining has influenced the region's landscapes, forests, water, and people over more than two centuries.

Keywords Coal · Forests · Industrial development · Railroad · Steel · Timber

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C. E. Zipper and J. Skousen (eds.), *Appalachia's Coal-Mined Landscapes*,
https://doi.org/10.1007/978-3-030-57780-3_1

1 Introduction

The Appalachian coalfield is a mountainous and forested region of the eastern US with biological resources that are among the world's most biodiverse (Fig. 1). The region is one of complexity, with a long history of landscape development and diversity of life forms. Within this ancient landscape, coal mining has been a major influence on human populations and environment. Many Appalachian communities developed with mining as a primary economic driver, and coal mining has affected human attitudes and culture (Bell and York 2010). Looking beyond regional boundaries, Appalachian coal has contributed to American prosperity and industrial development for more than a century.

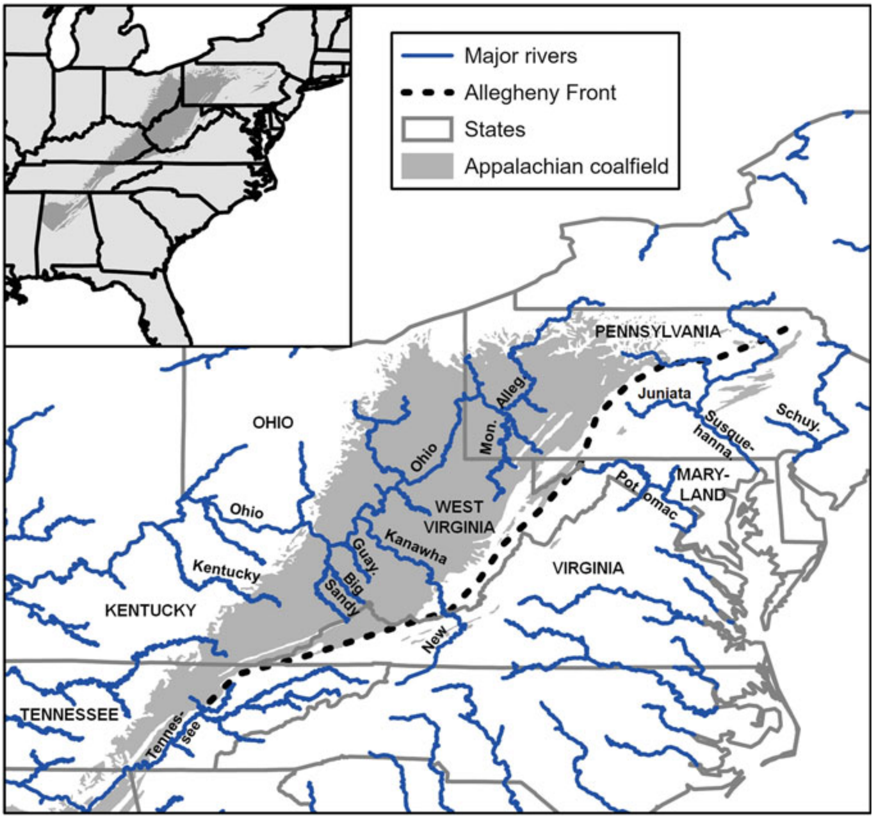

Fig. 1 The Appalachian coalfield, as it occurs in seven states of eastern U.S.A. The dark area represents surface expressions of geologic formations associated with bituminous and Pennsylvania anthracite coals. Rivers of the region include the Allegheny (Alleg.), Monongahela (Mon.), Schuylkill (Schuy.), Guayandotte (Guay), and other rivers as represented

This chapter reviews the Appalachian coalfield's natural and human history through the present day. In chapters that follow, the Appalachian coalfield's landscapes and communities are described as they have been affected by centuries of mining and removal of more than 45 billion tons of coal (Milici 1997; Zipper 2020).

2 Natural History

2.1 Landscapes

The Appalachian coalfield occurs within the oldest mountains on earth; their formation began early in the Paleozoic Era as thick layers of sediment and carbonate rock accumulated on the shallow sea bottom. When the seas receded, terrestrial plant communities thrived, producing organic matter that deposited with sediments. As drifting continental plates collided, they folded, faulted, and lithified former surface deposits. The mountain building was followed by deep erosion, with streams depositing layers of eroded sediments and rock debris downslope in nearby lowlands. Thus, the region's geology is sedimentary with beds of sandstone, shale, and coal, but often with overlying older rocks (Eriksson and Daniels 2021). Repeated uplift energized streams, which rapidly cut downward into the ancient bedrock. Some streams flowed along weak layers defining the folds and faults created millions of years earlier. Other streams down-cut rapidly across the resistant folded rocks of the mountain core. Then, around 220 million years ago, the prehistoric land mass known as Pangea began to break apart, and the plate tectonics that created the then-towering Appalachian Mountains were stilled. Weathering and erosion prevailed, wearing away the mountains and producing the complex and highly dissected mountainous topography found in the Appalachians today. In the eastern parts of Appalachia, terrain was formed within faulted and folded sedimentary rocks, and stream erosion has created a mountainous landscape of parallel ridges and valleys. Further west, a former plateau of generally flat-lying sedimentary geologic strata was dissected by stream drainages, forming a seemingly random pattern of narrow ridgetops, side slopes, and narrow valleys (Fenneman 1938). This mixture of youthful valleys and mature plateaus results in a complex terrain with steep slopes and deep gorges, narrow ridges, hills, and valleys prevailing in what is now known as central Appalachia, and with similar features but less steepness to the north and south.

There was a more recent geologic contribution to the development of landscapes and ecosystems in the Appalachian coalfield—continental glaciation. Rivers of ice, often thousands of meters in depth, covered the northern part of the region and contributed to the creation of current river drainages, particularly the Ohio River system. The glaciers, with their arctic air masses and icy winds, also created conditions suitable for boreal vegetation which extended as far south as present-day Georgia. As the glaciers retreated around 20,000 years ago, the climate changed again, and the boreal vegetation migrated to higher elevations and to the north even as humans began moving into the landscape.

Today, elevations in the Appalachian coalfield range from around 900 feet (275 m) in Ohio to as high as 4863 feet in West Virginia (1482 m). The region's climate is humid and temperate and varies with elevation and topography. The change in elevation, topography, and aspect can cause dramatic shifts in climate, e.g. the climate of a protected mountain valley will differ from that of an adjacent ridge top. Also, because major air masses move from west to east, terrain produces pronounced effects on precipitation, with a distinct rain shadow in some leeward areas east of the Allegheny Front divide. Mean annual precipitation ranges from 35 inches (890 mm) in valleys to 80 inches (2040 mm) on the highest peaks and is well distributed throughout the year. Because of the rugged topography, aspect exerts micro-climate effects. For example, southwest- and south-facing slopes which face the sun during mid-day and afternoon, are typically warmer and drier than adjacent northeast- and north-facing slopes. In steep terrain, west-facing slopes can receive more rainfall than east-facing slopes on the lee (drier) side of the ridges. The complex topography also drives variation in vegetation and soil, with differences in temperature and moisture often reflected by differences in forest composition and abundance, under-canopy vegetation, and productivity.

