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Agri-food Systems as Energy Systems: An Innovation for New Insights on Transformation to Sustainability

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***Abstract*:** Agri-food systems, indispensable but flawed institutions of the modern world, have partially accomplished their primary purpose, but in many cases, fail to reach all people. Moreover, associated environmental damages threaten future production. Climate change produces the most serious threats. Scientists have built different definitions and diagrams to guide research. Each emphasizes important points, but none have included everything. This paper offers a new diagram and definition based on displaying agri-food systems as an energy system. Agriculture is the source of biomass, one of the nine primary energy sources. With refining and processing, harvested products become food and feed, the sources of metabolic energy and nutrients. Together with other energy sources, especially fossil fuels, food and feed support the production of material wealth. Decision makers constantly direct streams of investments into perpetual production of agricultural biomass. The diagram shows that this agri-food system produces climate change, and the system is also a victim of climate change. This new perspective of agrifood systems as energy systems cannot show all components of the system, but it suggests new lines of innovation to mitigate the weaknesses of these systems.

Keywords: Agri-food systems, Climate changes, Energy systems, Sustainability, Investments

Agri-food Systems and Calls for Change

Agri-food systems, indispensable but flawed institutions of the modern world, have partially accomplished their primary purpose: producing and delivering enough food and fiber to feed and clothe people who do not farm for their livelihood or do not have sufficient land to produce enough. Unfortunately, deliveries remain uneven and, in many cases, fail to reach those most in need. Moreover, associated environmental damages, as noted below, threaten these systems.

Despite agri-food systems supporting 7.9 billion people-a number that is still growing-multiple criticisms have surrounded them for over half a century (Conti, Zanello and Hall 2021). Flaws with these systems include (1) insufficient quantities and qualities of food or (2) threats to perpetual functioning. Poverty usually contributes to the first set of flaws, a social-economic-political-cultural issue, not a physical absence of food and fiber. Other factors exacerbating poverty include inequality and insecurity of land tenure or access to water, discrimination based on gender-race-ethnicity, and geopolitical conflicts. Even in wealthier places, however, poor diets and obesity result from lack of easy access to nutritious choices.

A wide range of physical-chemical-biological problems cause the second set of concerns. For example, chemicals used to increase yields (fertilizers, pesticides, and others) unfortunately contaminate the environment and threaten the health of humans and other species (Houlton et al 2019, Sharma et al 2019). Consider just one example, a study of the herbicide glyphosate, often regarded as one of the safest pesticides to use. Recent studies, however, found that glyphosate blocked the ability of bumble bees to thermoregulate their nests. Without this ability, reproduction was likely to fail (Weidenmueller et al 2022, Crail 2022).

In the years after 1900, many scientists and social reformers began a systematic critique of industrial agriculture and its many hazards to health and sustainability. One of the most prominent examples centered on agroecology, an interdisciplinary enterprise to combine social and natural sciences. Francis et al (2003), defined agroecology as the ecology of food systems, a framework to reform many problems of industrial agriculture, both environmental and social.

Most importantly for agri-food systems, atmospheric changes caused by emissions of greenhouse gases have raised global temperatures, which have altered climatic factors, especially temperatures, precipitation, and storms. Such changes disrupt the physiology of crop plants and livestock, alter occurrences of pest populations and beneficial insects, reduce irrigation water, increase the frequency of “100-year” floods, and destroy farm infrastructure (Bezner et al 2022). Moreover, the processes of agri-food systems themselves contribute about one-third

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This paper was presented at the Indian Ecological Society International Conference 2022 of the greenhouse gases causing climate change (Crippa et al 2021)

Even so, the modern world depends upon agri-food systems for security and well-being. As a result, the systems must deliver enough food *to every person*, especially enough calories and nutrients to support metabolic energy needs, sound nutrition, and health. These requirements demand more than mere prevention of starvation. Agri-food systems must also be resilient, i.e., able to withstand and recover from disruptions such as heat waves. Finally, agri-food systems must deliver food and fiber in perpetuity. The needs for metabolic energy and adequate supplies of nutrients will never end, so agri-food systems must function forever.

Sustainability of agri-food systems, in other words, rests heavily on the need to produce and deliver calories and nutrients "forever," a very demanding criterion. Given the criticisms of both socio-cultural and bio-physical dimensions of agri-food systems, many just enumerated, they currently fail to meet this criterion. For agricultural scientists, cultivating sustainable agri-food systems requires research, development, and innovation. New agricultural science, technology, and knowledge can contribute to resolving both socio-cultural and bio-physical problems of agri-food systems.

But what exactly is an agrifood system? This paper first highlights the origins of agri-food systems as a concept for scientific study. Definitions and diagrams from multiple perspectives have captured many of the components, processes, and outcomes of these systems. The paper then presents a new perspective based on seeing agri-food systems as part of energy systems. This innovation leads to revised definitions and diagrams of agri-food systems, new ways of understanding needed changes, and new possibilities and justifications for research so that agri-food systems will be better able to achieve their mission for many years to come.

Agri-food Systems: A Concept for Scientific Study

Surprisingly, the word "agri-food" did not appear in the English language until 1968 when, according to the Oxford English Dictionary, a Canadian newspaper referred to an "agri-food centre." *Fortune*, an American business magazine, referred in 1977 to the "agri-food business" as comparable to other industries, even the oil industries. With a word came a concept, subject matter rich for scientific study.

Given the intense interest in agri-food systems within the agricultural science and technology community in 2022, it is important to note that systems thinking itself developed only about 60 years ago and started to become common only about 30 years ago (Richmond 1994). As explained below, thinking of agriculture as agri-food systems developed mostly in the last 20 years.

