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COMMENTARY FROM THE U.S. AGROECOLOGY SUMMIT 2023

Grain agriculture and the end of the fossil fuel era

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A great deal of attention is currently focused on how agriculture in highly industrialized countries contributes to greenhouse gas (GHG) emissions, and how certain farming innovations might curb the emissions of nitrous oxide and methane and draw down carbon dioxide from the atmosphere. What is not being discussed is how agriculture in general, and grain agriculture in particular, will need to change as society phases out its dependency on fossil fuels in order to achieve carbon (C) neutrality.

Over the last century in the U.S., the number of farmers on the land declined by about 66%, in close proportion to the increase in average farm size (U.S. Department of Agriculture Economic Research Service [USDA ERS], n.d.). Integral to these trends has been the simplification of farming systems in which practices like fertility-generating rotations have been replaced with lower-diversity monocultures maintained by applications of fossil fuel–based fertilizers and pesticides (Crews & Peoples, 2004). Between fossil fuel–powered mechanization and fossil fuel–based input intensification, the energy used by farmers to grow maize in the state of Nebraska is 99.7% from fossil fuels and 0.3% human labor (Grassini & Cassman, 2012; Pimentel & Pimentel, 2008). Even organic farming systems often require prodigious fossil fuel inputs with intensive tractor tillage, manure hauling, and mechanical harvesting (Smith et al., 2015). In contrast to our modern grain-producing agroeecosystems, ancestral agroecosystems and natural ecosystems of all types—forests, grasslands, deserts, tundra—have remained productive for millennia with no fossil fuel inputs. In this commentary I explore the dependency of grain agriculture on fossil fuel use in the U.S. set in a global context, and approaches for reducing this dependency,

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including a shift to perennial polycultures that rely on ecological intensification in place of energy-intensive inputs.

Before humans began harnessing fossil fuel energy, the muscles of farmers, and in some cases draft animals, supplied the power to prepare seedbeds, plant, cultivate, harvest, and process crops. Of course, for the farmers to carry out this work, they had to consume food calories, which in most cases were supplied by grains (cereals, pulses, and oilseeds) or tubers that they grew on their farms the previous year (Smil, 2017). Thus, in simple terms, to continue farming and avoid hunger, it was critical to grow at least as many food calories for next year as one consumes in the current year. But it was rarely that simple; for one, farmers have rarely been tasked with only feeding themselves. People in society who do not farm also need to eat. These include the elderly, infants, and toddlers, the sick, and in many societies there is a list of nonfarmers who include religious leaders, soldiers, weavers, artists, merchants, and others. Farmers, therefore, are expected to not only grow enough food so that they can farm another year, but also to grow enough food to feed numerous nonfarmers.

The amount of food a farmer produces compared to the food they consume can be expressed as a ratio of food calories produced per food calorie consumed, or kcal output/kcal input (Hall & Klitgaard, 2012). This ratio is frequently called the energy return on investment, or EROI. The EROI attainable by a farmer depends on many factors, which I depict in a simple conceptual model of the relationship between EROI and grain yields at four stages of agricultural evolution (Figure 1). Before society's reliance on fossil fuels, EROI was determined in part by the farming culture's accumulation of agro-ecological knowledge and experience as well as degrees of crop adaptation. When people moved to new places and began farming, EROI would be relatively low for years to decades as farmers gradually gained an understanding of what soil types were best suited for particular crops, which trees worked best to border fields, etc. Addition-

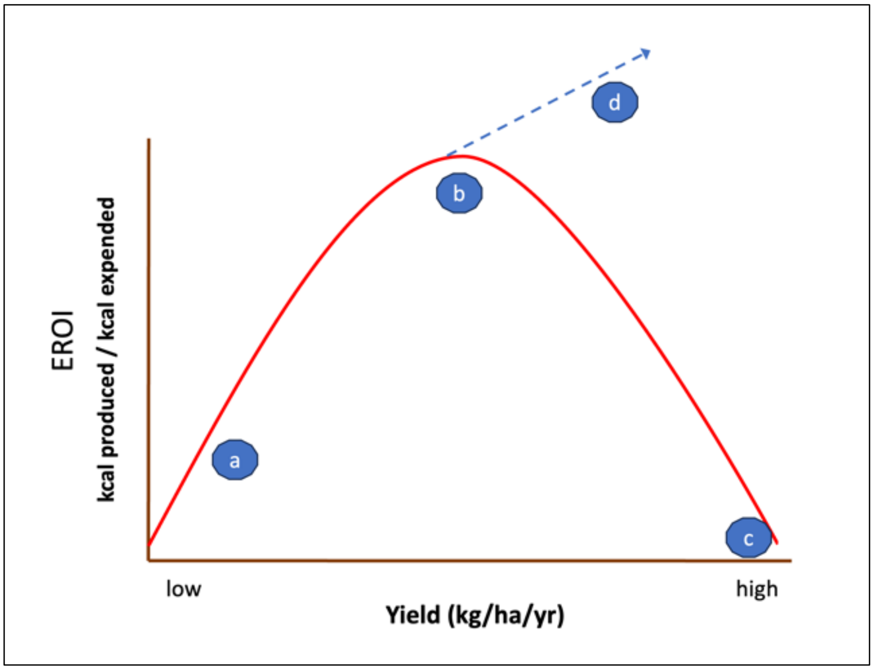

Figure 1. Conceptual Model of the Relationship Between EROI and Grain Yields at Four Stages of Agricultural Evolution