Because erosion is a major influence on these landscapes, soils are generally shallow except in depositional environments such as foot slopes, coves, and valleys, and along streams and rivers. The soils may be genetically young because of recent deposition but often with constituent sediments that are highly weathered. Due to forest vegetation, most soils are naturally acidic but high in surface organic matter. Water is generally abundant due to the ample and consistent precipitation throughout the year. Natural water quality is often dilute, with low concentrations of dissolved elements due to the highly weathered terrain. In forested watersheds, natural waters are generally of excellent quality but can be impaired after significant land-surface disturbances. Water flow in streams and rivers can be quite variable because of the high relief and shallow soils.

2.2 Ecosystems

Regional ecosystems have been shaped by the interactions of landscape, climate, natural and land-use history. The rich topography and dynamic climate created a complex set of varied ecosystems, with diverse flora and fauna (Butler et al. 2015). Pickering et al. (2003) reported that the Appalachian region is home to 2000 species of plants, 200 species of birds, 78 mammals, 58 reptiles, and 76 amphibians. The central and southern Appalachians are considered a "hotspot" for aquatic diversity because of the many diverse habitats created by the humid-temperate climate, the complex topography, diverse stream sections and patterns, and the relative geologic stability over evolutionary history (Chaplin et al. 2000; Flather et al. 2008).

The region is generally forested and has been since the last Ice Age. The region's extensive forests are well-described by E. Lucy Braun (1950) in her classic book *Deciduous Forests of Eastern North America.* As the Laurentide ice sheet retreated, the geographical ranges of temperate tree species migrated northward while boreal species followed the ice retreat northward and migrated to higher elevations. The generally northeast-southwest orientation of the ridges and valleys east of the Allegheny Front encouraged species migrations. Also, vertical zonation of vegetation prevails, that is, the lower elevation limits of each forest type increase toward the south, a result largely due to climate.

Like the topography, the vegetation is complex across landscapes, and indeed the two are often interrelated, with identifiable forest ecosystem types commonly found in particular elevational/temperature/moisture conditions. The most diverse are the mixed mesophytic forest types, which are largely confined to rich, moist montane soils, and may contain more than 25 tree species on a site. Some of the characteristic canopy tree species are red and white oak (*Quercus rubra* and *Q. alba*), sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), tuliptree (*Liriodendron tulipifera*), white ash (*Fraxinus americana*), white basswood (*Tilia heterophylla*), yellow buckeye (*Aesculus octandra*), and yellow birch (*Betula alleganiensis*). Other common trees are red maple (*Acer rubrum*), shagbark and bitternut hickories (*Carya ovata* and *C. cordiformis*) and black or sweet birch (*Betula lenta*). Small understory trees and shrubs include flowering dogwood (*Cornus florida*), hophornbeam (*Ostrya virginiana*), witch-hazel (*Hamamelis virginiana*) and spicebush (*Lindera benzoin*). Perennial and annual herbs are abundant, among them herbal and medicinal plants such as American ginseng (*Panax quinquefolius*), goldenseal (*Hydrastis canadensis*), bloodroot (*Sanguinaria canadensis*) and black cohosh (*Cimicifuga racemosa*).

These same trees, shrubs, and herbs are also widely distributed in less rich, mesic forests that generally occupy cool coves, stream valleys, and flood plains throughout the region at low and intermediate elevations. At higher elevations and in the north, these mesic forests give way to less-diverse northern hardwood forests with canopies dominated by American beech, sugar maple, American basswood (*Tilia americana*), black cherry (*Prunus serotina*), and yellow birch and with far fewer species of shrubs and herbs.

Drier and rockier uplands and ridges are occupied by oak-chestnut type forests dominated by a variety of oaks (*Quercus* spp.), hickories (*Carya* spp.) and, in the past, by the American chestnut (*Castanea dentata*). The American chestnut was virtually eliminated as a canopy species by the introduced fungal chestnut blight (*Cryphonectaria parasitica*). Today, it can still be found in the understory as sapling-sized root sprouts, which succumb to the blight when they are larger. In present-day forest canopies, chestnut has been largely replaced by oaks. The richer oak forests, which often grade into mesic types in coves and on moist slopes, have dominantly white and northern red oaks, while the driest sites, particularly those in the rain shadow of the Alleghenies, are dominated by chestnut oak (*Q. montana*), or sometimes by scarlet (*Q. coccinea*) or northern red oaks, often intermixed with shortleaf, Virginia and pitch pine (*Pinus echinata, P. virginiana* and *P. rigida*). The drier oak forests generally lack the diverse small tree, shrub, and herb layers of mesic forests.

At the highest elevations, conifers dominate, mainly red spruce (*Picea rubens*), Fraser fir (*Abies fraseri*), balsam fir (*Abies balsamea*) and hemlock (*Tsuga canadensis*). As remnants of the boreal and sub-arctic vegetation which flourished during the last glaciation, these spruce-fir forests, often bathed in clouds, are home to rare and endangered species. Decimated by timber-harvesting, pollution, and an introduced invasive insect (*Adelges piceae*, the balsam woody adelgid), these high elevation ecosystems are considered endangered in the Appalachians.

Recent threats are emerging as dangers to Appalachian forest ecosystems. Such threats include serious insect and disease outbreaks, invasive exotic plants, overabundance of white-tailed deer (*Odocoileus virginianus*), and climate change. Among the most dramatic are the insect pests such as the introduced gypsy moth (*Lymantria dispar*), which infests primarily oaks, causing severe defoliation and tree mortality. The decline and likely eventual extinction of green and white ash (*Fraxinus pennsylvanica* and *americana)* is the result of the introduction of the emerald ash borer (*Agrilus planipennis*). Other pests and pathogens include the hemlock woolly adelgid (*Adelges tsugae*), which is responsible for the loss of an important conifer species in these predominantly hardwood forests; and the beech bark disease complex, which includes both a scale insect (*Cryptococcus fagisuga*) and fungal components, and affects American beech (*Fagus grandifolia*); and Dutch elm disease, caused by a fungus (*Ophistoma ulmi*) spread by elm bark beetles, which is responsible for killing millions of elm (*Ulmus*) trees. All of these insect and disease threats are creating a less diverse forest overstory. Over-browsing by deer negatively affects forest regeneration, further driving down tree species diversity. Climate change is likely to be a subtle but significant interacting effect on the forests in the coming decades (Butler et al. 2015).

3 Human Settlement and Economic History

3.1 Early Humans

The region's human history began near the end of the last Ice Age, during the early Pleistocene. Evidence of human habitation 14,000 or more years before present was found at Meadowcroft Rockshelter in Washington County, Pennsylvania (Advaosio et al. 1990). During this era of receding ice sheets, the climate was colder and supported mixed vegetation with more open canopy than in present-day forests, while the landscape was occupied by animal species adapted to savannah-like vegetation (Guilday 1982). The region's earliest humans were likely nomadic hunters of large mammals, many of which are now extinct or displaced. Primary archeological evidence of human existence during what is known as the Paleoindian era is comprised of projectile points, carved from rock and with distinctive shapes. Such "arrowheads" have been found in the Appalachian coalfield, indicating significant human dispersal during the late Paleoindian era (Fig. 2). Most Paleoindian artifacts

