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Soil Fertility Transitions in the Context of Industrialization, 1750–2000

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Abstract

Fertile soils are essential for human health and nutrition and formed the foundation of human economies for millennia. Soils deserve close attention from environmental and economic historians and sustainability scientists. Most soil history literature addresses failure: misuse of soil, uncontrolled erosion, and the resulting collapse of past civilizations. More important, however, and of urgent interest for our present and future prosperity, are the mundane ways that historical farm communities sustained soil health, even while cultivating the same land for centuries. This article explains five strategies by which European and North American farmers accessed, recycled, replenished, and sustained soil fertility over 250 years. By evaluating inputs, extractions, transfers, and annual balances of potassium, phosphorus, and, especially, nitrogen, it models historical soil management in a variety of agroecosystems in various geographical settings and through time. This biophysical environmental history, based on socioecological metabolism methods borrowed from sustainability science, reveals ongoing adaptation to shifting social and environmental contexts. As industrialization, global trade, and population accelerated, farmers adjusted their soil fertility strategies to keep up with new pressures and opportunities. Each solution to existing soil fertility constraints created new obstacles and bottlenecks. Through the past quarter millennium, farm sustainability meant constant readjustment to new circumstances. As farmers innovated crop choices and rotations, corralled livestock, adopted new technologies, deployed novel energy sources, and expanded into new lands, they increased food productivity to feed growing world population and supply expanding markets, while maintaining the supply of soil nutrients necessary to fertilize next year's crop.

Introduction

As a primary determinant in the success of agriculture, and, thus, in our ability to provide our daily bread, soil is critically important to civilization. Yet historians have neglected the social and environmental history of soils (but see McNeill and Winiwarter 2006). Little historical research addresses the ways that societies successfully managed and sustained soils over the long term. As Swidler (2009) points out, most historical scholarship about soil is long outdated or susceptible to environmental determinism. Farmers devote considerable labor, care, and thought to the maintenance of healthy and fertile soils, and so should scholars.

Historians have engaged with soil primarily in the context of crises, when soils were degraded, exhausted, or eroded.

Attributing agency to soil as a destroyer of past societies is popular in literature analyzing the fall of great civilizations (Diamond 2004; Montgomery 2007). In these narratives, soil serves as an agent of ruin from Yucatan to Mesopotamia to the Easter Islands, where soil degradation, especially erosion and salinization, caused the collapse of ancient agricultural societies. The American Dust Bowl stands as a more recent example (Worster 1979). Turning away from "disasters" in favor of everyday farming, and adopting an interdisciplinary approach, reveals a more complex, intertwined relationship between soils and society. Long-term soil fertility management was a routine, but highly significant, component of global economic transformations over the past 250 years, as revealed by examples from Europe and North America. Understanding how farmers manipulated and transported soil nutrients to sustain food production connects land-use practices with economic growth, migration, and industrialization. Soil history is not only about ecological disaster and economic collapse but it is also about practical, mundane sustainability.

Successful agriculture required a combination of regionally adapted crops, water, sunlight, and nutrients. The three principle soil nutrients—nitrogen, potassium, and phosphorous—are critical for plant growth. Farmers' quest to access new nutrient stores influenced, directly or indirectly, the development of agricultural practices. Even before science "discovered" soil nutrients, the discourse around agriculture included ideas of soil quality and encouraged practices that maintained and enhanced soil fertility (Stoll 2002). Over time and throughout the world, the techniques farmers employed to renew nutrients varied, but ultimately led to the same result: continuous attempts to maintain or increase agricultural production. The ability to produce crops consistently required a delicate balance between population growth, climate, trade, and agricultural practice.

Soil is a historical product, a human-nature hybrid emerging from continuous interaction between society and its environment over time. Soils are living, evolving ecosystems that feature their own history, driven by an array of both social and biogeochemical processes. A soil's capacity to produce biomass for food, feed, fuel, and fiber depends upon a wide range of living and nonliving factors that constitute a soil's heath, including its physical texture and structure, its organic matter and moisture-holding capacity, and an ensemble of intertwined webs of living organisms. Some of these features change only in geological time, like soil texture, while human activity may alter others, such as nutrient cycling, over the course of generations or mere decades. Agriculture is a form of applied ecology (Loomis and Conner 1992). From time immemorial, farmers relied on organic methods to replenish soil fertility. Only in the past century have human impacts on global nutrient cycling, caused by an oversaturation of synthetic fertilizers, grown into a threat to human well-being and environmental sustainability (Steffen et al. 2015). Industrialization's dramatic changes thoroughly altered human–nature relations, as artificial fertilizers substituted for ecological soil replenishment processes. The interrelation between societal transformation and evolving nature underpins the "biophysical" approach to environmental history, one that considers human–nature interactions from the point of view of material and energy exchanges and employs the metaphor of "socioecological metabolism" (Fischer-Kowalski and Haberl 2007; Gonzalez de Molina and Toledo 2014; Singh et al. 2013).

Energy and material exchanges between societies and their environment changed dramatically over the past 250 years. The basic metabolism of preindustrial societies depended solely on biomass as a source of energy for food and fuel. The net energy gain provided by agriculture had to surpass the energy people invested in agroecosystems. Prior to industrialization, farmers maintained and even increased efficiency under growing pressures of urbanization and population growth without external inputs (Gingrich et al. 2018). Only in the past century did agriculture become a consumer of energy, due to the use of fossil fuels and chemical fertilizer. Fossil fuels triggered society's industrialization and the transition toward an extended metabolism, which broke the energetic barriers and bottlenecks formerly restricted by the availability of biomass—and consequently by the availability of land. This article adopts the metaphor of metabolism to explore the coevolution of farm communities and their agroecosystems by investigating soil nutrient exchanges (Gonzalez de Molina and Toledo 2014).

In her classic essay on "The Conditions of Agricultural Growth," Ester Boserup (1965) presented agricultural change as a progressive sequence of farm intensification in response to population pressure under decreasing labor productivity.[1] Boserup identified five increasingly intensive farming systems, which she distinguished according to the length of their fallow periods. First came forest fallow (with 20–25-year rest periods) and bush fallow (6–10 year rests), also known as swidden or "slash-and-burn" farming. Long-term cropland systems followed, with short fallow periods that rested the land for one year. Eventually fallow disappeared altogether, giving way to annual cropping or even multiple-cropping systems that produced more than one harvest per year. Each step of intensification required greater labor inputs, increasing area productivity but decreasing labor productivity. Boserup was primarily concerned with rising population and human labor, and said little about environmental constraints on productivity or about possible biophysical limits to growth. This article treats these same stages—or degrees of intensification—as soil fertility transitions, explaining how farmers deployed innovative land management strategies to increase the cycling of nutrients and consequently to raise both soil fertility and agricultural output. Preindustrial farmers increased yields by creatively advancing organic farming practices that improved nutrient availability. However, intensifying land use and reducing fallow put pressure on multiple ecosystems and created new environmental bottlenecks and sustainability challenges. Then, in the late twentieth century, industrialized agriculture decoupled itself from both population pressure and land constraints, due to the substitution of fossil fuels for agricultural labor and soil fertilization (Fischer-Kowalski et al. 2014).

Boserup's theoretical foundation underpins later scholarship about "induced innovation" in agriculture, which treats innovation as an internal process of

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[1] This article adopts a Boserupian view of agricultural productivity change, in which rising population pressure drove farm communities to produce more food. Other scholars reverse that causality, arguing that rising food productivity came first and facilitated a demographic transition that subsequently powered population growth. See Livi-Bacci (1990) and Wrigley (1997).

agricultural intensification, driven by the relative availability of land and labor. According to Hayami and Ruttan (1985), the relative price of land and labor incentivize new agricultural technologies meant to substitute for the most expensive factor. In preindustrial Europe, labor was abundant and cheap while land was scarce and expensive. New methods invested cheap labor to increase productivity on expensive land (Kopsidis 2006). The reverse was true on agricultural frontiers, such as in the North American Great Plains. There, land was abundant and labor scarce, so innovation aimed to save labor, even if it used land inefficiently.

