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SPECIAL ISSUE ARTICLE

Introduction to Soils and Sustainability Special Issue

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Soil is fundamental—to our economy, to our environment, and to our daily desire to put food into our bellies. It ought to be fundamental to historians as well (Worster 1990). For the past 10,000 years agriculture, rooted in the soil, not only fed the human population but it also delivered society's energy supply (Gingrich et al. 2018). Farmers fueled all human muscle power, from peasants and slaves in the field to blacksmiths at the forge, brickmakers by the kiln, or soldiers on campaign. Farmers delivered the transportation system's energy supply by means of the horses, mules, and oxen (and the grain and hay to feed them) that freighted goods across country, delivered supplies within towns, and sped couriers between cities (Smil 2017). Most of the energy that warmed homes, fueled bakers' ovens, and heated metalworking forges came from farms too, as firewood and charcoal from the rural countryside (Gingrich et al. 2012; MacFadyen 2016). The food, livestock feed, and firewood energy carriers that farmers delivered to society all originated in soils that they managed in complex ways. Modern societies cannot ignore soil either. The Industrial Revolution may have introduced fossil fuels that dramatically transformed the economy, society, and human-nature relations, but coal did not replace farm crops. We cannot eat coal, so to this day, farming provides 90 percent of human nutrition (fishing delivers the remainder). Indeed, industrialization and fossil fuels allowed farmers to boost the productivity of global soils, even as growing populations demanded ten times as much food by 2000 as they did in 1700. It is impossible to understand modernity, the global economy, or world demography without grappling with soil history. The story of soils should be at the center of economic history, environmental history, and sustainability studies.

Environmental and agricultural historians have not completely ignored soil history. Economic and agricultural historians explored the farm intensification that began in Britain in the eighteenth century (Allen 2008), and in the United States there is a robust literature about the history of soil erosion. From the 1920s historians addressed problems of water erosion in the eastern United States (Craven 2006), and from the 1970s the emergent field of environmental history tackled wind erosion in spectacular events like the Dust Bowl (Hurt 1981; Worster 1979). Soil erosion also features in the historical assessment of collapsed ancient civilizations

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(Diamond 2004; Montgomery 2007). Erosion is an important component of soil processes and of soil history, but it is only a small part of a more complex system.

A soil is an ecosystem, equivalent, say, to a tallgrass prairie, a coastal wetland, or a boreal forest. Soils are not just dirt; in fact, they are not even primarily dirt. Soils are a composite of mineral particles (sand, silt, clay), elemental nutrients (carbon, nitrogen, phosphorous, potassium), humus (partially decomposed bits of dead plants), microorganisms (worms, nematodes, algae, fungi, bacteria), plus small pockets of air and water. A few handfuls of soil contain entire food webs of tiny grazers, predators, and decomposers, each with their own consumption, metabolism, and waste systems, all tightly integrated (Tisdale et al. 1993). Together, those microorganisms decompose dead plant matter into essential nutrients that feed newly growing plants. Those ecological, chemical, and biophysical processes drive crop growth, agricultural productivity, and economic prosperity; farmers are fundamentally interested in managing soils to sustain their farms and their societies. Studies of soil erosion, which deal mainly with questions of soil texture, merely scratch the surface.

Soils are not only ecosystems, but *human-managed* ecosystems, and thus fall within the proper realm of history as well as ecology. Much like ocean fisheries, clear-cut forests, or drained wetlands, people have been using, manipulating, and altering soils for thousands of years, which means that soils have histories that go beyond the purely biophysical. These are "hybrid human-natural systems," "coupled human-environment systems," or "agroecosystems" to borrow terminology from a variety of disciplines (Turner et al. 2003). Since the Neolithic Revolution, people have transformed soils to deliver food and energy to human societies. In complex and sophisticated ways, farmers learned how to engage soils so that they produce crops year after year, century after century. They created fertile soils that sustained microorganisms; replaced soil nutrients annually; maintained a workable texture and pH; avoided compaction, salinization, and nutrient depletion; and supplied sufficient water (irrigation) or removed its excess (drainage). Failure to do any of those things, even for a few months, could be catastrophic, leading directly to starvation. Soils are not only a fit subject for science but also a necessary consideration of history.

Especially within environmental history, there have been some important recent studies of soil history that extend beyond erosion, including soil acidity, soil organisms, and soil nutrients (Cunfer 2004; González de Molina and Toledo 2014; McNeill and Winiwarter 2006; Stoll 2002; Winiwarter 2014). This special issue focuses especially on soil nutrients, exploring how farmers in diverse locations managed soils to replace fertility every year. Although crops require some fifteen nutrients to grow, three are most commonly limiting: nitrogen (N), phosphorous (P), and potassium (K). Globally, nitrogen is often the element that constrains plant growth, including crops, and so it deserves keen attention. The historical question at the core of this special issue is: How did farmers replace the N, P, and K in their soils that each year's harvest extracted? Simply cultivating the land diminished soil nutrients every spring. The fall harvest took more of them away. To farm sustainably, year after year on the same ground, elaborate and costly efforts were necessary to restore those lost nutrients. These articles reveal a multitude of ingenious ways by which local farmers maintained fertility over long stretches of time.