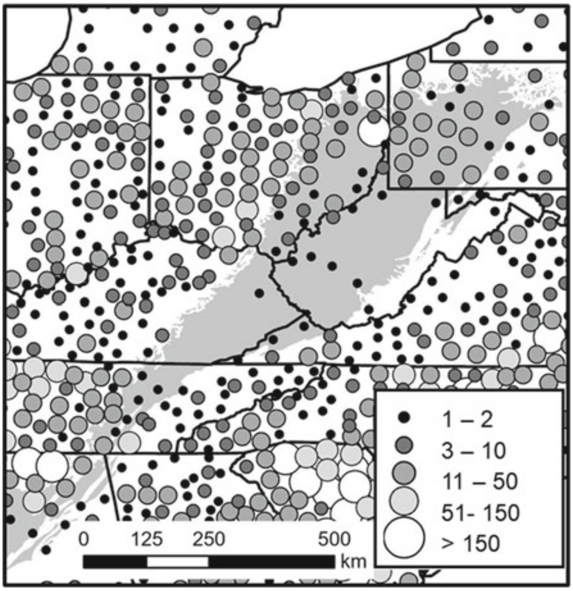

Fig. 2 Distribution of Paleoindian artifacts (arrowheads) in middle latitudes of eastern US, Numbers of artifacts reported by Anderson et al. (2019) by county are plotted by each county's geographic centroid. Counties lacking symbols have yielded no Paleoindian artifacts. Gray areas are the Appalachian coalfield

have been found in the coalfield's northern segments, where relief is less extreme than further south, and in wide river valleys such as the Ohio and Kanawha; while some artifacts have also been found in valleys of smaller rivers and in uplands (Rosencrance 2018). However, the geographic pattern of Paleoindian artifacts suggests that Appalachian coalfield regions south of present-day Ohio and Pennsylvania were not well-used by the eastern North America's earliest people, relative to the surrounding and less-mountainous terrain.

The period of Native American history known as the Archaic began approximately 9,000 years before the present as ice sheets receded further, climate warmed, and forest canopies closed. These changes were accompanied by extinctions of some megafauna that had sustained the region's Paleoindians (Maslowski 2017). Native Americans of this period tended to settle in river bottoms and establish livelihoods that included the gathering of edible plants as well as hunting of smaller game (Drake 2001). One of the most significant Archaic sites in the coalfield is at St. Albans, near the Kanawha River in southern West Virginia, which was used periodically for more than 10,000 years through 1700 A.D. (Broyles and Harding 1974).

In eastern North America, the Archaic period transitioned into what is known as the Woodland Tradition as native Americans increased reliance on cultivated plants. In Appalachia, this transition began in about 1000 B.C. (Drake 2001). During this era, indigenous peoples developed a capability to work with pottery, social structures became more complex and integrated, and some tribes constructed burial mounds for interring their dead. Archeological sites with evidence of Woodland-tradition Americans occur in the coalfield but it appears that large areas of this mountainous region remained unoccupied, even up to the time of European arrivals (Munoz et al.

2014). Resources needed for survival were found in fertile valleys near streams and rivers (Milner et al. 2001). A recent study estimated the total population of eastern North America at the dawn of European settlement, the year 1500 A.D., at about 1.2 to 1.7 million people (Milner and Chaplin 2010). However, analysis of maps published with that estimate and by Anderson (1991) suggest humans occupying what is now the Appalachian coalfield may have numbered only 100,000 or less and were most heavily concentrated in the Ohio—Monongahela, lower Kanawha, and upper Susquehanna River drainages.

3.2 Early European Explorations and Settlement

The earliest Europeans to enter the Appalachian coalfield likely were fur traders. It is known that the European fur trade with North America began in the early 1500s, but almost a century passed before fur traders penetrated inland to reach the Appalachian coalfield. During the sixteenth and seventeenth centuries, American furs were in great demand in Europe due to their high quality and scarcity from diminishing fur-bearing animals in continental trapping grounds. Hence, Europeans established trade with North American native peoples soon after their arrival, supplying them with manufactured items such as textiles, iron tools, and guns in exchange for furs.

Barriers to westward movement by early Europeans included dense woodlands, in some cases the indigenous peoples, and difficult terrain including the formidable physical barrier created by the western edge of Appalachian plateau, the Allegheny Front. As supplies of furred animals diminished along the east coast, the traders traveled further inland, often along river courses. An eastern Virginia fur trader, Abraham Woods, in alliance with the Virginia colonial government, sent several expeditions to explore western Virginia areas. Those parties came upon the westward-flowing river, which they named Woods River (now known as the New River). Woods organized one of the first recorded journeys into the central Appalachian coalfield in 1671, the Batts-Fallam expedition. With indigenous guides, the expedition followed the Woods River west to Peters Mountain, and then traveled overland to the Guyandotte River and Tug Fork of the Big Sandy, two Ohio River tributaries (Briceland 1991). Other explorations of the interior coalfield followed. In the 1690s, Albany fur traders sent an exploration party led by Arnout Viele south into the Delaware and Susquehanna River valleys. They found their way west following the Juniata River from the Susquehanna over the watershed divide and eventually reached the Allegheny and Ohio Rivers (Drake 2001).

If other seventeenth-century explorations of the coalfield region occurred, they are not as well documented; but the eighteenth century saw increasing exploration and settlement of the coalfield. In 1742, a party led by J.P. Salley followed the New River into southern West Virginia, reaching a river where he observed outcropping coal seams, now the Coal River. In 1750, a party led by Thomas Walker traveled through the southwestern Virginia coalfield and through Cumberland Gap into eastern Kentucky. The Walker party were the first Europeans to document Cumberland Gap, but they were not the first to travel that way as their journals described streams which had been previously named (Eavenson 1942). In 1751, an exploration party led by Christopher Gist entered eastern Kentucky by way of the Ohio River, then returned eastward by following the North Fork Kentucky River and then passing through Pound Gap (Eavenson 1942).

Once these exploration parties had found the way, settlers followed. Fur traders working out of Philadelphia had outposts in the Ohio Valley prior to 1750 (Drake 2001). Westward migration to the coalfield began in Maryland and Pennsylvania. Settlers reached what is now the Pittsburgh area by traveling up the Potomac River through the Allegheny Front and into the Monongahela drainage or by following the Susquehanna and Juniata Rivers (Flanders 1998). By 1770, around 10,000 families had settled in western Pennsylvania (Flanders 1998). Settlement of Pennsylvania's anthracite coalfield occurred later, as the first permanent settlement was established in 1769 (Harvey 1909). Virginia residents began migrating westward to the Kanawha Valley in the 1770s (Drake 2001). Daniel Boone led a party through Cumberland Gap to Kentucky, establishing the settlement now known as Boonesborough in 1775 (Flanders 1998). Following the Revolutionary War, settlers moved into the coalfield counties in large numbers. The first US Census, in 1790, counted approximately 200,000 people in the coalfield with the bulk of those (~85%) in Pennsylvania. By 1820, that number had increased to ~ 1,000,000 but still with the largest concentration (~85%) in the northern Appalachia area of northern West Virginia, Maryland, Pennsylvania, and Ohio (data from Forstall 1996).

3.3 Early Agriculture and Forest Use

Many of the region's early settlers were agriculturalists who established what can be described as "backwoods farms." They were generally located in areas with access to water and cleared the dense timber on flatter lowland landscapes for crops. They also raised livestock, often including hogs, by treating the woodlands as "open range." The form of agriculture practiced by the earliest settlers has been described as "yeomanesque," or a largely self-sustaining activity (Drake 2001). As the 1800s progressed, backwoods agriculture became more market-oriented with establishment of towns with merchants.