Boserup's primary concern was rising population and, thus, labor availability. While she acknowledged that land-use intensification risked environmental degradation (especially soil fertility), she said little about the biophysical constraints on crop productivity or consequent limits to growth. Nor did she elaborate on the impact of industrialization, such as the diffusion of fossil fuels, industrial technology, or the market forces in an increasingly globalized economy (Erb et al. 2014). By combining Boserup's understanding of land-use intensification with Hayami and Ruttan's understanding of relative land and labor factors, it is possible to introduce environmental considerations such as soil fertility and climate into the analysis of historical farm systems. A socioecological metabolism methodology makes it possible to differentiate transitions in soil nutrient management by farmers in relation to land, labor, trade, and energy. It also highlights pathways of investment in and use of agricultural technology, that is, the choices farmers made between land- and labor-saving technologies to improve soil fertility in various places and times (Fischer-Kowalski et al. 2011).

An analytical model of soil nutrient flows allows a comparison of fertility management practices in diverse parts of the world. The model is an analytical abstraction of the agricultural land-use system, illustrating soil nutrient processes as human-managed recycling or transfer flows across the agricultural landscape. It presents changing farm strategies and practices over several centuries, revealing the major challenges to soil sustainability and the ways farmers addressed them through space and time. It also reveals the most important environmental and societal constraints on crop production by identifying key turning points when farm communities broke through soil nutrient bottlenecks by employing new techniques and strategies which, over time, allowed farmers to increase production to feed growing populations in an industrializing economy.

Soil History and Case Studies

The literature on soil history includes a long-developed historiography about soil erosion as a variety of environmental disaster and a nascent literature concerned with soil fertility as an underpinning of economic and environmental history. Erosion, the physical movement of productive soils into unproductive locations, has long been a concern of historians interested in "the fall of civilizations." From the decline of ancient Mesopotamia (Butzer 2005) to the collapse of the Roman Empire (Simkhovitch 1916), the end of the Mayans (Cook 1949), and the depopulation of Easter Island (Mieth and Bork 2005), scholars pointed to soil erosion as a malignant agent of change. David R. Montgomery's *Dirt: The Erosion of*

Civilization (2007) captures the moral critique often repeated in these works: societies grew too large, too wealthy, and too inattentive to their environment, plowing land that was steep, dry, or fragile. When the soil washed away, agricultural production dropped off, population declined, and civilizations fell from their lofty heights. US history is replete with jeremiads warning of soon-to-arrive civilization-threatening erosion disasters. Accomplished scholars, agricultural reformers, and eventual members of Franklin Roosevelt's New Deal "brain trust," including Lewis C. Gray (1933) and Hugh H. Bennett (1939), published influential histories of soil erosion in the United States while implementing a reform program to save the nation from looming disaster. The drought and wind erosion of the 1930s Dust Bowl in the Great Plains spawned a raft of historical studies of erosion as a threat to modern American agricultural prosperity (Bonnifield 1979; Egan 2006; Hurt 1981; Lookingbill 2001; Worster 1979). Documentary films (Burns 2012; Lorentz 1936) were equally influential. The literature about soil erosion and its threat to civilizations is considerable.

Less prominent, but growing in importance, is the historical literature about soil fertility. Rather than environmental disasters and collapse, these works present soil as the underlying basis for national economies, which might grow and prosper with well-managed soil, or falter and decline in a context of overexploitation and abuse. Avery Craven (1925) was far ahead of his time when he published *Soil Exhaustion as a Factor in the Agricultural History of Virginia and Maryland, 1606–1860*. In this slender volume he laid out an analysis of frontier tobacco farming that, in the context of Atlantic markets, depleted soil fertility and led to economic and social change. It was a long time before scholars took up Craven's example, but in the past two decades environmental and economic historians have revisited his approach. J. R. McNeill and Verena Winiwarter (2006) aimed to jump-start the topic in a collection with global scope. Around the same time, several articles presented detailed analysis of soil nutrients, especially nitrogen, in historical agroecosystems (Allen 2008; Cunfer 2004; González de Molina 2002; Krausmann 2004) and more have emerged in recent years, most of them published in sustainability science journals (Aguilera et al. 2018; Delgadillo-Vargas et al. 2016; Galán del Castillo 2017; García-Ruiz et al. 2012; Gingrich et al. 2015; Gizicki-Neundlinger and Güldner 2017; Güldner and Krausmann 2017; Güldner et al. 2016; Olarieta et al. 2019; Tello et al. 2012).

Relying on those important works, this article presents a set of case studies in Austria, Spain, Canada, and the United States that reveal processes of intensification, on the one hand, and of frontier extensification, on the other, all with an eye to the ways that agricultural change related to soil nutrients. Details can be found in the other articles in this special issue of *Social Science History*. The earliest example, dating to the eighteenth century, comes from the Manor Bruck in Austria (Güldner 2021). Industrialization and urban growth in the nineteenth century created new markets for agricultural produce. Farm communities across Europe responded by transforming land use into what Wrigley (2006) called "advanced organic agriculture." Examples from Spanish Galicia (Corbacho and Padró 2021) and Catalonia (Galán del Castillo 2021) demonstrate this first phase of transition, which significantly boosted farm productivity without the assistance of fossil fuels. The same market demand that drove agricultural intensification in Europe prompted new land colonization in the Americas, exemplified here by case studies in the US Great Plains (Cunfer 2021) and the Canadian Prairies (Larsen 2021). Once farmers on these frontiers exploited stockpiled nutrients in new soils, they faced a looming soil fertility crisis. The solution was a second wave of transition in the mid-twentieth century, enabled by fossil fuels, especially natural gas-based synthetic fertilizers. A similar transition occurred in Europe, revealed by Portugal's experience (Carmo and Domingos, 2021).

Taken together, these case studies on either side of the Atlantic reveal the contours of five broad soil management strategies followed by farm communities over time, each based on nutrient-unlocking mechanisms grounded in natural processes but controlled by sophisticated human agency. This comparative article builds upon the existing published literature and these particular case studies to reveal the structural ways farmers managed soil fertility to sustain populations, engage in emerging markets, support growing economies, and transform agriculture across two continents over three centuries.

A Model of Managed Soil Fertility

The most important macro nutrients for soil fertility around the world are nitrogen, phosphorus, and potassium. Managing these nutrients is critical to maintaining a successful farm. The agricultural nutrient cycle encompasses human-managed *recycling* within and *transfer* flows between various parts of the agroecosystem. Recycling nutrients entailed reusing biomass wastes from the farm (e.g., composted stable bedding, plowed down stubble, burned pasture), whereas nutrient transfers comprised the physical movement of nutrients from one part of the landscape to another. Nutrient transfers connected the farm landscape into an integrated system, often at the cost of considerable labor. Once farmers abandoned long fallow periods in favor of permanent cultivation, cropland became a fertility sink, requiring annual nutrient inputs from various sources (Mazoyer and Roudart 2006). Consequently, agroecosystems became more diversified, requiring a variety of landscape types, such as pasture, meadow, and woodland, each of which, beyond their obvious purpose, also contributed nutrients to cropland. The resulting patchwork farm landscape illustrates the "land cost of sustainability," where extensive land acts as a fertility source to replenish nutrients in intensively cultivated cropland (Guzmán and González de Molina 2009).