The history of nitrogen alone is fascinating (Cushman 2013). Nitrogen is the most volatile soil nutrient, apt to escape into the air or wash away with the rain.

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All plants need a great deal of it and crop yields depend on it, so replacing N in the soil is the most urgent need in many agroecosystems. As industrialization and fossil fuels drove economic growth, urbanization, and increasing population, farmers needed to boost food production. In agriculture there are two ways to grow more food. Extensification means bringing more land into production. By plowing fresh land, farmers accessed previously unused stockpiles of soil nutrients. Intensification, however, means producing more crops on existing farmland. In this case, farmers found ways to deliver additional doses of nitrogen to cropland to increase yields. Through the past two centuries farmers did both, in interesting and complex ways. In the nineteenth century, European farmers colonized new farmland around the world, most especially in the vast, open grasslands (Richards 2003): the Russian steppes (Moon 2013), the North American great plains (Cunfer 2005), the South American pampas, and the grasslands of Australia and New Zealand (Brooking and Pawson 2011). They doubled arable land in production, exploited rich new stockpiles of soil nitrogen, and poured grain into industrializing cities to feed a 60 percent increase in human population, from 1 billion in 1800 to 1.6 billion in 1900 (Goldewijk 2001). Agricultural extensification fed nineteenth-century economic and demographic growth.

Then, in the twentieth century, with nearly all arable land already in production, farmers intensified. They mobilized fossil fuel energy, especially natural gas, to create synthetic fertilizers and irrigation systems that doubled crop yields and then doubled them again (Smil 2001; Watson 2020). After the 1950s, farmers poured synthetic nitrogen fertilizers onto their cropland, producing bumper crops never seen in history. And in doing so they fed another expansion of human population, from 1.6 billion in 1900 to 7 billion in 2012. Those dramatic developments, with widespread consequences that span economics, politics, diplomacy, energy, and environment, to name just a few, are fundamentally grounded in soil history. The largest, fastest increase in human population over the past 2 million years was based on agricultural management of soil nitrogen.

Farmers in different places employed various techniques to manage soil nutrients, and the articles in this special issue of *Social Science History* present case studies from Austria, Spain, and Portugal in Europe, and from Canada and the United States in North America. Most of these articles originated with an international, interdisciplinary research project entitled "Sustainable Farm Systems: Long-Term Socio-Ecological Metabolism in Western Agriculture," funded by the Canadian Social Sciences and Humanities Research Council, and with significant matching contributions from the Spanish Ministry of Science and Education and the Austrian Science Fund. That project borrowed "socio-ecological metabolism" and "material and energy flow accounting" methods from sustainability science (Fischer-Kowalski and Haberl 2007; González de Molina and Toledo 2014; Singh et al. 2013) and applied them to explore interesting environmental and economic history questions. The soil nutrient balance methods underlying many of the articles in this special issue originated with Dr. Roberto García-Ruiz, a soil scientist who visited several of the research teams and helped them adapt nutrient balance methods to historical case studies (García-Ruiz et al. 2012). This special issue would have been impossible without his generous contributions. While many publications from the Sustainable Farm Systems project appeared in sustainability science

journals (Aguilera et al. 2018; Delgadillo et al. 2016; Gingrich et al. 2015; Giziki-Neundlinger and Güldner 2017; González de Molina et al. 2015; Güldner and Krausmann 2017; Tello et al. 2012), here we aim to make this work accessible for historians.

Agriculture was not static, but changed through time, so each article also addresses transformations in soil nutrient systems as they evolved across decades and centuries. In Europe, two important transitions in soil nutrients happened between 1700 and 2000. Accompanying industrialization, but not yet directly employing fossil fuels, European farms developed an "advanced organic agriculture" in the nineteenth century that raised yields and fed growing cities (Allen 2000, 2008; Wrigley 2006). They accomplished this through crop rotations and livestock intensification that produced more manure to fertilize cropland, at the expense of much higher labor costs. Then, after World War II, most European agriculture underwent a "socio-ecological transition" that included mechanization but, most importantly, the adoption of synthetic fertilizer (Fischer-Kowalski and Haberl 2007). That shift increased yields dramatically, while also reducing labor costs and reshuffling the agricultural landscape (Krausmann 2004).