The first large-scale industrial activity to affect many rural coalfield areas was timber harvesting. Appalachian forests constituted an important economic resource for the new nation. Timber resources were in demand for a variety of uses: lumber for manufacturing, building construction, ship construction; bark for tanneries; conversion to charcoal for uses such as iron forging; and direct burning for heat. As demand for lumber by east-coast cities and export markets consumed coastal forests, timber-harvesting enterprises achieved greater scale as they moved west. Industrial harvesting of Appalachian forests began before the Civil War, often in areas close to rivers large enough to float logs to market. Pennsylvania was the first of the Appalachian states to experience large-scale timber harvesting, with an initial center along the Susquehanna River. After the Civil War, Pennsylvania timber harvesting expanded, driven in part by new demands created by railroad construction, and the state became the nation's leading lumber producer for a short period (Alban and Dix 2013). By the end of the century, much of Pennsylvania's woodlands had been reduced to "stumps and ashes" (Alban and Dix 2013) and Appalachian lumber producers moved further south. For example, most of West Virginia was still in old-growth forest in 1880, but most of the state's forests had been harvested by 1920 (Lewis 1998), while the timber harvesting "boom" in eastern Kentucky and southwestern Virginia peaked in the early 1900s (Eller 1982).

Expansion of timber harvest was aided by development of railroads, which moved products from harvest areas lacking rivers to markets. Railroad expansion also provided an important market for forest products, as lumber was used for fuel, rail ties, and bridge and coach production. American railroad construction began in the 1830s and accelerated in the following decades. From fewer than 3000 miles (4828 km) of rail in 1840, railroads expanded to approximately 9000 miles (14,484 km) in 1850 and more than 30,000 miles (48,280 km) in 1860 (Thompson 1925), primarily on the east coast.

The large-scale timber harvesting initiated some of the societal changes that carried over into the era of extensive coal mining. Timber harvesting of large areas interfered with what little remained of the "open-range" forest-grazing practices of early backwoods agriculturalists. Timber harvesting companies assembled large land holdings, some of which combined financial interests in both coal and timber (Eller 1982); while lumber haulage was an important revenue source for the railroads which enabled their further expansion and later transport of coal. When working large tracts in remote areas, timber companies established "man camps" that provided food and shelter for the workers, a forerunner of the "company towns" established by mining firms to house their workers. Hence, as coal mining expanded in the late nineteenth and early twentieth centuries, the model of industrial-scale natural resource extraction, along with the associated societal changes, was already underway.

4 Early Industry

4.1 Coal Mining

An early map of the upper Potomac River, dated 1736, shows the presence of "cole mines" at locations of coal outcrops (Eavenson 1942). Early commercial mining occurred at "Coal Hill" (now Mount Washington) across the Monongahela River from what is now Pittsburgh beginning in 1760 and those coals were extracted for use by soldiers at Fort Pitt. During the late 1700s, use of coal for both home-heating and commercial purposes expanded in Pittsburgh and additional mines were established. In 1800, a traveler noted that a "cloud of smoke" was visible over Pittsburgh. By the

1820s, words such as "dark veil," "gloomy," "filth," and "sulphurous vapor" were being used to describe the Pittsburgh atmosphere (Eavenson 1942).

Extraction and use of Pennsylvania's anthracite coal also began in the eighteenth century but its expansion did not occur as rapidly. Among the region's earliest settlers were blacksmiths who began using anthracite coal from the initial settlement in 1769 (Harvey 1909). Although anthracite was used locally through the rest of the century, expansion of mining beyond local needs was hindered by two factors: difficult transportation of coal out of the region, and the difficulties of burning anthracite in the open-air furnaces that were in common use at that time. Anthracite coals burn hotter and with fewer air emissions than bituminous coals but are more difficult to ignite. Anthracite mining expanded in the early nineteenth century with improvements in river-transportation and development of burning equipment designed for anthracite (Eavenson 1942).

Coal mining also began in other Appalachian areas during this period. By 1789, coal from western Maryland's upper Potomac basin was being transported to Hagerstown for use in nail making (Eavenson 1942). Late-eighteenth century land records from West Virginia describe the presence of coal as a valued commodity, but the state's first mine was not documented until 1810, in Wheeling where it supplied homes and blacksmithing (WVGES 2017). The first reported mining in Ohio dates from 1800 in Jefferson County, just north of Wheeling (Crowell 1995). In Virginia, the earliest recorded mining west of the Richmond Basin occurred in 1790, near Toms Creek at the base of Brush Mountain in Montgomery County, an area that is no longer in production; but no mining was recorded in the southwestern coalfield until much later (Hibbard 1990). By 1807, coal was being shipped from eastern Kentucky mines down the Kentucky River to Frankfort for use by blacksmiths (Eavenson 1942). The first documented production for Tennessee dates from 1839, when a state geological report described coal being hauled by wagon from Kingston to the Tennessee River for shipment on barges to markets downstream and several mines producing coal for blacksmithing (Eavenson 1942).

During that latter half of the nineteenth century, railroad extensions into and through the Appalachian coalfield aided coal-mining expansion. The Pennsylvania Railroad was extended to link Pittsburgh with Philadelphia by 1854. The Baltimore and Ohio extended a main line from the east coast up the Potomac River to reach Wheeling in 1858, and then after 1865 across the Ohio River and further west. Also following the Civil War, the Chesapeake and Ohio was constructed from Covington, Virginia, westward to the Ohio River, reaching Huntington, West Virginia, in 1873 (Thompson 1925). The Norfolk and Western Railroad was formed by merging smaller lines extending from the port at Norfolk to Bluefield, West Virginia, in the early 1880s; and was then extended through southern West Virginia to reach the Ohio River in 1892 (Lewis 1998). These rail lines provided essential transportation to markets for coals mined in areas away from the rivers.

4.2 Appalachian Coal Aided American Industrial Expansion

As the nineteenth century continued, Appalachian coal mining expanded, mining methods changed, and the geographic locus of coal mining changed within Appalachia (Fig. 3 upper). Nonetheless, Appalachia remained as the primary source of US coal up through the 1970s. (Fig. 3 lower). Readily-available and high-quality coal enabled establishment of numerous industries in the Appalachian frontier during early decades, reducing the young nation's economic dependence on other nations. Some of those industries continued expanding through the nineteenth and into the twentieth century as America became the world's leading economy.

4.2.1 Early Industry

Salt manufacturing was one of the first industries enabled by Appalachia's abundant coal. Salt springs provided a raw material source and coal provided the energy. A coal-fired salt works was established in western Pennsylvania in 1809. Wood-fired salt works in the Kanawha valley converted to coal beginning in 1817 (Eavenson