Without artificial fertilizers available, preindustrial farmers employed a number of biological techniques to manage these recycling and transfer flows by converting biomass into soil nutrients available for crop growth. Three practices utilized by farmers to mobilize nutrients from biomass were *burning* (combustion), *decomposition* (composting), and *livestock* (digestion). These practices were critical to successful agriculture because they converted nutrient-bearing biomass into plant-accessible soil nutrients. Each had advantages and drawbacks. Burning quickly converted inedible woody material into nutrient-rich ashes, conserving potassium and phosphorus, but losing nitrogen (Pyne 1997). In some cases, farmers produced biochar from agricultural residues and forest litter, especially useful in tropical agroecosystems due to their nutrient and water-retaining capacities

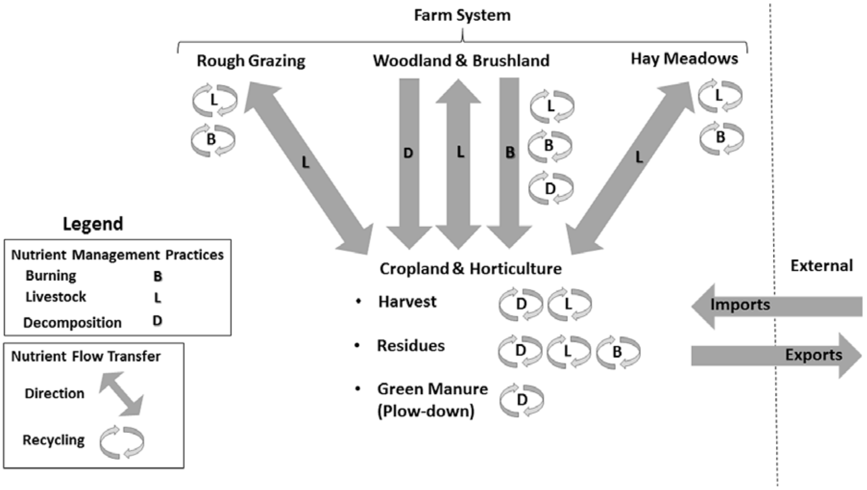

Figure 1. A model of agroecosystem soil nutrient flows, including internal recycling and transfers between land-use categories.

(Häring 2017; Olarieta et al. 2011; Tello et al. 2012). Decomposition was slow, but conserved the most nutrients and required little labor because microorganisms performed most of the work to turn organic compounds into plant-available nutrients. Recycling through natural decomposition could be either passive or enhanced by farmers. Rotting happens naturally, as soil organisms turn dead biomass (leaves, branches, refuse, litter, and roots) into mineralized nutrients. Feeding livestock was multifunctional: it produced meat and dairy products, draft power, transportation, and, most important, manure (Cunfer 2004). While burning, decomposition, and digestion are natural processes, their active agricultural management is the focus here.

Figure 1 presents a generalized model of soil nutrient flows in an ideal agroecosystem. The compartmental model of the farm nutrient cycle includes four fundamental *land-use categories* and, most importantly, the human-managed recycling and transfer flows. Arrows represent soil nutrients transferred between land-use categories or from outside the agroecosystem, as farmers sometimes imported soil nutrients by purchasing manure from other villages, night soil from nearby cities, guano from South America, or synthetic fertilizers. Circular arrows represent recycling flows. The letter codes inside flow lines and recycling circles indicate whether farmers managed these flows through burning (B), decomposition (D), or livestock (L).

This model does not conceptualize farms spatially, but rather as categories of land use, which may be scattered across the landscape in one agroecosystem, consolidated in another, or even overlapping. Four types of land use were fundamental:

- "Cropland and Horticulture" was arable land cultivated and planted in crops. Cropland provided staple subsistence crops such as cereal grains, legume peas and beans, or root crops and tubers. Cropland produced society's crucial energy supply: carbohydrates for people and their livestock. Horticultural land included vegetable gardens, fruit and nut orchards, or permanent woody crops like vineyards and olive groves. This land use was the nutritional source of vitamins, sugars, and oils. This model combines cropland and horticulture because they were the target of practically all soil nutrient transfers. Cropland and Horticulture *received* soil nutrients, while the other three land-use categories *provided* them.

- "Hay Meadows" were places where farmers mowed grass to feed livestock and often dried hay and stored it for winter use. These could be native grasslands, especially along watercourses, or planted grass crops interspersed within cropland.
- "Rough Grazing" included uncultivated pastures such as grasslands, savannahs, or brushland, where livestock roamed freely and grazed with limited supervision.
- "Woodland and Brushland" included forest environments that agricultural studies often ignore, but which were crucial and integrated components of agroecosystems in many places. They typically provided additional grazing for livestock and firewood for fuel.

Sometimes land transitioned between land-use types as strategies evolved. Shifts between Cropland and Horticulture, Hay Meadows, and Rough Grazing were common from one year to another, as farmers could change use on a short-term basis, compared to the greater effort required to convert Woodland and Brushland into another type of land. In the North American Great Plains, for example, farmers sometimes transitioned cultivated cropland into Hay Meadows in a single year by planting and harvesting a hay crop instead of a grain crop (Larsen 2021). In many European farm systems, however, land use often remained fixed for decades or centuries (Güldner 2021).

In figure 1, nutrients funnel toward Cropland and Horticulture, the land-use compartment where people remade landscapes most intensively, transforming wild land into fields, vineyards, orchards, or gardens. In systems with short fallow, farmers interspersed intensive cereal and cash crops with an annual period of fallow. Nutrient restoration in Cropland and Horticulture comprised nutrients recycled through livestock feeding, burning, and decomposition. Domesticated animals recycled part of the harvest—feed crops like oats, corn, turnips, and forage—through manure that farmers then applied to cropland. In modern industrialized agriculture, harvesting typically focuses on the collection of just one type of product, such as grain, tubers, or cultivated hay. In traditional agriculture, however, the harvest was often multifunctional, with primary and secondary products. For instance, farmers cultivated tall varieties of wheat with the intention of harvesting both the grain (primary harvest) and the straw (secondary harvest), the latter used as feed or for livestock bedding that eventually decomposed to become next year's fertilizer. Both components were valuable and necessary parts of the farm system. Cereal and cash crops mainly went toward human consumption. Farmers fed only a small share of the primary harvest (grain, seeds, fruit) directly to animals, whereas the majority of the secondary harvest (straw) was either winter livestock feed or litter for bedding. Smil (1999: 302) notes that "feeding is, in fact, the largest off-field use of cereal straw in many poor countries … [and] relatively large shares of residues are fed to ruminants even in rich countries." Farmers extracted nutrients from residues left on the field after harvest by either burning or letting livestock graze them. Short fallow in succession with one or two harvests allowed cropland to recover nutrients from soil stocks through decomposition. Fallow was either bare land plowed for weed control ("black fallow") or land grown up in spontaneous herbaceous vegetation grazed and manured by livestock ("natural fallow"). Another option was to plant nutrient-rich "cover crops," such as legumes or tubers, later plowed into the soil as "green manure." Plowed down cover crops were especially important in farm systems that supported few livestock and thus produced little manure. Cover crops deployed nutrients derived from the atmosphere through legumes or appropriated from deeper soil layers through roots and tubers, circulating these additional nutrients through the agroecosystem.

Rough Grazing, also known as pasture or rangeland, fed dispersed livestock. Animals deployed on Rough Grazing literally walked nutrients from outfields to infields. Nighttime stables for animals that grazed in outfields during the daytime captured nutrient-rich manure near adjacent arable land. Farmers hauled livestock manure onto Cropland and Horticulture fields, or they moved livestock onto cropland to deposit manure directly. Livestock also grazed on Hay Meadows or consumed cured hay, unlocking its nutrients through their manure. In well-watered agroecosystems, Hay Meadows could be planted hay crops or mown natural grasses, and the most productive fields generated several cuttings in a growing season. Farmers sometimes managed natural Hay Meadows with seasonal burning that quickly recycled nutrients and ensured vigorous new growth.

Woodland and Brushland offered farmers a full breadth of nutrient management practices, creating the most diverse landscapes. Forests provided grazing for livestock and received their manure in turn, an internal recycling process. Decomposition of prunings, fallen leaves, and litter also provided natural internal recycling. Farmers might collect and burn biomass to speed up internal recycling. Woody brush rotted in place or farmers moved it to a centralized compost pile to decompose for later application on cropland.