(a) early in ancestral farming system development before germplasm and cropping systems are optimized to conform to local resource constraints;
(b) highly developed ancestral farming systems in which germplasm has been adapted to local conditions and farmers have developed agroecological knowledge and practices that minimize the labor required to reduce limiting factors of crop growth; EROI for specific geographic conditions is near maximum and ultimately limited by site-specific limiting factors such as climate and soil characteristics;
(c) the introduction of fossil fuels replaces metabolic energy and ecological intensification with input intensification, decoupling the energy in food with the energy required to farm;
(d) the development of perennial polyculture agroecosystems in which high yields are supported by less metabolic *or* fossil energy inputs and more by ecological intensification.

Note: Figure inspired by Odum's maximum power principle (Odum, 1995).

ally, it took time to terrace slopes and dig irrigation ditches, and for crop germplasm to adapt to new environmental conditions through cycles of selection (a in Figure 1). With time, often remarkable agroecological innovations and crop adaptations resulted in large increases in yields and in EROI (b in Figure 1). These increases ultimately plateau, however, due to inherent and unique site characteristics such as rainfall amounts and distribution, soil texture and mineralogy, slope of the land, and seasonal temperatures, as well as the productivity limits of specific crops.

Starting in the nineteenth century and culminating in the twentieth, farmers in more industrialized nations underwent an unprecedented energetic transition in which "work" carried out by fossil fuel–powered machinery was substituted for human and animal labor (termed here "metabolic energy") (Grassini & Cassman, 2012; Pimentel & Pimentel, 2008). This substitution effectively decoupled the caloric energy required to grow food from the caloric energy contained in the food grown. The industrialization of agriculture marks the first time that the EROI of food acquisition by humans (or arguably any other animal) could be one or below one for extended periods of time (c in Figure 1). In other words, it was now possible to expend more energy growing food than the food provided back in calories. For the first time, low EROI values did not translate into hunger, and the energy input into agriculture (the denominator of EROI) was largely derived from fossil fuel energy rather than the solar energy embodied in food.

Gasoline, diesel, and other fossil fuels have remarkably high energy densities relative to the metabolic energy of humans and animals. Pimentel and Pimentel (2008) calculated that one gallon of gasoline (3.79L) contains the work energy equivalent of 97 hours of human labor. The contrast in the cost of a gallon of gas compared to almost 100 hours of labor helps explain the rapid adoption of labor-reducing technologies powered by fossil fuel, as well as the challenge of voluntarily forgoing fossil fuel power in the future. In addition to fossil fuels substituting for labor, they have been used to manufacture inputs such as fertilizers, pesticides, and machinery as well as for irrigation, seed production, and grain drying (Grassini & Cassman, 2012). Nitrogen fertilizers remain the single greatest input of fossil fuel power into industrial agroecosystems (Smil, 2022).

Before the industrial revolution, metabolic power provided most of the power to grow wheat, maize, and other grains. Today, farms fall along an energy gradient. On one end is large-scale industrialized grain production like that which occurs in the U.S., where 90% to 99% of the power used to grow and harvest grains is derived from fossil fuels (Grassini & Cassman, 2012; Pimentel & Pimentel, 2008). On the other end of the gradient are the small farms (< 5 acres or 2 ha) in which metabolic energy remains a significant power source for farm operations. The differences in labor productivity (food produced per farmer per unit time) on the two ends of this gradient are sobering. For example, a Kenyan farmer's labor productivity is 1.2 kg maize/hour, whereas the labor productivity of a U.S. farmer from Iowa is 1,470.6 kg/hour (Gollin, 2018, p. 21). These dramatically different statistics in labor productivity fail to account for the fossil fuels that provide over 99% of the "labor" to grow maize in Iowa; remove fossil fuels and the Iowa farmer's productivity would fall close to the Kenyan farmer's 1.2 kg maize/hour.

Of the more than 608 million farms in the world, 84% have land areas of 5 acres (2 hectares) or less (Lowder et al., 2021). These smallholdings make up only 12% of the world's farmland, and they vary in terms of their reliance on fossil fuel–based mechanization and inputs. In contrast, less than 1% of the world's farms are greater than 124 acres (50 hectares) in size, but they comprise 70% of the world's croplands. Almost all U.S. grain production occurs on farms that fall within this 1%. The scale of these large farming operations necessitates the use of prodigious amounts of fossil fuels to power mechanization and manufacture inputs (Pimentel & Pimentel, 2008).