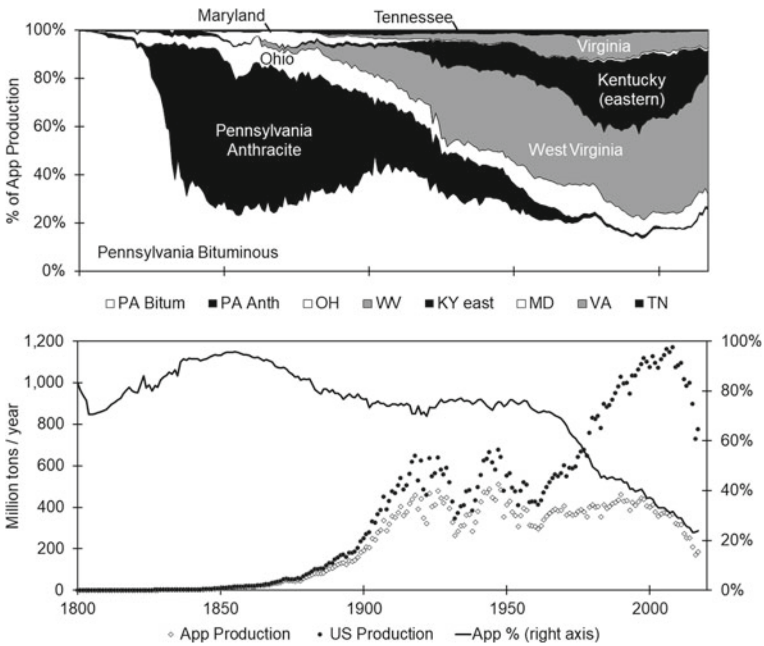

Fig. 3 Appalachian coal production, 1800–2017. (upper) Production by individual states expressed as a percentage of total Appalachian production. (lower) Annual Appalachian (App) coal production compared to total US production and expressed as a percentage of total US production (Milici 1997; EIA 2019a; Zipper 2020)

1942). By 1829, these areas were producing well over half of the new nation's salt (Lippincott 1912).

Another early American industry fueled by Appalachian coal was glass manufacturing. Following the Revolutionary War, the US had no significant capacity to produce glassware so most glass items were imported. Two glass-producing firms opened in the Pittsburgh area in 1797 using coal as fuel (Eavenson 1942). In 1800, two of the five known US glass-making factories were located in Pittsburgh (Davis 1949). By 1820, the number of US glassmakers had expanded to 33 and most of those, other than the nine west of the Alleghenies, used wood as fuel. Over the next 40 years, the wood-fired kilns suffered cost disadvantages as coal became the dominant glass-making fuel and the Pittsburgh region became the center of the US glass industry (Lamoreaux and Sokoloff 1997). This transition occurred as the industry expanded production, displacing imports to meet most of the nation's needs (Davis 1949). In the decades following 1860, natural and coal-derived gas supplanted solid coal as a glass-making fuel, but firms located in western Pennsylvania, northern West Virginia, and southern Ohio maintained leadership of the American glass industries. By the 1920s, Pittsburgh-area firms remained as dominant producers of American glass (Lamoreaux and Sokoloff 1997).

Another of earliest industries in US was iron making. Blast furnaces extract an impure form of iron, called pig iron, from the raw ore through the application of extreme heat. Multiple blast furnaces were present in the colonies even before the Revolutionary War (Hogan 1971). Following independence, iron works spread throughout the new nation. Except in the Pittsburgh area, however, many iron works relied on pig iron imported from Britain (Chandler 1972). Where available, coal was used for forging and working iron from the earliest days, but charcoal was the primary blast furnace fuel until the 1830s when a process enabling substitution of anthracite coal for charcoal was developed (Hogan 1971). This development enabled US iron production to increase from approximately 165,000 tons in 1830 to nearly 1 million tons in 1860 (Hogan 1971). The cost advantages of producing raw iron using anthracite were so profound that, during the 1840s and 1850s, much of the raw iron used by Pittsburgh's industry was being shipped from regions with better access to anthracite coal (Chandler 1972). In the late 1850s and following the Civil War, American iron manufacturers began adopting bituminous-coal and coke-based iron-making processes (Hogan 1971). By 1860, more than half of the new nation's iron-production capacity was located in Pennsylvania, and more than one-third was in Ohio, New Jersey, and New York, states with easy access to Appalachian coal (Hogan 1971).

By the late 1830s, Pennsylvania anthracite coal started to become widely available on the east coast, stimulating iron manufacturing and associated industry outside of coal-mining areas. New canals enabled anthracite shipments from production areas in central Pennsylvania, near what is now Wilkes Barre and Scranton to Philadelphia. From there, it was shipped up and down the east coast to multiple markets. Anthracite's high heat value and low price, relative to charcoal, enabled production expansion by multiple iron works in the northeast. Their expanded output enabled additional industrial activity, including expanded production of iron products by secondary manufacturers. The availability of coal for use in steam power also enabled expansion of factories for textiles and other products beyond limits imposed by reliance on water power (Chandler 1972). The northeast's rapid industrialization during this period fueled demand, enabling Pennsylvania anthracite coal production to increase from less than 250,000 tons in 1830 to more than 10 million tons in 1860 (Milici 1997).

4.2.2 Transportation

Coal was also important to pre-Civil War transportation, as it gradually supplanted wood as the power source for the steamboats that traveled the nation's rivers (Schuur and Netschert 1960). Appalachian coal was more essential to development of the young nation's network of railroads. Iron, and then steel, enabled the rail network's construction. Early in the rail industry's development, many of its iron and steel products were imported, but Pennsylvania's anthracite coal enabled expansion of the US iron industry in the decades following 1840 as the rail industry was expanding. By 1860, the domestic iron industry was fueled predominantly by anthracite coal (56% of tonnage), with some producers (13% of tonnage), primarily in the Pittsburgh area, also using bituminous coal and coke (Hogan 1971). By this time, the developing railroad industry was consuming one-fourth of domestic iron production (Fogel 1964), and domestic iron had largely supplanted imports for the production of rail (Hogan 1971). In decades following 1860 when Appalachia was the US's major coal-producing area (Fig. 4), coal displaced wood as a fuel for railroad engines and by 1921, almost 25% of US coal use was as locomotive fuel. Also during this period, shipping coal from Appalachian mines to distant markets provided the railroads with a major source of revenue.

Railroads were essential to the US's rapid industrialization during the late nineteenth and early twentieth centuries, providing low-cost transportation for the nation's widely dispersed raw materials and manufactured products (Bunker and Ciccantell 2003). Railroads have also been called a major contributor to the "take off" of the American economy, i.e., the period when a largely agrarian nation was transformed into a more industrialized economy, capable of strong economic growth (Fogel 1964). It is clear that this rapid expansion of the rail industry during the late nineteenth century was enabled by Appalachian coal.

4.2.3 Steel and Related Industries

Although small amounts of steel had been manufactured in America as early as 1810, the steel industry did not begin rapid growth until after 1860 (Hogan 1971). By 1860, Pittsburgh was already the center of the young US steel industry by virtue of its proximity to necessary raw materials, including coal. In 1867, the Bessemer process for converting pig iron to steel was established commercially, primarily for producing rail materials. By 1880, US rail production had grown seven-fold from