Modifying this model to fit the characteristics of specific places reveals nutrient transfers between compartments and allows comparison between case studies. In particular, the model reveals how the abundance or unavailability of particular land-use categories, often driven by climate and geography, affected cropland productivity. Water availability from rainfall was an important determinant of potential biomass growth in any given area, regardless of human land management practices. For example, well-watered places with a plentiful mix of woods, pasture, and meadow could support higher cropland productivity than dry places with little forest or pasture. Climate constraints functioned through soil fertility as well as through soil moisture.

Soil Fertility Transitions

Driven by rising population that began in Europe in the eighteenth century, intensification transformed the farm nutrient cycle. The first section that follows addresses the remnants of long-fallow "swidden" agriculture still present in a few early modern farming systems, such as in Galicia, Spain. The subsequent section presents the short-fallow system that dominated agriculture in most of Europe from the Middle Ages, based on a diversified agroecosystem with extensive landscapes acting as nutrient sources. The most common examples appeared in preindustrial farm systems featuring biannual and triannual crop rotations. The following section addresses the transition into "advanced organic" agriculture connected to early industrialization. It explains how, through efficiency gains in nutrient recycling and transfer flows, farmers broke through the nutrient bottlenecks of the traditional land-use system. In doing so, they soon encountered new limitations and sustainability constraints. The final sections deal with the extensification of agriculture through colonization of fresh land in the New World and then with the advent of fossil fuel-subsidized industrial agriculture in the mid-twentieth century. These latter strategies freed farming (and thus world population) from age-old land and soil fertility constraints, at least temporarily.

Long-Fallow Swidden Agriculture

Early agriculture interspersed a few years of crop production with long intervening fallow periods. Abundant land and low population densities allowed communities to clear forest for a few years of cropping, until soil fertility and yields declined; then they cleared new land and planted crops elsewhere. Farmers returned only after 20 years or more, when they could once again unlock nutrients built up in forest biomass by burning (Pyne 1997). Because swidden farmers relied on fire to clear land, anthropologists called it "slash and burn" farming, a derogatory term for what they considered primitive and wasteful land use (Stewart 1956). The agroecosystems of farm communities practicing swidden agriculture centered on moving Cropland and Horticulture through the landscape. Nutrient transfers between intensive and extensive land-use compartments using livestock, for example, were absent. The removal of nutrients with crops and nutrient recycling by burning biomass, which enriched soils with potassium and phosphorus, was the extent of human-mediated nutrient flows. Fires instantaneously unlocked nutrients in woody vegetation; then cultivation and harvest depleted nutrients from the soil in short order. As long as ample land was available, swidden produced abundant, if short-term, harvests with minimal labor.

Swidden clearance of arable land by burning is typically associated with Indigenous and tropical agriculture, but examples existed in European farming as well. When Russians pushed southward in the eighteenth century into Ukraine's great steppe grasslands, for example, they practiced a form of swidden with 20- to 30-year rest intervals (Moon 2013a: 19). Likewise, in 1750s Galicia, Spanish farmers supplemented permanent cropland by occasionally slashing, burning, and cultivating rough brushland on a 30- to 50-year cycle (Corbacho and Padró 2021). But long-fallow swidden was a thing of the past in most of Europe by the Middle Ages.

Short-Fallow European Agriculture

The alternative to moving cropland through an uncultivated landscape was to create permanent cropland whose annual rotations moved fallow through arable land. The most widespread European systems were biannual and triannual rotations, with fallow every second or third year (Gingrich et al. 2015; Hoffmann 2014). Another alternative to this approach was several years of natural fallow followed by a few years of cropland, such as the "Egart" system in alpine Austria. The classic three-field rotation included two different annual crops plus a year of natural fallow that revolved through cropland (Cunfer and Krausmann 2009). The short fallowing period served various purposes, including pest control and food diversification, as well as fertility restoration (Sieferle and Müller-Herold 1996). In traditional open-field systems, such as those that persisted in Austria until the late eighteenth century, farmers used natural fallow as communal livestock grazing.

In contrast to swidden, short-fallow systems required farmers to direct a flow of nutrients toward Cropland and Horticulture, as fallow alone could not restore all the nutrients depleted by harvests. The trade-off was permanent cultivation, with stable but lower yields. Interspersing a fallow year between one or two crop years did not replenish all the nutrients lost in harvests. Small annual surpluses of nitrogen and phosphorus accumulated during the fallow period, mainly from natural processes such as atmospheric deposition (Güldner 2021). Tillage of fallow land built fertility for subsequent harvests as microorganisms decomposed organic matter and slowly released nutrients. The replenishment of soil nutrients facilitated by fallow was not sustainable in the long run. Long-term agriculture thus hinged on additional nutrients transferred from extensive land-use compartments using manure, decomposition, or burning of collected biomass.

Livestock propelled the transfer of nutrients throughout the agricultural landscape, subsidizing Cropland and Horticulture with nutrients originating in outlying parts of the agroecosystem. In some places, livestock ranged widely day and night, eating grasses, forbs, and brush, and deposited their manure throughout the landscape, where it was unavailable for Cropland and Horticulture. In eighteenth-century Austria, for example, peasants whose cattle roamed freely barely produced enough manure to support cropland needs and struggled to feed their livestock (ibid.). A similar manure shortage occurred in eighteenth-century Galicia, Spain. Extensive grazing in hilly brushland supported large numbers of livestock, but it was impossible to collect their manure for cropland fertilization (Corbacho and Padró 2021).

Alternatively, herding livestock into confined shelters at night ("stabling") enabled manure collection for field application, effectively transferring nutrients from Rough Grazing to Cropland and Horticulture. In the nineteenth century, Galician farmers continued to pasture livestock during the day, but began to stable them at night in the village, where they collected manure to fertilize nearby cropland. Yields, labor costs, and population all rose, but over time Rough Grazing land suffered a decline in soil nutrients (ibid.).

A yet more labor-intensive form of transferring nutrients, evident in dry Mediterranean areas that could not support high livestock densities, depended on composting and burning. Farmers transferred vegetation from Woodland and

Brushland to Cropland and Horticulture for composting or burning to release nutrients (Olarieta et al. 2011; Tello et al. 2012). In Catalonia, Spain, farmers dug *hormigueros*, where they hauled brush into vineyards, buried it, and burned it underground, unlocking potassium and phosphorus (Galán 2021).

The configuration of European landscapes into nutrient sources and sinks was not arbitrary. Communities reserved the richest land for Cropland and Horticulture. Where sufficient rainfall allowed, meadows and pastures were an adaptation to characteristics of the local environment, including topography, soil structure, climate, and water availability. Their relative extent reflected the land cost for a rural society to sustain its livestock for draft power and manure production. Soil nutrient sustainability rested on extensively used Rough Grazing, Hay Meadows, and Woodland and Brushland that replenished nutrient shortfalls on intensively used Cropland and Horticulture (Güldner and Krausmann 2017). With short fallow, a ratio emerged between cropland on fertile soils and outlying marginal land unsuitable for cropping. While yields were stable, these systems faced hard productivity limits, and a nitrogen bottleneck prohibited further intensification (Allen 2008).

The ratio between nutrient inputs and outputs in various land-use categories became unbalanced when demographic pressure or market opportunities encouraged higher crop production. Then land-use types serving as nutrient sources experienced significant depletion that compromised the long-term sustainability of the entire system. Furthermore, farmers' techniques to manage recycling and boost transfer pathways were complex and often inefficient. Nitrogen, for example, is highly volatile and prone to gaseous losses during manure storage and application. The availability of land and its stockpiled nitrogen were the most limiting constraints on agricultural intensification and the greatest sustainability challenge for agricultural systems reliant on short-fallowing (García-Ruiz et al. 2012; Tello et al. 2012).