Traditionally, before modern transportation and manufacturing, local farmers supplied their regions with the foodstuffs needed to sustain them. Energy intensive agriculture, based on cheap nitrogen fertilizer, irrigation, and mechanization, prompted development of larger farms worked by fewer people. Younger generations moved to cities in search of higher incomes and different opportunities. Food production instead of being local increasingly became far removed from population centers, dependent on well-functioning agri-food systems. Some of the new opportunities for employment were in agri-food systems (Christiaensen et al 2020). Despite these changes, the historical record clearly points to a longstanding interest in the inabilities of "modern" agriculture-i.e., developments since the early 1900s-to resolve deficiencies in food supplies, social inequities and injustices among people working in agri-food systems, and environmental degradation threatening future food and fiber production (Thompson and Scoones 2009).

Global recognition of the failures of agri-food systems came in 2002 at the Rio +10 Summit on Sustainable Development, which led the World Bank and the UN Food and Agriculture Organization to launch the International Assessment of Agricultural Knowledge, Science, and Technology for Development (IAASTD). Stimulated originally by concerns with the growing use of biotechnology and transgenic crops, the effort grew into a wholistic assessment of the abilities of agricultural science and technology to reduce hunger and poverty, improve rural livelihoods, and facilitate sustainable development (IAASTD 2009, Herren et al 2020).

The broad scope of IAASTD's assessment suggests that, in 2009, the assessors saw agriculture as a system with multiple components interacting to produce a wide variety of outcomes, some beneficial and some not. Nevertheless, explicit use of agri-food systems as a concept appears to have played little role in the 2009 assessment. The term appears a few times in the contexts of defining standards of quality and safety of food (p. 351) and of concerns about concentrations of economic power within a small number of companies (p. 465). Nevertheless, no definition of agri-food systems appears in IAASTD's 2009 report, and the term does not appear in the Glossary (p. 560) or Index (p. 577). Its common acronym today, AFS, stood for "agroforestry" in the report (p. 568).

In the decade following IAASTD's report, however, the concept of agri-food systems began to appear frequently and signaled recognition of a flawed, unsustainable system that, at a bare minimum, needed incremental change. Some agricultural scientists, both natural and social, called for transformational innovations, a far more ambitious target.

Thompson and Scoones (2009) criticized modern, high-input agriculture as the result of research looking at agriculture as a static entity, with yield and economic productivity as the only outputs of interest. They maintained instead that agri-food systems are dynamic, uncertain in behavior, and shaped by multiple, changing, interacting variables, which could not be managed by science based on studying one variable at a time.

Calls for transformative changes grew rapidly after 2015. The International Panel of Experts on Sustainable Food Systems called for new analytical frameworks, new transdisciplinary science, and knowledge revolutions (IPES 2015). More importantly, adoption by the United Nations General Assembly of seventeen Sustainable Development Goals in 2015 galvanized action, especially by international organizations (United Nations, 2016). Specifically, SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health), SDG 12 (new systems of production and consumption), and SDG 13 (combat climate change) each pointed to an element of sustainability of agri-food systems and set a new context for the direction of agricultural research and innovation (Hall and Dijkman 2019).

After adoption of the Sustainable Development Goals in 2015, researchers associated with CGIAR, organized in 1971 through the World Bank and UN Food and Agriculture Organization (Özgediz 2012), developed a theory of change by identifying eight specific objectives for transformative research (Campbell et al 2018). A group of 100 organizations subsequently developed a vision and agenda for this ambition (Steiner et al 2020).

Other papers also stimulated efforts for transformative research. "Sustainable Intensification" was the objective for transformed food systems that preserved both yield and livable environments (Pretty 2018). Hall and Dijkman (2019) also emphasized the need for transformative changes if agri-food systems were to continue feeding the world while preserving livable environments and fostering social justice.

In 2020, some participants from the original IAASTD assessment reviewed developments since the 2009 report. They highlighted "*. . . how a new food system narrative has been firmly established since 2008, which is distinctly different from the post-war chemical narrative that still dominates mainstream farming* (Herren, Haerlin et al 2020)." This report emphasized the need for a "paradigm shift" in agricultural science and technology, a transformation of scientific knowledge by completely new concepts and methods (Kuhn 1962), i.e., a radical shift indeed.

The themes of the 2020 report have been echoed in subsequent papers. Conti, Zanello, and Hall (2021) outlined multiple reasons for resistance to change in agri-food systems, for example, technological lock-ins, persistence of dominant technologies, patterns of power and political economic, and infrastructure rigidities. Wojtynia et al (2021) assessed the same theme of resistance to change in one country, The Netherlands. They found broad agreement in recognition of social (human health and livelihoods) and environmental problems (water quality, chemical use, and biodiversity) among Dutch stakeholders, but little consensus on possible solutions. The differences reflected adherence to an export market and economic growth model compared to the embrace of wholistic visions in agroecology.

Participants in the 5th Global Conference on Climate Smart Agriculture in Indonesia in 2019 also accepted the need for innovation to preserve and improve functioning of agri-food systems in the face of climate change. Already, the theme of Climate Smart Agriculture has attracted significant support, about $56 billion per year, but some scientists argue the focus is on incremental changes of agri-food systems, not transformational changes needed (Dinesh et al 2021).

A convenience survey of 410 participants in the 5th Global Conference in 2019 sought to measure such opinions. Of participants surveyed, 262 replied, and 66 percent of the respondents were research scientists. Collectively, the respondents identified 629 issues needing research. Top priority for the largest group of respondents (34 percent) was "climate-resilient and low emission practices and technologies," a clear indication that climate change was the top priority among those surveyed (Dinesh et al 2021).

Because the conference focused on Climate Smart Agriculture, it's not surprising that climate change preoccupied these respondents. Nevertheless, results indicated that at least a significant contingent of agricultural scientists endorsed this goal as top priority. Moreover, this target for research identically matched one of the eight targets identified a few years earlier as an integral part of a theory of change for agri-food systems (Campbell et al 2018).

But what exactly are the agri-food systems now the focus of global concern and scientific study? Unfortunately, precise definitions of them have not yet stabilized (Hall and Dijkman 2019), which complicates efforts to produce useful innovations. Examples below illustrate different efforts for both textual and diagrammatic definitions.