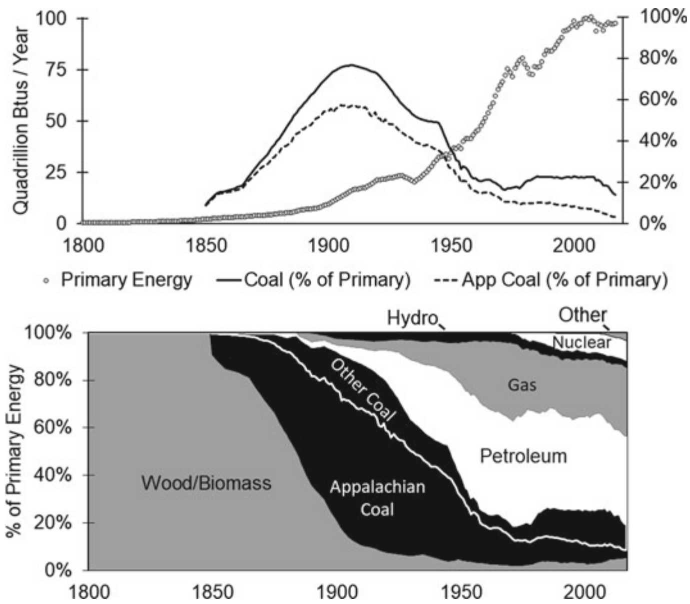

Fig. 4 US consumption of primary energy by source, 1800–2017. (Upper) Total primary energy consumption (left axis); proportion of primary energy consumption provided by coal (right axis); and estimated proportion provided by Appalachian coal (right axis). (Lower) proportions of primary energy consumption provided by various energy sources (other = geothermal, wind, solar, and miscellaneous). Data from EIA (2011, 2020b; Zipper 2020). Coal is segmented into Appalachian (App) and other sources based on sources cited for Fig. 3; hence, Appalachian coal contributions to US primary energy consumption, as a fraction of total coal contributions, are likely overestimated for recent decades since those estimates do not account for coal exports and imports

pre-Civil War levels, and steel had largely supplanted iron for rail manufacturing. By 1880, Pennsylvania facilities fueled by Appalachian coal were dominant producers of steel rail, and of iron and steel more generally. Other dominant producers were located in states with direct access to Appalachian coal, including Ohio, New York, and New Jersey (Hogan 1971).

As American industrial development continued past the era of rail expansion, the steel industry continued to play an essential role. Those contributions have become more diverse and pervasive in more recent times. Throughout most of the nineteenth and twentieth centuries, America's steel industry remained centered in mid-Atlantic areas supplied by Appalachian coal, and Appalachia's mines supplied steel producers within and well beyond Appalachia with high-quality metallurgical coals.

Another major contribution of Appalachian-supplied steel producers to American industrial development was the construction of steel-skeleton tall buildings. Pioneered in Chicago in the 1880s with steel produced by Pittsburgh's Carnegie companies (Misa 1995), these tall buildings came to dominate urban skylines. Similarly, the American military undertook a major effort to construct steel warships in the decades prior to World War I. The evolving technology required new types of steel, as guns were being developed to shoot large projectiles for long distances, along with armor-plating capable of protecting American warships from similar projectiles fired by enemies. Much of that steel was produced by the Appalachian-coal supplied firms Carnegie Steel and Bethlehem Steel (Misa 1995).

The latter half of the nineteenth and early twentieth centuries, a period during which Appalachian coal played a major role in the US economy, was a period of dynamic growth of US industrial production. During the latter half of the twentieth century, automobiles became a common mode of transportation, and automobile manufacturing became a major consumer of steel. The vast majority of American autos were domestically produced, as was the steel used in their manufacture. Throughout much of the twentieth century, Appalachian metallurgical coal was an essential input to American steel manufacturing.

4.2.4 Electric Power and Other Energy

Also, during the early-to-mid twentieth century, major changes occurred in energy sectors as coal was replaced by other fuels, including petroleum-based fuels and natural gas, for many industrial processes other than steel making. Yet another major change during this period was the electrification of the American society (Rosenberg 1998). During its early days of electrification, coal-fired steam generation was the primary means of producing electricity in areas without direct access to hydroelectric power (Fig. 5), and most American coal was Appalachian. Coal remained as the power source for more than 50% of US electrical generation for most years through the early 2000s, with Appalachia supplying more than 70% of US coal through the 1970s (Fig. 3).

5 Coal Production

5.1 Historic and Recent

Coal mining, although simple in concept, is difficult in practice, especially when prioritizing worker and environmental protections. Surface miners remove the earth materials overlying coal seams so as to extract the coal while underground miners burrow into the earth. Early mining relied on human labor, as miners removed the loose soil and rock overlying coal beds (“overburden”) and then followed the coal seam into the earth for underground-mine extraction. As time passed, demands for coal increased, the excavations expanded in size, and the hazards to worker health and environment of these mining methods became more apparent. Over centuries, mining firms have innovated by developing technologies that address difficulties inherent to mining processes while remaining profitable and creating safer work spaces (Skousen and Zipper 2021).

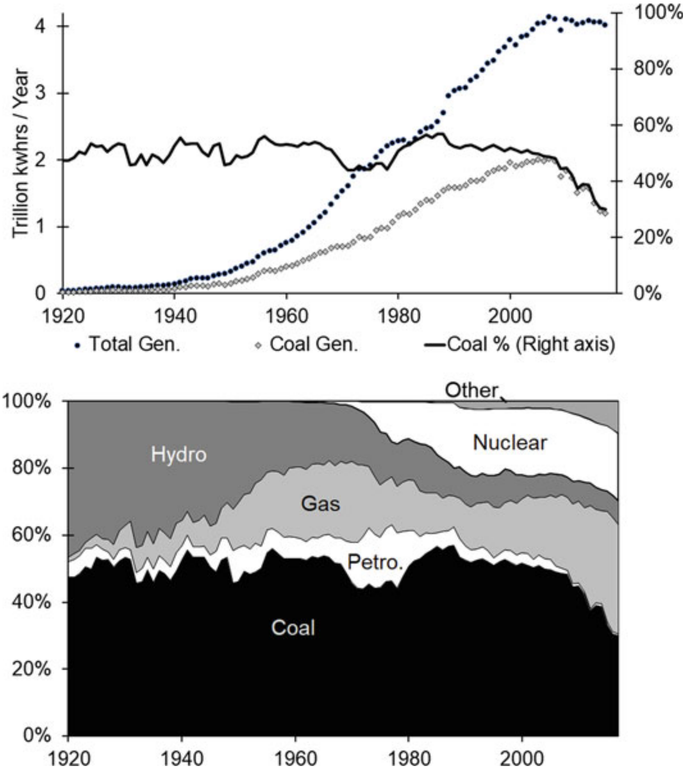

Fig. 5 Energy sources for electrical energy, 1920–2017. (Upper) Total electrical energy consumed in the US, estimated electrical energy fueled by coal, and proportion of the US-consumed electrical energy fueled by coal. (Lower) Proportions of US electrical energy consumption powered by various energy sources. Data from BOC (1975) and EIA (2020b) as compiled by Zipper (2020). "Other" energy sources include wood/biomass, wind, solar, geothermal, waste, and other miscellaneous

Appalachian coal production increased steadily through the nineteenth and early twentieth centuries, reaching 478 million tons in 1926 before declining almost to half that level in 1932 during the depths of the Great Depression (Fig. 3). Production increased leading up to World War II and then exceeded pre-depression levels, reaching 511 million tons in 1947; but declined again to <400 million tons annually during the economic transition following the War. Through the mid-twentieth century, coal was the fuel of choice for multiple uses that rely on other fuels today. During much of the twentieth century, coal producers served multiple markets, many of which were economically sensitive, resulting in dramatic fluctuations of mining activity (Fig. 6). Railroads, industrial plants, home heating, and even ocean shippers, for example, were major coal consumers in past years. American coal production, and pricing for Appalachian coal, boomed again during the late 1970s in response to the oil supply disruptions of that era which stimulated greater coal demand for

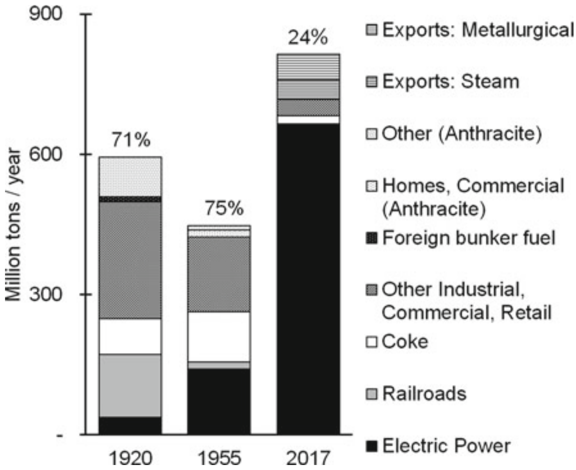

Fig. 6 Markets served by US coal in 1920, 1955, and 2017, with percentages of total production provided by Appalachian producers designated at the top of each bar. Market categories as listed by the data sources vary among years. Market segments are arranged vertically in the same order as the figure legend. Data sources: Schuur and Netschurt (1960), Table 19 for 1920 and 1955; and US EIA (2018) for 2017

electric power (Fig. 5; Black et al. 2005), even as other market sectors were reducing coal usage.