Intensification: Advanced Organic Agriculture

German agronomist Nepomuk von Schwerz (1836) compared preindustrial agriculture to a machine, "where one gearwheel continuously interlocks with the other, but the main driver is livestock and, therefore, the production of forage crops." His notion of agriculture as an "organic machine" fits an analysis of soil nutrient flows across coupled landscape compartments and invokes the spirit of industrialization, which presented farmers with new challenges and opportunities. Eighteenth- and nineteenth-century agronomists were aware of the shortcomings of nutrient transfer and recycling pathways, complaining about manure shortages and nitrogen scarcity in short-fallow farm systems. These worries grew from a concern about food shortages for growing populations. Their solution was simple: increase fertility by funneling forage crops on fallow through livestock stabled year-round to collect their manure. Under the rational banner of the Enlightenment, liberal governments and universities generated innovations that, alongside liberal land-tenure reforms, saw farm communities across Europe transition to an "advanced organic economy" that intensified production (Overton 1996; Wrigley 2006).

Von Schwerz was at the cusp of an agricultural revolution that turned remaining European feudal states into advanced organic economies. Allen (1992) has proposed that in England there were two consecutive transitions, the first led by the yeomen and the second by landlords who took over the agricultural innovations developed by the former. The literature presents the English system as a forerunner of advanced organic farming that subsequently spread across the continent. In central and northern Europe, however, farmers were already intensifying fallow with cover crops in response to population pressure and market opportunities (Slicher van Bath 1978). Besides, England's agricultural revolution coincided with the influx of Flemish and Dutch immigrants in the late sixteenth and early seventeenth centuries who brought such techniques with them. Advanced organic systems coexisted in continental Europe from the sixteenth until the nineteenth century. In Galicia and Catalonia, Spain, annual farming spread in the seventeenth century, followed by Austria in the eighteenth. Differences in advanced organic agriculture in these places arose from biophysical resource endowments that varied widely. Raising forage for livestock required adequate water availability, so in drier places farmers rarely found long-term success. Instead, they adopted other strategies better suited for semiarid climates (Galán 2021).

Europe's agricultural revolution into advanced organic economies intensified using only biological techniques, without external energy subsidies or synthetic fertilizers. Agroecosystem diversification with new varieties of forage cover crops, green manure, and an intensification of livestock production were the main gearwheels to increase nutrient recycling and transfer flows. These strategies provided more manure and organic amendments, improving nitrogen supply to cropland soils (Allen 2000, 2008; Gingrich et al. 2018). Increasing the efficiency and intensity of nutrient recycling and transfers depended on increased labor in the context of growing rural populations. At the same time, crop diversification and livestock intensification presented unforeseen challenges and created new sustainability problems.

Farmers in abundantly watered England adopted "high farming" that replaced the old natural fallow with forage crops like clover or turnips that served as either livestock feed or green manure. No longer was a third or half of arable land unproductive each year. The English Norfolk four-course rotation is an often-cited example of "seeded fallow," comprising one or two "break crops" interspersed between summer and winter cereals (Overton 1996). Seeded fallow in four- to six-year rotation cycles prevailed across Europe in the early twentieth century, and current organic farming systems still use these sequences.

Cover crops were legumes (clover, alfalfa, and pulses like peas or vetch), root crops, (turnips, beets, or potatoes) or corn. One part of this new land-use strategy resulted from the "Columbian Exchange" that introduced new crops from the Americas (Crosby 1972). Most important were corn and potatoes, which in Europe provided livestock forage long before they became a staple in human diets. Legumes, however, were traditional Old World crops now enjoying a renaissance. Farmers long understood that growing legumes improved yields. Roman farms, for example, rotated legumes such as field beans and vetches with grain to improve yields (Brevik 2005; White 1970). Livestock may have been the physically largest gearwheel driving nutrient flows in the organic machine, but equally important were microscopic lifeforms. Long unknown to science, fungi, bacteria, and a myriad of other tiny creatures enriched the earth by powering decomposition (Winiwarter

2013). In fact, the mass of microbiota populating the soil weighs more than twice as much as the aboveground livestock grazing on any given patch of grass (Dash and Dash 2009). These tiny creatures were crucial for the decomposition of organic residues, such as roots and stubble, turning them into soil nutrients available for next year's crops.

Some bacteria naturally fix atmospheric nitrogen. One variety, called *rhizobia*, formed a symbiosis with legumes. These microscopic, organic power plants in root nodules made legumes invaluable. They improved cropland nitrogen replenishment and created a positive feedback loop in advanced organic agriculture. A small portion of nitrogen derived from the atmosphere went directly into the soil through "rhizodeposition," but most of it remained in the root nodules and bodies of the plants until livestock consumed them or they decomposed (García-Ruiz et al. 2012). Because the largest part of the newly fixed atmospheric nitrogen resided in legumes' above-ground plant matter, famers utilized these crops as forage to increase livestock production and, subsequently, the manure supply. Farmers fed nitrogen-rich legumes, such as clover, alfalfa, or field beans, to livestock who converted it to manure. Thus, nitrogen originating in the atmosphere moved through legumes before livestock recycled it as manure, which then fertilized Cropland and Horticulture. Root crops also found their way into the new rotations. Through a similar soil-to-plant-to-livestock recycling pathway, deep-rooted crops such as turnips and potatoes appropriated nutrients from deep soil layers that cereals rarely reached. Nutrients in root crops returned through livestock via manure and onto cropland, steadily increasing the soil's content of plant-available nitrogen and phosphorus for later cereal crops (ibid.).

This legume and root-crop intensification strategy came without the additional "land costs" of nutrient transfers from outlying Rough Grazing, Hay Meadows, or Woodland and Brushland. Long before the twentieth-century revolution in synthetic fertilizers, this groundbreaking agricultural innovation lifted the limitations on farm systems that had been constrained by finite land availability for nutrient transfers and recycling. The ability of legumes to fix nitrogen from the atmosphere and of root crops to draw nutrients upward from deep underground broke through agriculture's rigid land-use constraints. Legume and root crop cultivation on a small fraction of cropland mobilized considerably more nitrogen than the old nutrient transfers from outfields could manage, even with large labor inputs. Legumes effectively multiplied the land area of a farm. In Austria, for example, legumes contributed 30 kg of new nitrogen per hectare to cropland soils. Legumes grown on one hectare of cropland provided as much nitrogen as manure-based transfers from 13.5 hectares of Rough Grazing, or from 4 hectares of Hay Meadows (Güldner 2021). Legumes created a remarkable boost in available soil fertility with no need for additional land or labor.

In adopting new crops, rotations, and livestock densities, farmers restructured their traditional landscape. Europe's advanced organic economies expanded and intensified Hay Meadow cultivation and reduced the extent of Rough Grazing. Advanced organic farmers decreased the number of extensively grazed livestock and relocated them to stables near cropland for intensive feeding and efficient manure collection. In some cases, intensive forage production and livestock stabling increased manure supply even as the number of livestock declined (Corbacho and

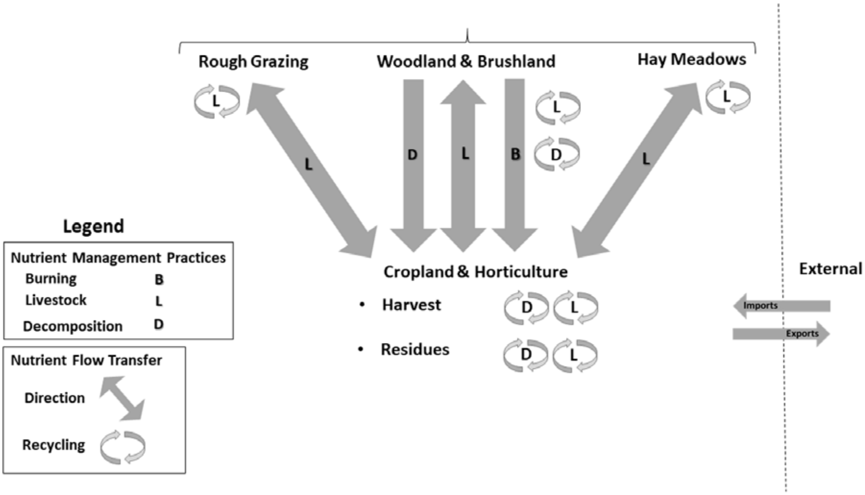

Figure 2. A model of agroecosystem soil nutrient flows for Austria's advanced organic farm system in the early nineteenth century.