Textual definitions of agri-food systems: Calls for research to understand and transform the way we produce, distribute, and consume food have stimulated definitions emphasizing the scope of agri-food systems from the farm through to the consumer, and ultimately disposal of waste food and packaging (IPES 2015):

. . .web of actors, processes, and interactions involved in growing, processing, distributing, consuming, and disposing of foods, from the provision of inputs and farmer training, to

product packaging and marketing, to waste recycling. . . .

Hall and Dijkman (2019) characterized agri-food systems as a metaphor encompassing social, environmental and political processes but not emphasizing the continuum of processes from farm to waste disposal:

> *. . . a descriptive metaphor for the interconnected elements of food production and consumption, and the defining social, environmental and political context in which these sit.*

Hall and Dijkman (2019) also pointed to a definition developed by researchers on food systems at the University of Vermont in the United States. This one included health, economics, and scale not included in the above definitions.

> *[A]n interconnected web of activities, resources and people that extends across all domains involved in providing human nourishment and sustaining health, including production, processing, packaging, distribution, marketing, consumption and disposal of food. The organisation of agri-food systems reflects and responds to social, cultural, political, economic, health and environmental conditions and can be identified at multiple scales, from a household kitchen to a city, county, state or nation.*

Diagrammatic definitions of agri-food systems: An approach different from using words to spell out the elements of agri-food systems relies on diagrams. A few of many examples show a range of "agri-food systems images," from simple to elaborate. They differ in the density of ideas, components, processes, scales, and crops portrayed. All diagrams depend upon text to identify components and processes, and to explain their functions. Nevertheless, images can often show relationships among interacting components more clearly and easily than texts.

Perhaps the simplest diagram traces the flow of agricultural products from farm to consumption and disposal of waste (Fi. 1), quite comparable to IPES (2015), quoted above. At the end of the flow, extra illustrations and the legend draw attention to hunger, food insecurity, and food policy, issues not involving the flow of physical agricultural products from production through processing and marketing to consumption and disposal of waste. Absent from Figure 1 are (1) links between hunger/food security and policy and physical flows; (2) inputs of knowledge, water, energy; and (3) any reference to periodic and repeating passage of time. It is also unidirectional with no feed-back loops. Nevertheless, the diagram successfully conveys many of the components and processes that occur between farm and consumer.

Another simple diagram of a food system (Fig. 2) shows four main steps in movement of food from farm to consumption (Sustainable Food Center 2020). The key idea of a repeating cycle appears in the circular arrangement of the components, in which consumption leads around to the starting component, production. Periodicity of flow, typically annual, however, appears only by inference from the perpetual need for food. Icons outside the circle indicate that labor, energy, waste, policy, and climate accompany the cycle, but it's not clear how they relate to the four components. Water appears only indirectly through the icon for climate. Other components, such as inequality-hunger, policy, and knowledge-science do not appear.

Corke and Olewnik (2019) built an elaborate, information-dense diagram (Fig. 3). Primary overlapping and interacting components include Politics-Governance, Socio-cultural, Economics, and Environment, each of which also has sub-components. Like Figure 2, this diagram includes the idea of a cycle, from producers of foods to consumers and back again, but it, too, leaves the reader to infer both periodicity and perpetual functioning. One interesting difference compared to Figures 1 and 2 is the inclusion of aquatic as well as terrestrial sources of food. Also included in Figure 3 are money, water, and energy, plus issues of food security and education-training-expertise.

A final example, Figure 4, includes the idea of past time or history, explained in the text with an example, adoption of synthetic chemical pesticides after 1945. These chemicals required new skills and attitudes among the adopters. As farmers made pesticides a routine part of their production practices and increased yields, other players in the agri-food system also became accustomed to the chemicals, e.g., people involved in processing, marketing, and finance as well

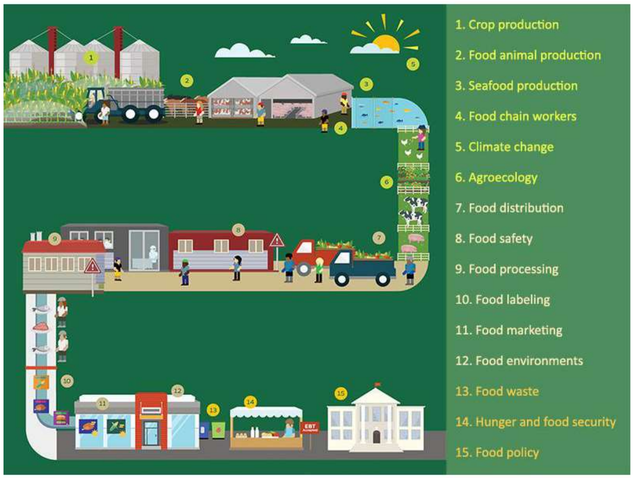


Fig. 1. Definition of an agri-food system by diagraming flow of agricultural production on the farm to consumption and disposal of waste. Hunger/food insecurity and food policy appear at the end of the flow. (Center for a Livable Future, 2022, https://www.foodsystemprimer.org/ the-food-system/, accessed 7 July).

as manufacturers making the chemicals. Consumers, too, became accustomed to cosmetically perfect fruits and vegetables at cheaper prices. Now, to suggest a new set of practices, e.g., integrated pest management (IPM) requires not only farmers learning new skills but also adjustments by other players in the system. In other words, changes in pest control practices involve not just the technology itself but also many other socio-political changes. For these reasons, use of synthetic pesticides persists or is "locked-in," even in the face of resistance to pesticides and previously unknown health hazards (Conti et al 2021, Perkins 1982).