There is general agreement that nations of the world will need to achieve net zero GHGs by 2050 if the Earth's temperatures are going to stabilize and the worst impacts of climate change be avoided (Huang & Zhai, 2021; United Nations, n.d.). The prospects for grain farmers to reduce or eliminate their dependence on fossil fuels will vary by farm size and economic context. Many smallholder, subsistence farmers are already reliant on metabolic energy to provide much, if not most, of the work to prepare fields, plant, and harvest crops. These farmers also commonly manage ecological processes to maintain soil fertility and regulate pests rather than apply fossil fuel–based inputs.

In contrast to the smallholder grain farms of the world, large grain-producing farms such as those found across the central U.S. will face immense challenges in reducing what currently can only be described as extreme fossil fuel dependency. While to date there has been limited discussion focused on this topic, we can anticipate at least two perspectives being advanced by the agroecology or regenerative agricultural communities on how the 1% of farms that are over 50 ha can phase out fossil fuels. The first and by far most widely embraced mirrors the renewable energy optimism that permeates mainstream approaches to achieving C neutrality in the economy more broadly: that is, a transition to renewable energy sources that can replace diesel and gas with electricity for powering farm equipment and irrigation (Gielen et al., 2019; Nitta, 2023). If renewable sources were able to meet society's projected electricity demands, including those in agriculture, then around half of on-farm fossil fuel–based energy costs could be converted to renewables (Grassini & Cassman, 2012; Pimentel & Pimentel, 2008). There are, however, many skeptics who argue that renewables will not be able to replace the fossil fuels powering the current electricity grid plus the greatly increased demand following the shift to an electric vehicle fleet and electric heating in the built environment (Cox, 2023; Smil, 2022). Aside from the uncertainty around whether renewables will generate sufficient affordable electricity to supply industrial agriculture, half of on-farm fossil fuel dependency cannot be replaced in the foreseeable future by renewables, especially nitrogen (N) fertilizer (Pimentel & Pimentel, 2008; Smil, 2022).

Another less common but increasingly voiced approach to achieving C neutrality by 2050 involves a rapid shift toward smaller farm sizes, much greater metabolic energy input from human and animal labor, and increased reliance on ecological intensification such as biological N fixation (Fink, 2022; Pahnke & Goodman, 2022). When applied to grain agriculture, this approach would greatly reduce labor productivity, as depicted in the contrast between Kenya and Iowa maize farmers, above. Without economic interventions, less food produced per hour of farmer labor would result either in higher food prices or lower farmer incomes. If the greatest challenge to the renewable energy path to C neutrality is technological, the greatest challenge to the smallholder path is social. Land redistribution, rural repopulation, new farmer education, and policy revisions are processes that are notoriously slow and would have to accelerate dramatically to have any impact on fossil fuel dependency by 2050.

The renewable and smallholder transitions are essentially substituting fossil fuel–derived energy with non–fossil carbon energy sources. Highly complementary to these, and possibly essential for either to be successful, are farming systems that require fewer energy inputs, meaning reduced need for sources of renewable or metabolic energy without decreasing food production. The development of perennial grain crops grown in ecologically functional polycultures is an emerging model of agriculture that could elevate EROI values well above what is possible in agroecosystems based on annuals (d in Figure 1).

Diversity and perenniality are increasingly recognized as key attributes of virtually all plant communities that comprise the Earth's major ecosystems, including grasslands, savannahs, temperate and tropical forests, shrublands, tundra, and deserts (Crews et al., 2018; Poppenwimer et al., 2023). Water infiltration and uptake, nutrient retention, erosion prevention and formation, pathogen regulation, soil organic matter accumulation, and net primary production are all ecosystem attributes tied to perenniality and diversity, and undergird the sustainability of natural ecosystems (Crews et al., 2018). By introducing greater perenniality and diversity into grain agroecosytems, these beneficial ecosystem functions occur as a byproduct of farming. Energy savings are predicted in perennial polycultures because crop planting only happens periodically, opportunities for weed establishment are reduced, nitrate losses through leaching are reduced, and inputs of N from biological fixation increase. In addition**,** perennial polycultures show promise for drawing down atmospheric carbon dioxide (CO_2) in soil organic matter, and for reducing nitrous oxide (N_2O) emissions, especially in legume intercrops (Crews et al., 2022; Siddique et al., 2023).

If society as a whole manages to eliminate its dependence on fossil fuels in upcoming decades to reduce GHG emissions, agriculture is unlikely to be given a pass. Reducing fossil fuel dependence in grain agriculture, especially in industrialized countries, remains a formidable challenge, both in organic and conventional systems. This is true even if the most optimistic scenarios of renewable electricity substitution for fossil fuels are realized, and even if rapid changes in land tenure are achieved, making reliance on metabolic energy more feasible. The development of diverse perennial grains presents a third path to reducing reliance on fossil energy—not through substitution for fossil fuels but by replacing low-functioning annual monocultures with highly functional perennial agroecosystems that require far less human management and inputs to capture sunlight and produce food.

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