Padró 2021; Güldner 2021). Liberal land reforms reduced common land through enclosure, fallow area declined, and communities converted open fields to private management. The ability to access soil nutrients from the atmosphere and from deep underground transformed agricultural landscapes and restructured farm communities from top to bottom.

Figures 2 and 3 present variations of advanced organic agriculture in Europe. Figure 2 models rural Austria in the early nineteenth century (Güldner 2021). It highlights the nutrient transfers from Woodland and Brushland, Hay Meadows, and Rough Grazing to Cropland and Horticulture. Abundant rainfall in Central Europe allowed a diversity of techniques for accessing and transferring nutrients, including internal recycling within Cropland and Horticulture. Figure 3, in contrast, presents the advanced organic farm system in Catalonia, Spain around 1920 (Galán 2021). Legume cultivation, both as a source of nitrogen and as livestock forage, played an important role here, contributing a substantial amount of nitrogen inputs into cropland. However, Catalonia's dry climate meant that Hay Meadows were virtually nonexistent, closing off one nutrient pathway that was important in Austria. Similarly, burning as a means to quickly recycle nutrients was crucial to Catalan nutrient management, but rarely employed in Austria.

By unlocking new nutrients, farmers created a positive synergy of livestock-keeping and forage production, tightening the gears of the organic machine. Soon, however, the revved up organic machine faced different sustainability challenges. Once the nitrogen constraint on crop growth eased, other nutrients became limiting. Higher crop yields meant farmers mined phosphorus and potassium at faster rates, exporting some of them to external markets. On Austria's manorial estates, more legumes increased nitrogen availability but also caused phosphorus depletion (Güldner and Krausmann 2017). Unlike with nitrogen, farmers could not replenish phosphorus from the atmosphere. Natural mineralization of the land's

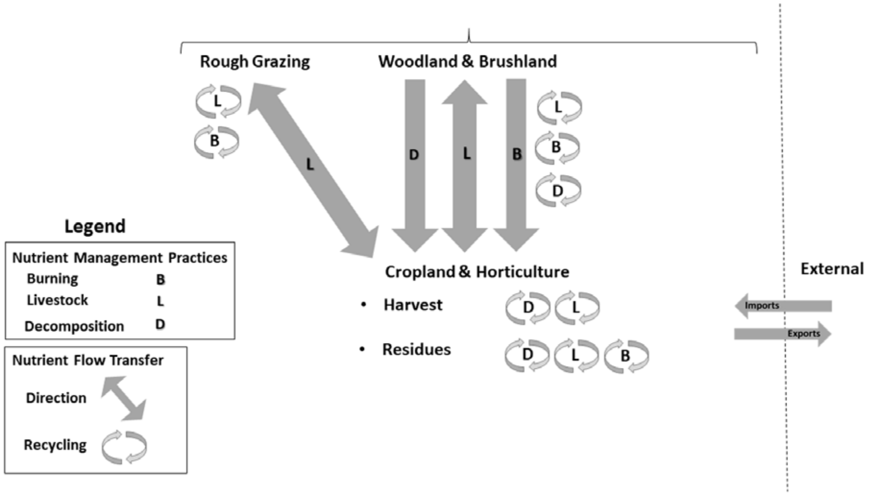

Figure 3. A model of agroecosystem soil nutrient flows for Catalonia's advanced organic farm system in the early twentieth century.

bedrock deep underground was the only source of additional phosphorus, and it could not keep up with rising demand (Frossard et al. 2009; Güldner and Krausmann 2017). Livestock consumed phosphorus in forage crops and recycled it via manure into the soil, but some phosphorous departed the system each year through exported grain, and total soil phosphorus declined. Similar processes were evident in Spain's Basque region (Olarieta et al. 2019). After decades of advanced organic agriculture had surpassed the old nitrogen constraints, many European agroecosystems encountered phosphorus limitations for the first time.

Extensification: New World Land Colonization

Another important strategy for accessing scarce soil nutrients was the colonization of new land. Practiced since time immemorial, converting forest, grassland, or swamp into arable land provided access to additional soil fertility for growing, expanding, or colonizing populations. The scale of land colonization might be small—a few extra furrows plowed into adjacent pasture—or large—sodbusting 45 million hectares of the North American Great Plains—but the fundamental objective was the same: to tap into stockpiled soil nutrients in new land (Cunfer 2005).

Land colonization varied depending on local ecosystems. In many places it initially entailed deforestation: back-breaking labor to kill, cut, remove, or burn trees, grub out their roots, then plow cleared land (Cronon 1983). The job could take decades, as slash slowly decomposed and subterranean roots snarled plowshares (Donahue 2004). Fire might speed the processes and deposit a quick dose of ash fertilizer, but many pioneers planted their first crops among the standing or felled trunks of large trees resistant to surface fires (Pyne 1982, 1997). Years might pass before fields were clear and easily cultivated.

In other places colonization of new arable land first required drainage, damming, canal-digging, and diking to remove water from wetlands and then to keep it out (Stewart 1996). Drained wetlands could be immensely rich in nutrients, but making them dry enough to cultivate required considerable labor and constant maintenance to prevent flooding (Amato et al. 2001; Stunden-Bower 2011). In the Netherlands, for example, the Dutch expanded cropland into the ocean from the thirteenth century, diking, draining, and eventually planting some 700,000 hectares of land formerly inundated with sea water. Across the English Channel, farm communities drained and “reclaimed” the fens on England’s eastern coast from the seventeenth century.

Between the 1780s and 1920s, new land colonization focused on grasslands (Cunfer et al. 2018; Moon 2013b). Grassland sod is difficult to plow, but it covers some of the world’s richest soils. In general, grassland soils are deeper and more fertile than forest soils, and their global extent is enormous. Connected especially with European colonization, agricultural settlers undertook a massive plow-up of grasslands in the long nineteenth century. Displacing Indigenous people, European farmers brought livestock draught power (oxen, horses, and mules), iron and steel technology (moldboard plows), and a rapidly increasing population to the project. In just more than a century, they opened millions of hectares of new cropland in the Russian and Ukrainian steppes (Moon 2013a), the Argentine pampas (Adelman 1994; Scobie 1964), the North American Great Plains (Cunfer 2005), and in Australia and New Zealand (Brooking and Pawson 2011). It was the largest and fastest conquest of new arable land in human history. The crops grown on those rich soils fed the world’s growing population (up 60 percent during the century) with grain and meat, and delivered fiber, hides, and lubricating oils to industrializing cities (Clifford 2021).

Boserup (1965) argued that increasing population pressured communities to find new resources, but emerging market opportunities also drove expansion into new lands. A few examples illustrate the varied character of this ubiquitous soil appropriation strategy. Medieval Europe’s “Great Clearances” provide a starting point. Following the collapse of the Roman Empire, Western Europe’s population first stagnated, then began long-term growth in the ninth century that peaked in the fourteenth. Between 850 and 1350 Europeans cleared forest for new arable land to feed ever more mouths (Hoffmann 2014; Le Roy Ladurie 1974). In the modern era, Enlightenment-inspired liberal land reforms broke up feudal estates and freed land for small-holder expansion (Carmo and Domingos, 2021; Infante-Amate et al. 2016). In the Americas, democratic ideology drove state land distribution policies begun by Thomas Jefferson’s 1795 Northwest Ordinances, the pinnacle of which were the 1862 Homestead Act in the United States and the 1872 Dominion Lands Act in Canada (Robbins 1942). A century later Brazil reprised those settlement schemes, opening the Amazon for rainforest clearance and agricultural settlement by hundreds of thousands of impoverished citizens (Pereira 2003).