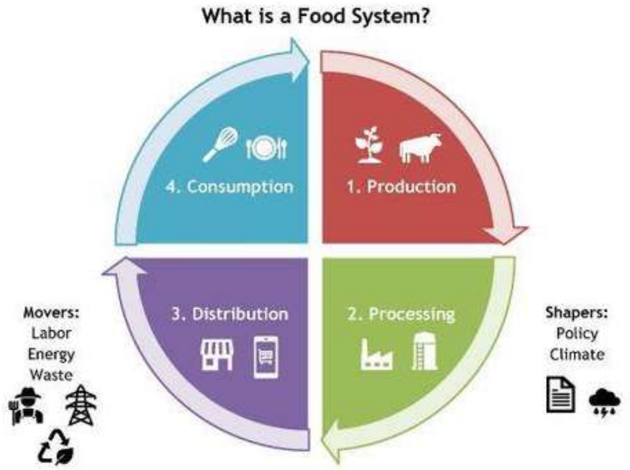
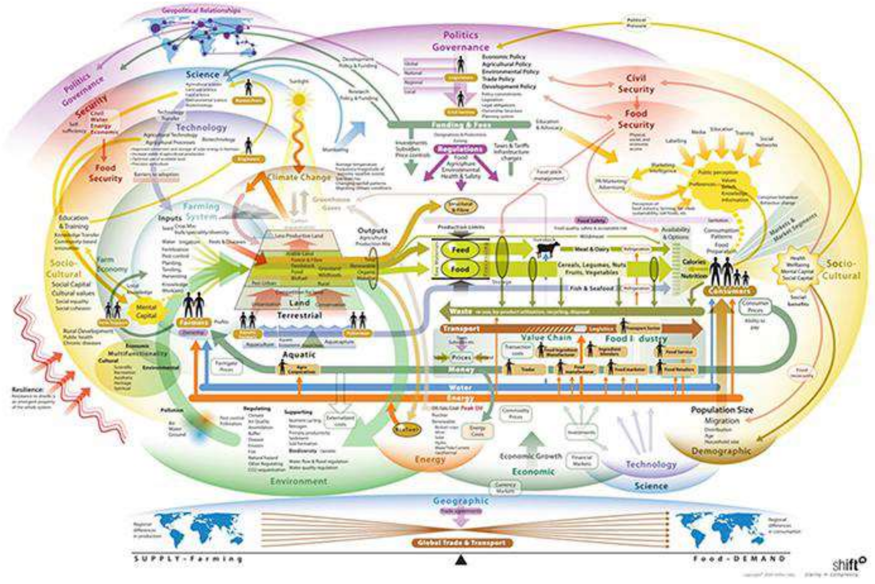


Fig. 2. A simple diagram of a food system showing four main steps in movement of food from farm to consumption. The idea of a repeating cycle appears in the circular arrangement of components surrounded by arrows showing direction of flow. Period of flow, typically annual, however, does not appear. Icons outside the circle indicate that labor, energy, waste, policy, and climate play a role in the cycle. Water appears only indirectly through the icon for climate. Other components, such as inequality-hunger and knowledge-science do not appear (Sustainable Food Center 2020)

A second line of logic from economic history also led to "history matters:" the "treadmill theory" (Cochrane 1979, Global Agriculture 2022). Early adopters of a new technology-if it works-increase yields and thus earn more income. Their peers see the benefits, and they, too, adopt the new practices. When many farmers adopt new practices, however, total yields increase enough to drive prices lower. Early adopters make money, but later adopters don't. Farmers who don't adopt see prices drop while their yields remain the same. Thus, their incomes drop, and many leave agriculture. Early adopters with extra money buy or rent the land of the leavers. The treadmill theory thus explains why farmers must adopt profitable new technology: they are on a treadmill, and not adopting risks financial failure. Abandoning the new technology isn't possible, because it, too, risks financial collapse. The new technology persists, even if turns out to be unsustainable.

Figure 5 depicts a systems science approach to an agri-food definition. Agri-food systems scientists have developed an alternative way of portraying agri-food systems, the Food-



2019 Cereal Foods World *super theme: Global Food System. Source: shiftN*

Fig. 3. An information-dense diagram of a food system (Corke and Olewnik 2019)

Energy-Water nexus (FEW). Systems scientists seek to describe, explain, predict, and manage systems, ". . . a set of things connected in a way that creates some unified whole) (Saundry and Ruddell 2020). Studies of FEW incorporated previous work on the interactions of human and natural systems (Liu, Dietz, Carpenter et al 2007, Saundry 2016).

Saundry and Ruddell (2020 34) defined FEW systems as a ". . . set of sources, movements, uses, and sinks that constitute a way of understanding the unified whole in the context of a particular place and time." Relationships between components could be non-linear, multivariate, and multi-scaler; boundaries of the system could be multifaceted. Where agricultural scientists studied granular connections between components of agri-food systems from farmer to consumer, systems scientists sought to understand interactions among food, energy, and water in food production.

One example of a diagram defining a FEW nexus (Fig. 5) shows four major components: food, energy, water, each affecting each other and interacting with climate change (California Department of Water Resources, 2017, as cited in Saundry and Ruddell 20206). Rather than emphasizing the actors and organizations in the annual production of food and fiber, diagrams drawn from systems science emphasize interactions among natural resources and with driving factors external to the FEW nexus. The figure incorporates water, food, energy, and climate change, but not the power and politics of Figure 3 or historical grounding of Figure 4.

In sum, the verbal and diagrammatic ways of defining agri-food systems complement each other, but neither approach has captured every dimension of these systems.

Agri-Food Systems As An Energy System: A New Perspective

Saul and Perkins (2021) developed a new diagrammatic portrayal of energy systems-the Energy Regulatory and Industrial Complex (ERIC)-to promote better education on climate change. Their argument was that resolution of the risks of climate change required an energy transition from fossil fuels to renewable energy without carbon emissions. The heart of making that transition required changing investment flows away from building and maintaining fossil fuel infrastructure toward infrastructure for renewable energy. Without perpetual streams of investment, no modern energy system can persist.