Appalachian coal production volatility declined and production increased steadily during the latter half of the twentieth century as coal producers' dependence on the relatively stable but growing electrical generation markets increased. Appalachian production averaged 428 million tons/year in the 1990s (Fig. 3). But this period also continued a major shift of American coal production to non-Appalachian areas, especially the western areas that dominate US coal production today (Fig. 5). The early twenty-first century saw a modest decline of Appalachian production to levels similar to those of the 1950s (368 million tons/year, on average, for 2002–2008), even as national production increased, but western coal producers took an increasing share of electricity markets. Over the next decade, Appalachian production declines steepened to reach production levels of <200 million tons/year by 2016 through 2019.

Although Appalachian coal has been largely displaced by other coals and fuels for electrical-generation, Appalachia remains as a primary producer of metallurgical coal for domestic coke production and for export. Metallurgical markets demand coals of specific qualities that Appalachian producers can provide. In 2018, US average prices for coking coal were more than three times those of electric power markets (US EIA, 2019a). Miners in Appalachia experience higher costs than those in other US regions due to factors such as mountainous terrain and reserve depletion that is directing production toward increasingly thinner seams. Hence, Appalachian producers' abilities to gain high prices in metallurgical-coal markets is an important driver for much of today's Appalachian mining.

Coal mining and related industries have been important contributors to Appalachian economy throughout its modern history (Thompson et al. 2001; Bowen et al. 2018). Mining's greatest local influence occurs in the central Appalachian counties of central and southern West Virginia, eastern Kentucky, and southwestern Virginia where coal production has been most intensive (Fig. 7). These areas that

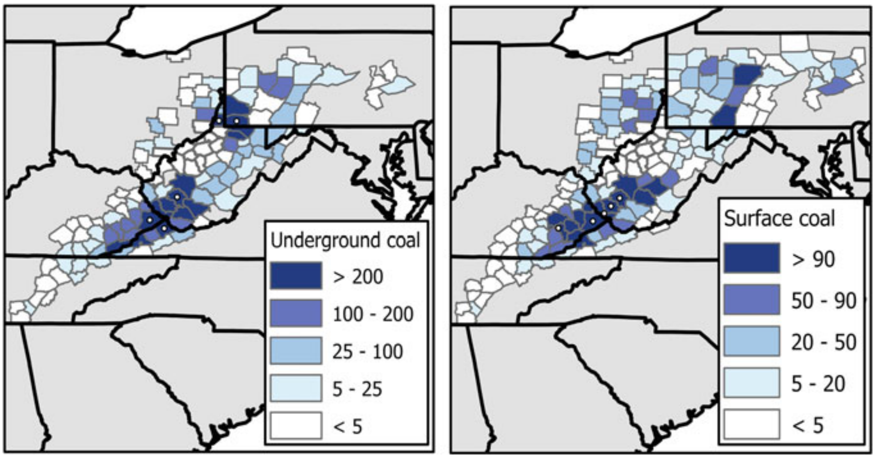

Fig. 7 Cumulative coal production (million tons), 1980–2018, by underground (left) and surface (right) mining methods, for Appalachian coalfied counties. The top five coal-production counties for each mining method are designated with small white circles. Data from US EIA (2019a) and predecessor publications

also experience high levels of poverty (Lobao et al. 2016). In 2005, coal mining was responsible for > 20% of total employment in 13 central Appalachian counties (Bowen et al. 2005). Recent declines of Appalachian coal mining have created economic hardships in these counties (Santopietro and Zipper 2021).

5.2 *Current and Future*

Appalachian coal production is declining in response to multiple factors, many of which appear unlikely to reverse (Zipper et al. 2021b), despite the ~100 billion tons of coal known to remain unmined in Appalachia (US EIA 2019a). Much of the region's unmined coal is in thin or difficult-to-access seams that are costly to mine. Such problems are exacerbated by difficult terrain, especially in central Appalachia, and increasingly strict environmental regulations including those concerning water (e.g. US EPA 2016).

Meanwhile, the nation's fleet of coal-fired electrical generators is aging and affected by increasing environmental restrictions, especially concerning air emissions (Revetz and Lienke 2016). More than 40 gigawatts of coal-fired generating capacity in primary markets for Appalachian coal, representing more than 1/3 of those states' 2011 total, was retired during 2011–2019 (US EIA 2019b, 2020c) while additional retirements are projected but no new coal-fired generation is planned (US EIA 2019c). In contrast, Appalachian natural-gas production has been expanding rapidly as prices declined in response to new extraction methods, while advancing technology also enabled declining cost and expanding capacity for electricity generation from solar and wind (US EIA 2019b). These changes are occurring as human-induced climate-change becomes more apparent, which acts as another disincentive for the long-term capital investments required for new coal-burning burning plants. Appalachian coal producers are rapidly losing their primary market, and declining production is projected to continue over future years and decades (US EIA 2020a).

6 Coal's Legacy

As mining declined in the Appalachian coalfield, the legacy of the region's coal-mining history remains. Although the Appalachian forest remains among the most biodiverse in the non-tropical world, major areas of forest have been lost (Drummond and Loveland 2010). Approximately 2.5 million acres (10,000 km^2, as compiled from federal government data by Zipper 2020), about 6.5% of the >150,000 km^2 Appalachian coalfield area, have been disturbed by surface coal mining since the late 1970s, in addition to prior disturbances. In central Appalachia, 5900 km^2 of surface-mine disturbances, approximately 7% of an 83,000 km^2 study area were evident from analysis of satellite data (Pericak et al. 2018). Many of those forests have been replaced by plant communities dominated by exotic invasive species (Sena et al. 2021) which host wildlife that also differs from those of unmined areas (Lituma et al. 2021). Soils on mined areas are transformed, as miners typically replace some or all of the natural soil with fractured rock; the resulting mine soils vary dramatically in their capabilities to support economic activities such as agriculture and development and restoration of natural ecosystems (Skousen et al. 2021; Zipper et al. 2021a). We are unaware of any estimate of the land-surface area undermined by underground coal mining. Given that underground mines have produced more than three times the tonnage extracted by surface mines (Zipper 2020), we expect such undermined areas to exceed and extend well beyond surface disturbances.