Key to new land colonization was the richness of previously uncultivated soils. Land never farmed, or unfarmed for centuries, contained soil nutrient stockpiles built up over time. Plant litter—leaves, stems, branches, dried grass, and all manner of wetland sedges, reeds, and forbs—dropped annually onto the ground. There they decomposed, sometimes burned, or sank into shallow mud, depositing nutrients into soils year after year, decade upon decade. When farmers cleared such land, plowed the soil, and planted seeds on fresh ground, they gained access to centuries of accumulated soil fertility, now diverted from native plants toward human-selected crops. Yields on freshly plowed ground were phenomenal—quadruple or more those on old cropland. Bumper crops in the early years were key incentives for land clearance. In some places—tropical rainforests are notorious—productivity lasted only a few years. In other places stockpiled soil nutrients sustained high crop production with limited fertilization for 50 years or more. Farmers colonizing colonial New England in the seventeenth century (Donahue 2004) and 200 years later in the Great Plains (Cunfer 2004, 2021) benefited from the natural supply of nitrogen for decades before yields declined and labor-intensive nutrient management became necessary.

While yields may have been spectacular on newly colonized land, they could not persist. Every frontier began with impressive production that fell away. Simply cultivating soils released nitrogen into the atmosphere. Rainfall leached nutrients below the plowline and erosion channeled them into rivers and lakes. Harvests took away nutrients annually—after all, that was the goal. Year by year, yields declined. Either farmers switched to the laborious and endless process of restoring soil nutrients, or they moved on, searching for fresh land just over the horizon or perhaps across the ocean.

Whether driven by hunger, greed, ideology, or opportunity, people incrementally added to cultivated land area over millennia, sometimes in long-term ebb-and-flow cycles, other times in great bursts of expansion. Whether they cleared forests, plowed grasslands, or drained wetlands, the objective was the same: farmers converted natural landscapes into managed agroecosystems. They tapped soil nutrients that had previously sustained natural vegetation. Now those nutrients flowed into human-managed pathways, through selected crops, domesticated animals, people, and eventually into human economies. New land colonization was one of the most important ways people acquired access to the essential soil nutrients at the base of human livelihood and wealth.

The Advent of Industrial Agriculture

By the late nineteenth century in Catalonia and Galicia, Spain, as well as on Austria's manorial estates, phosphorous shortages emerged on Cropland and Horticulture. Rough Grazing and Hay Meadows developed shortages of both phosphorus and potassium. It was a tipping point for agriculture, requiring the introduction of soil nutrients derived from outside farm systems at ever-increasing energy costs. With artificial fertilizers, farmers could relieve phosphorus and potassium bottlenecks and further boost soil nitrogen. Early artificial fertilizers were a consequence of the Industrial Revolution, political liberalization, and mechanized sea and land transport. Factories supplied phosphorus fertilizer as industrial byproducts, such as bone meal from slaughterhouses or Thomas Slag and superphosphate from steel mills (Mazoyer and Roudart 2006). Guano, the accumulated excrement dropped by Pacific Ocean birds on the coast of Peru, was an organic source of phosphorus and nitrogen that arrived in Europe and North America through global trade routes (Cushman 2013). Once farmers solved phosphorus and potassium deficiencies, nitrogen again became the limiting nutrient. Rich nitrate deposits in Chile's Atacama Desert also flowed across the ocean. To increase yields to satisfy markets in industrializing cities, farmers tapped into global nitrogen, phosphorus, and potassium reserves through the international fertilizer industry.

Early in the twentieth century, German chemist Fritz Haber and BASF industrial engineer Carl Bosch brought agriculture fully into the industrial age when they developed a process to synthesize ammonia (Smil 2001). BASF opened its first plant in 1913, and by the mid-twentieth century the Haber–Bosch process flooded farms with inexpensive, abundant nitrogen fertilizer. Ammonia synthesis depends on fossil fuels, primarily natural gas, to fix atmospheric nitrogen. Haber–Bosch synthesis operates under very high temperatures (2,000 degrees C) and pressures (100 atmospheres), conditions that require large energy inputs. Natural gas not only provides the energy (heat and pressure) but it also provides the hydrogen for ammonia. By the end of the twentieth century, nitrogen fertilizer production had doubled the amount of plant-available nitrogen in the world, utterly transforming the global nitrogen cycle and feeding increased cropland productivity worldwide (Galloway et al. 2004). For thousands of years agriculture had been an energy supplier to society; now it became an energy consumer through its reliance on synthetic nitrogen (Gingrich et al. 2018).

North American Great Plains farmers broadly adopted synthetic nitrogen fertilizers in the 1950s, with stunning results (Cunfer 2004). In Nemaha County, Kansas, for example, corn, hay, and oat yields had fluctuated between 1.5 and 3 tons per hectare from 1880 to 1950 (Cunfer 2021). Thereafter they quadrupled, from 2 tons per hectare in 1950 to 8 tons in 1997. New hybrid seed varieties were capable of exploiting higher levels of soil nutrients, and crop productivity accelerated across the plains (Anderson 2009: 53–54). In Rooks County, Kansas, wheat yields rose from 1.5 to 5 tons per hectare in the second half of the twentieth century. With a boost from irrigation, farmers in Pawnee County, Kansas did even better, raising wheat and sorghum yields from under 1 ton per hectare in 1940 to nearly 6 by the end of the century. To the north in Canada, wheat farmers in Wise Creek, Saskatchewan raised yields from 0.5 to 2.5 tons per hectare by the 1980s (Larsen 2021). In the more diversified Livingston, Saskatchewan, farmers planting wheat, canola, and hay saw yields rise from 1.5 tons per hectare in 1941 to 4 in 2001. Across North America's breadbasket, farm communities delivered energy-rich synthetic fertilizers to their soils, doubling crop production and then doubling it again.

Figure 4 presents a nutrient model of management practices across the North American Great Plains in the late twentieth century (Cunfer 2021; Larsen 2021). This industrial, export-oriented agricultural system relied on high inputs of synthetic fertilizer with very few nutrient transfers between landscapes. Livestock transferred some nutrients across the landscape, but in the twentieth century Great Plains, most of the nutrients were recycled within cropland or came from imported fertilizer, with comparatively few transfers between land-use components. Burning, although rare, happened occasionally when crop residues were especially heavy. Green manure is one way that North American farmers utilized legumes, by plowing the entire plant into the soil, a method often found in farm systems with no livestock and thus no manure (García-Ruiz et al. 2012). Legume green manure crops fixed atmospheric nitrogen during their growing period, then "plow-down" utilized

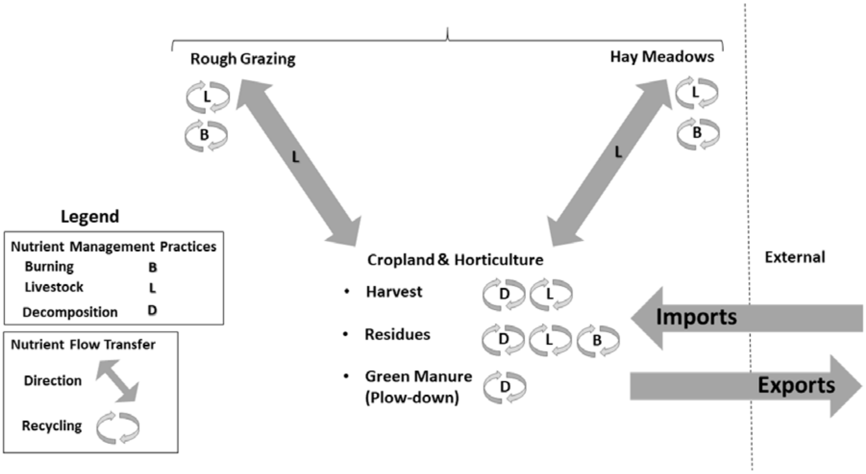

Figure 4. A model of agroecosystem soil nutrient flows for the North American Great Plains industrial farm system in the late twentieth century.

decomposition to unlock that nitrogen in the soil for future crops (Cherr et al. 2006; Mazoyer and Roudart 2006).