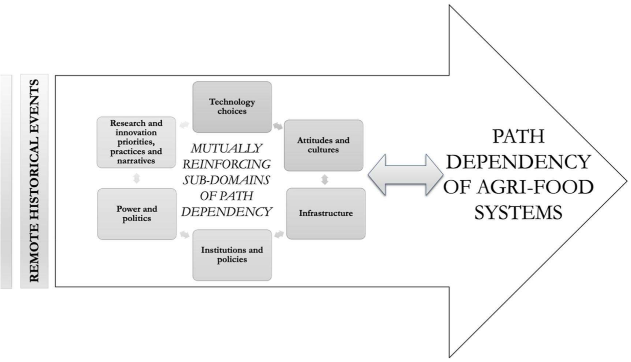


Fig. 4. A food system diagram that includes flow of time and maintains that historical changes affect the operations of current-day systems and the possibilities of changing them (Conti, Zanello and Hall 2021), i.e., "history matters"

A simple change in ERIC transforms it to a portrayal of an agri-food system based on an energy system (ERIC-AFS) (Figure 6). Unlike Figures 1-5, ERIC-AFS emphasizes the production of food and feed to provide an "energy service:" metabolic energy for people and their livestock. Production of food and feed operates cyclically and perpetually if the requisite investment streams persist. As with energy systems in general, transformation of agri-food systems requires redirecting perpetual streams of investment.

Key to this new perspective is recognition that "biomass" is a primary energy source (PES), i.e., one of the nine natural resources that yield energy services. Ordinarily, biomass

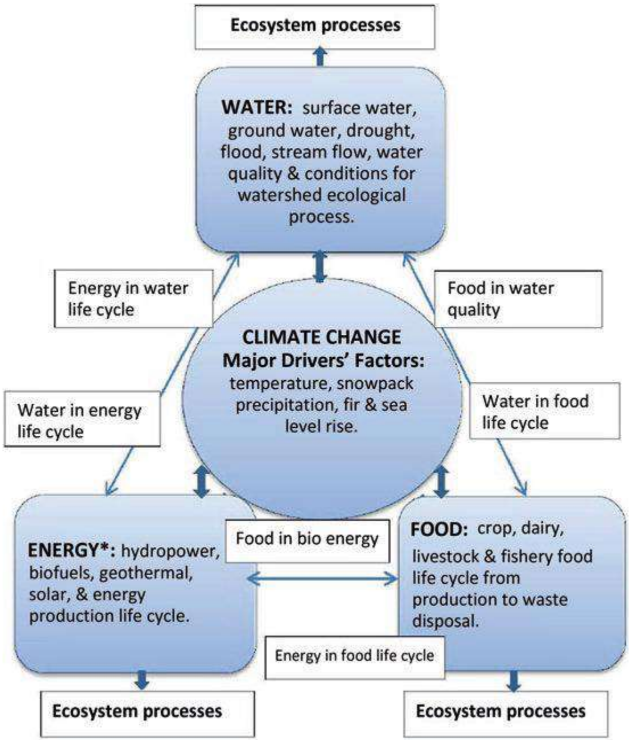


Fig. 5. One example of a diagram to define a FEW nexus emphasizes interactions among food, energy, and water, all affected by climate change. Each of the four major components changes and is changed by its interactions (California Department of Water Resources 2017; found in Saundry and Ruddell 2020)

yields energy when combusted directly (e.g., firewood) or fermented to a fuel before combustion (e.g., grain or sugar cane into ethanol). Food and feed, special forms of biomass, are sources of life-sustaining metabolic energy. Food and feed come from agri-ecosystems, and ERIC-AFS shows "Agriculture" instead of the more generic "biomass" as one of the nine PES (Figure 6).

In Figure 6, energy services produce development/ wealth/money controlled variously by companies, individuals, and governments. Decision making in turn perpetually invests some of this money into Innovation-Building-Maintaining-Operating-Rebuilding infrastructure needed to produce Pes, Fuels, and Energy Services, to again produce Development-Wealth-Money and thus continue the investment cycle.

Climate Change is the inevitable by-product of the world's current energy systems, based on production and use of fossil fuels, which emit the largest share of greenhouse gases. Fossil fuels (coal, oil, natural gas), the most widely used PES, provide about 80 percent of the world's energy services, and historically they created modern societies. These fuels also underlie the creation and operations of high-yielding, energy intensive agriculture, especially through the production of cheap nitrogen fertilizers and powering the harvesting, manufacturing, and transport processes embedded in agri-food systems. Production and use of fossil fuels release the two most important greenhouse gases, CO_2 and CH_4. Warmer temperatures and climate change from fossil fuels have already damaged agricultural yields, due to physiological harm to crops and livestock and to changes in precipitation: more floods and more droughts (Benzer et al 2022). Loss of yield has already damaged human health and ultimately will destroy the benefits from fossil fuels and high-yielding agriculture.

In addition, however, as shown in Figure 6, agriculture itself not only is damaged by climate change but it also contributes to climate change by increasing emissions of three greenhouse gases (N_2O, CO_2, and CH_4). Crippa et al (2021) estimate that agri-food systems, from production to consumption, produce 34 percent of the global emissions of greenhouse gases causing climate change. In other words, energy-intensive agriculture is both cause and victim of climate change.

Dangers to agricultural yields from climate change created the Central Dilemma: if humanity stops using fossil fuels to mitigate climate change, yields decline, and agri-food systems collapse. If fossil fuels continue in use and continue driving climate change, yields also decline and agri-food systems collapse. The Central Dilemma powerfully supports placing agriculture in a diagram of an energy system, clearly illustrating agriculture's role, along with the fossil fuels, as the source of an essential energy service and as a cause of climate change.