The story was considerably different in North America, where vast areas of new farmland opened after 1870 (Cunfer 2005). Until the 1950s, many American and Canadian farms benefitted from the exploitation of nitrogen stockpiled in newly plowed grassland soils (Cunfer and Krausmann 2009). For fifty years after initial sod breaking, for example, many Great Plains farms continued to grow crops without significant inputs of manure, complex crop rotations, or the high labor costs those techniques entailed (Cunfer 2004). But already by the 1930s plains soils were becoming depleted, crop yields fell, and spent land began coming out of production. Then, the socioecological transition, based on petroleum and natural gas, saved the day. By the 1930s American farmers were rapidly mechanizing (Anderson 2009; Fitzgerald 2003), in the 1950s they began applying large quantities of synthetic fertilizers (Cunfer et al. 2018), and by the 1970s the driest parts of the grassland were widely irrigated (Opie 1993; Watson 2020).

In this special issue readers will discover fine-grained analyses of each of these historical processes, as they played out in local contexts. Dino Güldner's "Contested Grasslands: Commons and the Unequal Land-Costs to Sustain Soil Fertility in Pre-Industrial Agriculture" evaluates an Austrian manorial estate in the eighteenth century. The article brilliantly reveals how soil fertility supply using manure depended on access to pasture land for livestock, a resource that drove social inequality. A shortage of grazing land meant insufficient manure to fertilize cropland, which meant poverty for many peasants. Plentiful pasture access, however, provided wealth in preindustrial Europe. Beatriz Corbacho González and Roc Padró Caminal move the story to northwestern Spain, where farmers faced the same manure supply constraints. There they innovated in the nineteenth century, increasingly exploiting "rough grazing" land in the hills to increase livestock populations, which in turn raised manure production, cropland fertility, and grain yields. "Agricultural Intensification and Soil Fertility in Atlantic Spain, 1750–1890" is a terrific example of the development of an advanced organic agriculture in Europe that directly drove population increase on long-farmed land without any application of fossil fuel energy. Shifting to the opposite corner of Spain and a

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few decades ahead, Elena Galán's "Regional Soil Nutrient Balances for Cropland in 1920s Catalonia, Spain" reveals an early transition to synthetic fertilizers as a way to restore depleted soils. Galán's article also explicitly demonstrates the methodology of soil nutrient balances using historical sources that underlies most of the articles in this special issue. Moving across the Iberian Peninsula once more, Miguel Costa Carmo and Tiago Domingos reveal the process of agricultural intensification in Portugal in the twentieth century. "Agricultural Expansion, Soil Degradation, and Fertilization in Portugal, 1873–1960: From History to Soil and Back Again," connects farm soil management with politics, addressing how Portugal's fascist dictatorship attempted to boost farm productivity through the middle of the twentieth century, with varying success. These first four articles thus span more than two centuries of Europe's soil history. They represent three different countries, including well-watered places in Central Europe and northwestern Spain as well as semiarid Mediterranean climates in Catalonia and Portugal. They also cover a variety of political and economic contexts, from feudal Austria to industrializing Spain and fascist Portugal.

The two articles from North America include some similarities with Europe, especially in the late twentieth century, but their pre–World War II trajectories were quite different. Geoff Cunfer's "Soil Fertility on an Agricultural Frontier: The U.S. Great Plains, 1880–2000" presents Kansas as a quintessential example of newly colonized agricultural land. Rich with nitrogen that had accumulated in native grassland soils over millennia, farmers initially grew bumper crops, but then watched yields decline over the next fifty years as they depleted soil fertility and invested little in replacing it. Those trends only changed with the advent of tractors, synthetic fertilizers, and irrigation in the mid-twentieth century. Nonetheless, the Great Plains became a breadbasket of the United States and the world, and Kansas wheat flooded world markets, feeding ever more people. If Kansas launched Great Plains agricultural colonization in the 1860s, Saskatchewan drew it to a close in the 1910s. The early-twentieth-century settlement of the Canadian prairies marked the end of the great plowup of the world's grasslands, and the close of arable land extension that had begun in the 1780s in the Ukrainian and Russian steppes. Laura Larsen's "Trawling the Ocean of Grass: Soil Nitrogen in Saskatchewan Agriculture, 1916–2001" compares two farming communities in the Canadian prairies, revealing how quickly they depleted native soil fertility, and how they adjusted land management in response. As in so many of the case studies in this special issue, it came down to adjusting livestock management to reduce grain-based nutrient depletion, followed by the adoption of synthetic fertilizers.

The special issue concludes with a comparative article by Dino Güldner, Laura Larsen, and Geoff Cunfer that pulls together soil nutrient data from all six of the case studies to present a broader analysis of soil history. "Soil Fertility Transitions in the Context of Industrialization, 1750–2000" identifies not a simple story of the rapid industrialization of agriculture, but rather a two-phased process that played out over more than a century, and differently in the Old and New Worlds. It also reveals the complexity and importance of soil history as a subject for economic and environmental historians, as well as the incredible ingenuity, sophistication, and adaptability of farm people who have tended their soils with care and wisdom to feed a huge, growing, and always hungry world.

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