Similar processes transformed European farms in the second half of the twentieth century, once again restructuring soil nutrient management, landscape organization, and agricultural productivity. Most importantly, livestock lost their central role in soil nutrient management. With synthetic fertilizers, it was no longer necessary to integrate livestock with cropland, hay production, forage crops, and extensive grazing. Each of those agricultural functions continued, but they no longer remained in close proximity. Farms could specialize exclusively in grain production, dairy, or livestock feeding (Krausmann 2004). At regional and global scales, some places focused on crop production, others on meat, dairy, fiber, or oils. Fossil fuel-powered soil nutrient supplies, coupled with fossil fuel-powered transportation networks, created a disaggregated agricultural landscape where supply chains and markets spanned continents and crossed oceans. The application of fossil fuel energy to farming in the mid-twentieth century was a turning point in the industrial transformation of agriculture. Prior to fossil fuel's widespread adoption, biomass stored society's available energy and fertility, and land area limited available biomass. Deploying petroleum and, especially, natural gas for agricultural applications lifted the energetic boundaries of a society that had been limited by its land-based energy and soil nutrient resources (Cunfer et al. 2018; Grigg 1992). Fossil fuels decoupled nutrient flows from land and labor resources. The "Boserupian link between decreasing labour productivity and increasing population density [was] overridden by the industrial link between increasing use of fossil fuels and industrial technology increasing labour productivity" (Fischer-Kowalski et al. 2011: 155).

Conclusion

Farmers developed five basic strategies for replenishing the good earth upon which we all rely for our daily sustenance and economic prosperity. One solution was to colonize new land, tapping into soil nutrients stockpiled by natural processes over geological time. A second was to employ crop rotations with fallow that alternately extracted and replenished soil fertility. Third, farmers might relocate nutrients from distant outfields for concentration on arable infields. These nutrient transfers across the landscape required labor to haul biomass from Woodland and Brushland onto cropland, or domesticated livestock that consumed feed in one place—such as Rough Grazing land—then walked to another before dropping their nutrient-rich manure. In many agroecosystems livestock were crucial vectors by which farmers transferred soil nutrients from one part of the landscape to another. A fourth strategy used legumes to draw nitrogen from the atmosphere or root crops to access phosphorus or potassium from deep underground. Plowing those forage crops into the soil or feeding them to livestock tightened the gears of the organic machine and doubled European yields in the nineteenth century. The fifth, industrial, option used fossil fuel energy for synthetic nitrogen fertilizer. Combined with phosphorus and potassium supplements, industrial nitrogen fertilizers quadrupled yields and made many of the labor-intensive techniques unnecessary.

In the natural world, nutrients cycled from atmosphere to soil to plant to soil to atmosphere through physical and ecological processes powered by sunlight and photosynthesis. Nutrients bound up in biomass recycled slowly (through decomposition) or quickly (through combustion). Both "unlocking mechanisms" made nutrients available for new plant growth. Farmers intervened in natural cycles to extract material useful for human bodies and human economies. They applied controlled fire to speed nutrient recycling. They redirected decomposition by plowing down residues and cover crops, transferring brush across the landscape, or composting bedding straw with manure. And farmers added a third and crucial unlocking mechanism: livestock that ate plants, decomposed their contents by digestion, and excreted manure chock full of soil-ready nutrients. What's more, livestock walked, with a bit of guidance, from where the nutrients were to where they were needed. The strategies for sustaining crop productivity relied on sophisticated management of these three unlocking mechanisms.

Farming is a form of applied ecology. The way people worked the soil emerged from traditional social patterns and available knowledge. Preindustrial societies relied on natural, biological processes of nutrient replenishment that today's society would call "organic," but it does not follow that traditional, organic agriculture was inevitably sustainable. Every agricultural practice entailed a disturbance of the soil by extracting resources from accumulated nutrient stocks that then required replenishment. When extensive swidden agriculture was impossible or there was no new land to colonize, farmers resorted to in-situ fallow. Fallow conserved resources over the long term, but meant lower land productivity. To maintain the fertility of intensively used land, farmers organized nutrient transfers from extensively used land. They applied the resulting manure, compost, or ashes onto Cropland and Horticulture. The availability of extensive land as a source of nutrients thus limited the extent and productivity of arable land. But landscape transfers were inefficient and labor intensive.

The diversification of agroecosystems by leguminous and other forage crops improved soil nitrogen supplies (Allen 2008). Although organic intensification overcame one nutrient bottleneck, it shifted sustainability challenges to soil phosphorus and potassium instead. The nineteenth-century agricultural crisis, which agronomists perceived as a phosphorus deficiency, did not derive solely from a rural–urban imbalance, described by Foster (1999) as a “metabolic rift.” Rather than a problem of industrialization per se, agriculture *always* faced the challenge of balancing nutrients within the agroecosystem and between land-use compartments. The advanced organic economies were no exception because farmers could only compensate for the depletion of nutrients in arable land through intensified transfer and recycling processes, which drained resources elsewhere. Nineteenth-century privatization, enclosure of commons, and emergent global markets created the latest, but not the first, nutrient imbalances within farm systems.

Neither traditional agriculture, nor advanced organic agriculture, nor pioneer agriculture was sustainable; nutrient imbalances occurred long before the advent of industrialization. Advanced organic agriculture raised cropland productivity, but insufficiently replenished nutrients extracted from outlying areas. New land produced bumper yields, but quickly depleted its naturally stockpiled nutrients. Without the arrival of synthetic fertilizers, farmers could not have sustained the nineteenth century’s productivity gains. Industrial fertilizers, based on fossil fuel energy, were so cheap, in cash and labor, that farmers could afford to apply large quantities as productivity skyrocketed around the world. Industrialization enabled long-distance transport of fertilizers and later produced inexpensive synthetic fertilizers. Those developments made livestock suddenly unnecessary for crop production, leading to the geographic disaggregation of livestock and crop agriculture. In a world now awash with excess nutrients, nitrogen has become an environmental pollutant, a situation that would have shocked farmers only a century ago. Manure from livestock feedlots pollute watercourses, while excessive nitrogen fertilizer contributes to river eutrophication, ocean dead zones, and global warming.

Farmers constantly sought ways to maintain yields without sacrificing productivity in other areas. The search for balance evolved throughout agricultural history, driving land-use innovation and social change. Population growth repeatedly overcame periods of equilibrium, requiring creativity to achieve higher productivity. Trade and market opportunities also created incentives for higher production. Farmers reacted to economic incentives by prioritizing certain crops, and trade also opened a wider source area from which to import nutrients. The export of food and fiber from rural to urban areas was obvious, but the flow of soil nutrients in the other direction was equally important.

The effort to increase productivity over the past 250 years, which underwrote both the Industrial Revolution and an increase in global population from 1 billion in 1800 to 7 billion in 2000, required overcoming distinct biophysical limits on productivity, limits that operated at a global scale for thousands of years. Nitrogen was often, but not always, the most limiting soil nutrient, and many agricultural innovations aimed to deliver more nitrogen to cropland to raise yields. Europe’s advanced organic agriculture did so by integrating livestock tightly into the crop system, diversifying forage crops, and transferring nutrients from outfields to infields in ever larger quantities. As they overcame the nitrogen limits, however, farmers encountered new nutrient constraints. Having burst through the nitrogen bottleneck they encountered a phosphorus or potassium bottleneck. Likewise, fossil fuel energy inputs into fertilizer production have only shifted sustainability challenges from the local to the global scale. Each increase in crop productivity required new management or technological solutions, as farmers grappled with successive limiting resources.

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