Water resources have also been affected by Appalachian mining; those effects extend beyond the mined areas themselves as mining-origin water contaminants move downstream (Clark et al. 2021; Kruse Daniels et al. 2021). Within central Appalachia, more than 1200 miles (1900 km) of headwater streams, approximately 2% of the regional stream length and 4% of first- and second-order headwater streams, were covered or otherwise lost to surface coal mining prior to 2002 (US EPA 2011), while additional losses have occurred since. Multiple studies have demonstrated extensive impacts on regional headwaters by geologic-origin contaminants in mining-influenced waters (e.g. Cormier et al. 2013; Pond et al. 2014), and that larger rivers receiving those headwaters have also been affected (e.g. Zipper et al. 2016). The region's extensive underground mining has also affected water resources. Underground mining can affect groundwater hydrology, water yields of household wells, and groundwater chemical quality while also affecting surface water quality and flows (Skousen and Zipper 2021). The geologic-origin water contaminants released from current and reclaimed Appalachian mines affect aquatic ecosystems and biota (Merovich et al. 2021).

The legacy of Appalachian coal mining, which has been so essential to the American economy, also includes a human toll. More than 150,000 people perished in US coal mines (Breslin 2010; US MSHA 2019), including more than 100,000 since the year 1900 (Fig. 8 upper), with most fatalities occurring during the era of Appalachian coal dominance. In the early twentieth century, average fatality rates exceeded 3 per 1000 workers, which means that a miner with 25-year career had nearly a 1 in 100 chance of dying in a mining-related incident. Fatality rates since then have fallen dramatically, but those rates do not include mining's other human-health effects. Among the most well-documented is a condition known as "black lung," the impairment of lung function caused by inhalation of coal particles. In the early 1970s, 25% of mine workers with >20 years of experience and participating in black-lung health assessments were diagnosed with coal worker's pneumoconiosis, a lung impairment (Fig. 8, lower left). With improving dust control in underground mines, those rates declined over subsequent decades but have been increasing recently, as have diagnoses of a related disabling lung condition, pulmonary massive fibrosis (PMF) (Fig. 8, lower right). Researchers attribute the PMF increase to exposure to air-borne particles created by excavation of rock layers above and below thin coal seams; rock particles have greater impairment effects on the lung than coal particles (Cohen et al. 2016). Underground coal-mine workers experience elevated mortality relative to the general population (Attfield and Kuempel 2008).

Appalachia's populations also reflect coal's legacy. Regional populations of coal-producing areas have been stable or declining over the twenty-first century, in contrast to national population increases. The region's population fraction of retirement age ($\geq$65 years) is greater than that of the nation at large, and the region's working-age population is declining. Similarly, salaries and wages are lower and poverty rates higher in Appalachian coalfield counties than in the nation at large (Santopietro and Zipper 2021). Central Appalachian coalfield residents experience high rates of mortality, cancer mortality, and heart and respiratory disease relative to US population averages (Gohlke 2021), while residents of areas with close proximity to mountaintop mining, or in counties with mountaintop mining, experience elevated mortality and adverse cardiopulmonary and respiratory effects relative to residents of other areas (Broyles et al. 2017; Hendryx 2015). Whether these effects are caused by mining or are associated with mining because of socioeconomic conditions in the high-intensity mining counties is debated.

7 Conclusion

The Appalachian coalfield has changed dramatically during its natural and human history, especially over the past two centuries as nearly 50 billion tons of coal, more than half of the US's cumulative production, were extracted from Appalachian

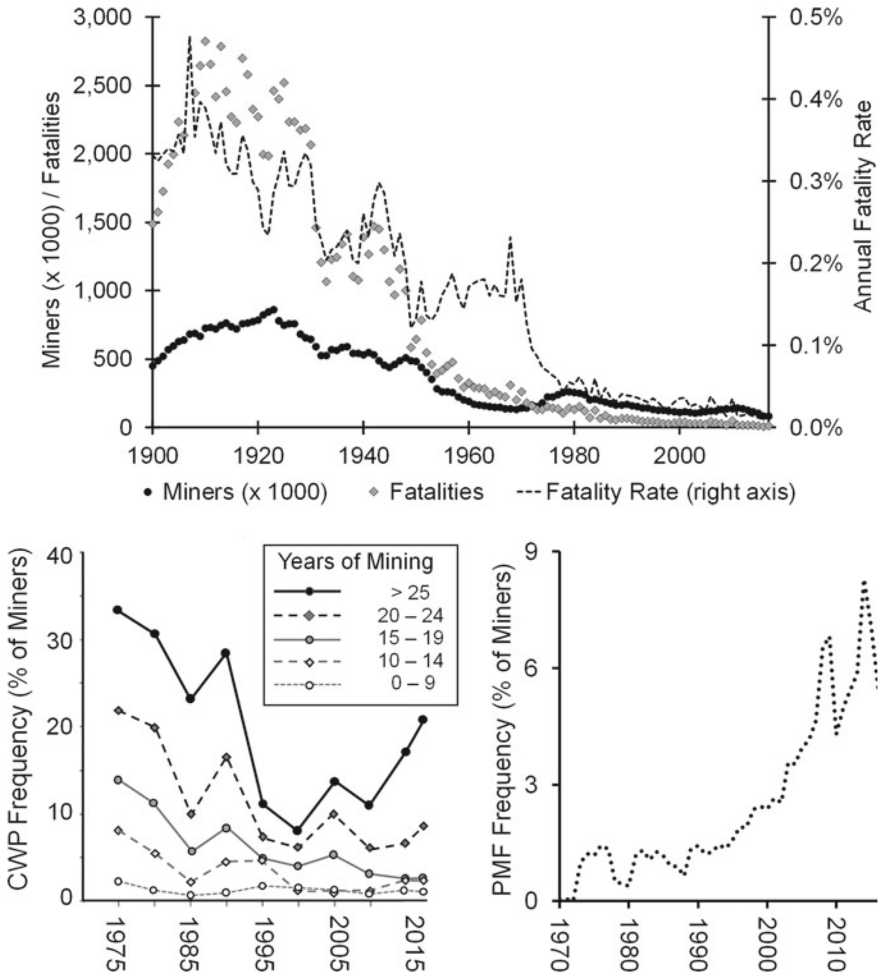

Fig. 8 (Upper) Numbers of coal miners (× 1000), numbers of fatalities, and coal-mine fatality rates by year, 1900–2016 (MSHA 2019); fatality rate is the number of fatalities divided by the number of miners for each year. (Lower) Frequencies of coal worker's pneumoconiosis (CWP) among central Appalachian coal miners, 1970–2017 five-year averages (left) and of pulmonary massive fibrosis (PMF) among US coal miners, 1970–2016 (right), participating in federal program that screens coal workers for the presence of conditions commonly known as "black lung". CWP is a condition of lung impairment caused by coal-mine dust and a significant predictor of PMF, which is totally disabling. CWP data from Blackley et al. (2018); PMF data from Almberg et al. (2018)

mines (Milici 1997; EIA 2019a). Appalachian coal was essential to the US's industrial development and remains an input to the US's electrical energy supply and its production of steel. Today, revenues gained by Appalachian coal exports aid in offsetting currency effects of imports of other products. Appalachian coal production has generated on the order of $1 trillion in sales revenues (2017$ equivalent) since the mid-1960s (Santopietro and Zipper 2021).

Appalachia is a vast and varied region, with history, culture, communities, and natural resources that extend well beyond coal. Within coal-mining areas, however, coal remains as a major influence, both economically and culturally. Those segments of Appalachian society linked with coal are facing an uncertain future while dealing with coal mining's legacy and the reality that coal's revival to production levels of past eras is unlikely.

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