ERIC-AFS is a complex diagram and merits a more detailed guide to reading it (Appendix 1). Here, however, we turn to a new definition suggested by ERIC-AFS:

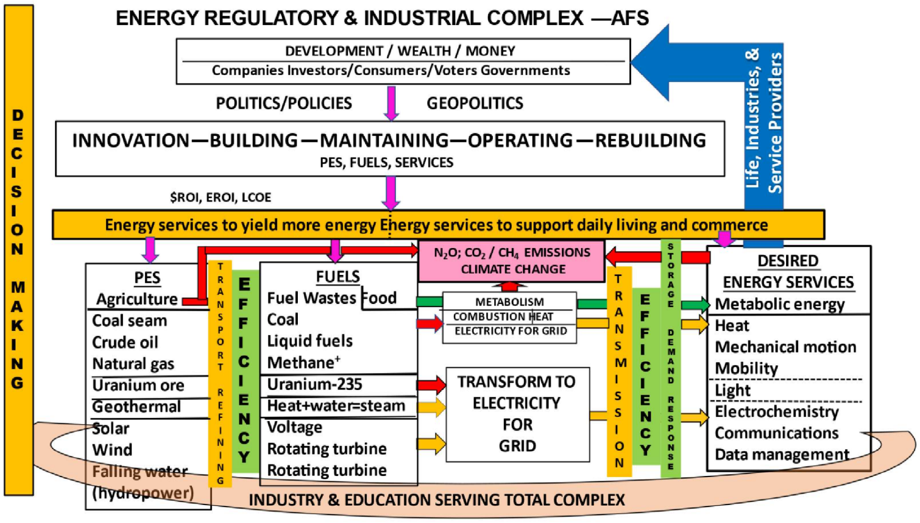


Fig. 6. The Energy Regulatory and Industrial Complex (ERIC) portrays an energy system so as to emphasize the production of the nine primary energy sources, their transformation into fuels, and the provision of energy services. Modified from Saul and Perkins (2021), ERIC-AFS shows a cyclic agri-food system in which metabolic energy services enable human activities in modern societies leading to development and wealth. In a perpetual cycle, some of this wealth must be invested to renew supplies of energy sources, one of which is agriculture, so that food and feed can again support metabolic energy essential to life

Agri-food systems are arrangements of components promoting multiple, perpetual, cyclical flows of physical materials, energy, decisions, and investments, all designed to promote agricultural production of biomass, one of the nine primary energy sources. In turn, harvested biomass undergoes refining, processing, packaging, and transport to produce and deliver food and feed, the fuels providing metabolic energy, existentially important for humans and their livestock. In collaboration with other primary energy sources providing other energy services, food and feed support the continuity of developed economies, which of necessity must allocate a perpetual flow of investments to promote continued agricultural production to provide perpetual flows of food and feed to support metabolic energy.

Discussion

As with each of the earlier textual and diagrammatic definitions of agri-food systems, neither this textual definition nor ERIC-AFS (Figure 6) captures all elements of agri-food systems. Instead, all definitions and diagrams highlight points, which authors choose to emphasize. These are points not made elsewhere or information less visible in other renditions. ERIC-AFS and the definition provide platforms for discussing agri-food systems and their needed changes.

ERIC-AFS and its associated definition emphasize several important points. Figure 6 explicitly indicates a key feature of all agri-food systems: financial investments required to produce food and feed, the fuels providing metabolic energy. Every farmer knows the sacrifice of up-front investments to purchase and plant seeds well before the payoffs of harvest sales. The risk: crop failure and no harvest, a devastating blow, especially if the farmer borrowed money at the outset. In some cases, farmers use pesticides to avoid the risks of damages to their crops, which would endanger their ability to pay debts at the end of the harvest (Perkins 1982). People not in agriculture, especially those in cities who have never seen a farm, can easily forget or underestimate this factor..

Not only are investments cyclic and perpetual for production, they aim carefully at supporting specific production practices. To put innovations into practice, the investment targets must change. For the investment targets to change, decision making by investors must change. Multiple sources currently invest annually in agriculture: individual farmers, banks, governments, and others.

Targeted investments also guide the work of agricultural scientists. Decisions about scientific investments, too, must change and might, therefore, go to different communities of scientists. for example, only 9 percent of those surveyed at the 5th biennial conference of Climate Smart Agriculture, noted earlier, identified “innovative finance to leverage public and private sector investments” as a top priority, the smallest percentage among the five groups identified as top priorities (Dinesh et al 2021). The small percentage of researchers seeing investment as a topic of low priority suggests a need to increase attention to this point. Changing the direction of investments always creates winners and losers. Accordingly, political conflict may arise because of changing investment patterns, and they must be expected.

Despite the low interest respondents had in investments, their interest in climate resilient and low emission practices was the top priority for 34 percent of respondents, essential for addressing the Central Dilemma. The Dilemma calls for two separate lines of research: one to make the systems more resilient to climate change and the other to reduce the emissions of greenhouse gases from the systems. Both avenues will change agri-food systems, some in incremental ways and others more transformational. A complete review of these lines lies far beyond the scope of this paper but consider the following examples from both lines.

To make agri-food systems more resilient to hazards of climate change

- Plant and animal breeding for resistance to heat, drought, floods, and storms
- Architectural and construction changes in farm buildings to resist heat and floods
- Policy changes to improve financing of needed research
- Institutional changes to develop needed research facilities and stimulate coordination among them
- Innovations in climate change education to assist public understanding of vulnerabilities of agri-food systems to climate change, for both urban and rural audiences
- Educational programs for financial industry and their regulators about climate change and agri-food systems

To mitigate emissions of greenhouse gases by agri-food systems

- Electrification of machines and transport serving agri-food systems, based on renewable primary energy sources, not fossil fuels; scales to include utilities, community infrastructure, and on-farm generation
- New methods for synthesis and application of nitrogen fertilizers, to increase efficiency of use, decrease emissions of nitrous oxide, and reduce runoff into waterways
- Synthesis of farm chemicals, steel, cement, and ammonia with low or no emissions of carbon
- Management of soils and agricultural wastes to reduce emissions of N_2O, CO_2, and CH_4

- Educational programs for participants and beneficiaries of agri-food systems about needed changes by companies, work forces, and consumers
- Design of policies for agri-food systems to promote lower emissions of greenhouse gases, for example, by lowering transport during production, processing, and marketing of agricultural goods

ERIC-AFS and the new definition also prompt new insights not usually associated with changes in agrifood systems. For example, seeing agriculture as an energy source indicates the centrality of the energy service, that is, metabolic energy to support human life and livestock. While a farmer will see the value of his or her activities as the harvested material, humanity as a whole values agriculture mostly for its provision of metabolic energy and nutrition. The same is true for all energy sources. For example, a coal miner values the monetary worth of the rock taken from the ground, but humanity doesn't really want coal as a rock. Instead, the value lies in the heat energy when the rock is burned.

This point may seem obvious and trivial, but in fact it carries the most radical ideas for innovation. If ways other than agriculture can produce metabolic energy for people and livestock, then commercial development of such methods may be highly useful innovations. For example, the culture of insects for livestock feed or human food may not be called “agriculture,” but the metabolic energy produced may be highly prized as an energy service (Halloran et al 2018).

Another feature of ERIC-AFS is a clear emphasis on geopolitics as a factor affecting investment decision-making in agriculture. In earlier work (Perkins 1997). I reconstructed the role of geopolitics influencing decisions to support investments in the Green Revolution in South Asia as well as in the United States and the United Kingdom. These factors originated in the conflicts of the Cold War between The United States and the USSR after World War II. More recently, the invasion of Ukraine by the Russian Federation has shown that geopolitical factors can disrupt supply chains associated with agri-food systems (Economist, 2022). Russian naval forces blocked grain shipments from Ukraine to countries in northern Africa, leading to potential food shortages in countries that usually import Ukrainian wheat (Dahir and Peltier 2022).

In addition to the strengths of placing agri-food systems in an energy context, ERIC-AFS and the new definition have gaps leaving important points for supplementary discussions. To keep the diagram simple and the definition concise, essential subsystems are not included. For example, the inputs of agricultural production include steel, cement, chemicals, and water, each of which requires energy to produce and deliver to farmers. Most of this energy currently comes from fossil fuels. An agri-food system, therefore, relies on collaborative combinations of energy sources. Innovators must not forget about the important roles played by other energy sources, and, to mitigate climate change, these other energy sources must be changed from fossil fuels to sources not emitting greenhouse gases.

The diagram and the definition also do not include demography, spatial distributions, social factors, and social institutions. The population size, for example, determines the amount of metabolic energy needed but says nothing about the location of populations. As noted earlier, development of fossil fuels was essential to mechanization of agriculture. And with mechanization came a shift in where people live. Less labor was needed in the countryside, and people left rural areas for the cities. Harvested food that used to travel very short distances to consumers must now travel thousands of kilometers. The harvest must be preserved and transported to deliver metabolic energy to consumers.

Another gap in the diagram and definition lies in the lack of any information about a multitude of social factors, each of which could affect the success of achieving new investment patterns end new deployment of technology in practice. Women farmers compared to men may have more difficult pathways to investments, finance, and expertise. Small holders compared to large landowners may also be at a disadvantage in adopting new practices. Those working to reform agri-food systems must remain highly conscious of the detrimental effects of such inequalities.

Another key element of agri-food systems not directly visible in ERIC-AFS or the textual definition lies in the realm of “history matters.” “Mechanical motion” and “mobility,” energy services powered by fossil fuels, historically replaced animal and human muscles (Cochrane 1979), and a major portion of global warming resulted from greenhouse-gas emissions from engines in agriculture, transport, and industry. Mechanization of agriculture lay behind a profound transition in agri-foods systems. In the United States, for example, the proportion of the American population in agriculture dropped from 34.7% in 1910 to 1.8% in 1995 (Lobao and Meyer 2001). Simply put, machines made it possible for fewer people to do agricultural work, and many people left the countryside for work in industry and services in the cities. Today, fossil fuel powered transport supports both movement of food to urban centers and the supply chains of goods from cities to countryside to serve agriculture.

One additional factor results from the historical movements of people. Political support for innovation in agri-food systems depends partially on urban populations, which now house most people. Out-of-sight causing out-of-mind, however, results in injustices in agriculture that too often escape the notice of city people, who in turn neglect to support needed agricultural reforms. For example, in the United States, farmworkers have been excluded from the Fair Labor Standards Act of 1938; only in 2016 did California pass legislation to ensure farmworkers would receive overtime pay for working more than a standard 40-hour work week. Washington's governor signed similar legislation in 2021; Oregon passed its law in 2022 (AP 2022).

CONCLUSIONS

Climate change poses serious threats to the well-being of people across the globe. It doesn't matter whether they live in the cities of modern societies or whether they practice subsistence agriculture in a less industrialized country. A major part of the threat centers on the effects of a warmer climate on agriculture and agri-food systems. If yields seriously decline, then food insecurity, food shortages, hunger, famine, sickness, and death loom.

First signs of damages to agricultural yields have already occurred due to climate change. If the current level of damages, plus the more serious threats of future damages were not enough, other factors also demand innovations in agrifood systems. Given these pessimistic statements, why should anyone hold optimism for the future? Two major points from this paper, however, provide grounds for cautious optimism.

The concept of agri-food systems as an object for scientific studies has already bolstered seeing the future through an optimistic lens. Many efforts to define and diagram these systems have helped organize and fund needed research. Multiple perspectives found in the different definitions and diagrams emphasize multiple facets, all of which stimulate different useful pathways for innovation.

The value of portraying agri-food systems as part of the global energy system brings out yet more perspectives and components of these systems. Combining the energy lens with the sense that history matters points to the second major conclusion: agricultural scientists working in the traditional agricultural disciplines must pay close attention to the energy connections embedded in modern agri-food systems. They should support efforts to transition away from fossil fuels to renewable energy without carbon emissions. These transition efforts will undoubtedly affect the work and possibilities of traditional agricultural scientists. Evidence already exists that agricultural scientists are keenly aware of climate change and connections to fossil fuel energy. This awareness must translate into supportive agricultural practices that work well with energy from renewable sources.

Appendix 1: Agri-food systems in ERIC-AFS, details of a new perspective

Drawn from Saul and Perkins (2021), ERIC-AFS (Fig. 6) emphasizes investments, a key feature of energy systems they had not seen elsewhere: a perpetual cycle of investments builds, maintains, operates, and rebuilds all energy systems. ERIC-AFS acknowledges the technology and natural resources involved in energy systems and includes social, political, economic, cultural, institutional, and environmental dimensions. Science, technology, and broad political-ecological factors shape “Decision Making” about investments and innovation.

Agri-food systems both use and produce energy, but usually assessments of innovation in these systems don't picture them as energy systems. This paper modifies ERIC by placing Agriculture in the framework as a primary source of energy, ERIC-AFS (Fig. 6). ERIC-AFS depicts a cycle, so one can trace its operation starting at any point. Start with the vertical box on the left, “DECISION MAKING,” the processes upon which innovations and investments in ERIC-AFS depend.

From DECISION MAKING, move to the row of boxes at the bottom of the diagram. In the lower left-hand corner, “PES” (Primary Energy Sources) indicates the nine Primary Energy Sources, all of which originate “naturally,” i.e., without human agency, although humans can, in the case of Agriculture, augment the natural processes. These nine sources are the only energy sources available. Agriculture, more generally called “biomass,” means plant and animal products derived directly and indirectly from photosynthesis. It also includes biomass from forests, managed or unmanaged.

Move right to “Fuels,” materials or processes ready to use for energy and derived from primary energy sources; fuels exist due to human actions. For agriculture, crops can yield fuels directly, e.g., grain can be turned into ethanol for motor vehicles. Similarly, burning wood wastes and paper yields energy as heat and light, and landfills of garbage produce methane, a fuel. Most importantly, only Agriculture yields food and feed for people and livestock.

Primary energy sources and fuels are useful, but the value of energy systems lies in the box at the lower, right-hand side, “Desired Energy Services.” Simply put, people don't really want sources and fuels; instead, they want the services energy performs, usually by using an appropriate machine.

Energy services exist in eight distinct categories, one of which is to provide metabolic energy for people and other animals. Only food as a “fuel” can provide this service; the other eight primary energy sources, plus non-food biomass, cannot directly provide metabolic energy. All nine primary energy sources, however, can power each of the other seven energy services. As presented elsewhere, different fuels have unique profiles of strengths and weaknesses, and certain services generally derive from only one or a few of the primary sources (Perkins 2017). For example, fuels for transport powered by internal combustion engines currently come almost entirely from crude oil refined into diesel or gasoline fuels.

Note the boxes between PES and FUELS and DESIRED ENERGY SERVICES. These capture various human interventions making the progression possible and more efficient, e.g., transport (moving materials) and refining (chemically or physically modifying materials and processes). The most important box is "Transform to electricity for the grid." Electricity is a manufactured energy carrier, also called a secondary energy source. It does not exist in nature, at least not in a useful form, but electricity is preferable for many purposes, e.g., light, which also comes from combustion. For the bottom three listed energy services, electricity is the only source of energy to power electrochemistry, electronic communications, and data management.

The processes of moving from Primary Energy Source to Desired Energy Services cause the box depicting climate change. The two most important greenhouse gases (CO_2, CH_4) come from multiple parts of ERIC, and N_2O comes mainly from Agriculture, along with CO_2 and CH_4. Agriculture emits most nitrous oxide from degradation of nitrogen fertilizers.

Powered by the eight energy services, Life, Industries, and Service Providers-shown in the blue arrow moving up and to the left-create the products and services of modern industrial societies. Plentiful and inexpensive products and services create material prosperity and comfort in developed, wealthy societies. Virtually all modern people relish modernity and have no desire to revert to premodern conditions. Climate change clouds the future, but many remain oblivious to it as they eat and live well.

Many also remain uninformed about the origins of food in developed countries. Agriculture is an industry, courtesy of energy services. Machines, chemicals, and improved varieties yield vast quantities of food to power metabolic processes. With mechanization, very few people produce food and fiber, and transport companies move agricultural products from production on farms to consumption in cities, powered almost entirely by fossil fuels. Many people live far from farmlands, have never been on a farm, have little understanding of agri-food systems, and remain oblivious to the energy that feeds them.

From the Development/ Wealth / Money box, the perpetual investment cycle embedded in ERIC-AFS begins, with decision-points in purple arrows. Decisions-made in a context of politics/policy and geopolitics-direct money flows to innovation and to the endless building-maintaining-operating-rebuilding of energy systems.

Continually, energy industries marshal profits and borrowed funds for investments to produce more primary energy sources and fuels. For example, as oil and gas fields decline, geologists and petroleum engineers must develop new fields. As refineries wear out, companies maintain and replace them. A company making electricity from geothermal heat and steam must maintain existing equipment and replace it when needed. An electric power company using solar panels and wind turbines must buy, install, maintain, operate, and replace worn-out equipment. Farmers, too, must continually maintain, operate, and replace equipment.

In all cases, decision-makers invest "surplus money," i.e., money not needed for immediate consumption but instead used to satisfy future needs. Outside investors, financial industries, and governments also loan, subsidize, or grant money for investments.

Consumers of energy also invest in perpetual cycles, not to produce primary energy sources and `fuels but to produce energy services. They buy, operate, maintain, and replace equipment to stay in business or to live. For example, a citizen using an automobile or air conditioner must buy, operate, maintain, and replace machines, or the energy service disappears.

Investors use their own funds and borrow from financial institutions and governments. Financed by taxes and borrowing, governments provide grants and subsidies. A plethora of politics, laws, and policies surround all investments. More indirectly, each country with investment activity also has geopolitical concerns, and governments in each country shape investment processes to meet geopolitical goals.

Regardless of the source of investment funds, all investors expect a return from the expenditure, either more money, more service benefits, or some political payoff. Returns to companies producing primary energy sources come from selling sources and fuels. Failure to receive expected returns will sour decision-makers on making the same investments again in the future. Most importantly, without perpetual streams of investment, energy systems grind to a halt. Without energy services, modern societies collapse.

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