Meeting Global Challenges with Regenerative Agriculture Producing Food and Energy

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The world currently faces a suite of urgent challenges: environmental degradation, diminished biodiversity, climate change, and persistent poverty and associated injustices. All of these challenges can be addressed to a significant extent through agriculture. A dichotomy expressed as "food versus fuel" has misled thinking and hindered needed action toward building agricultural systems in ways that are regenerative, biodiverse, climate-resilient, equitable, and economically sustainable. Here, we offer examples of agricultural systems that meet the urgent needs while also producing food and energy. We call for refocused conversation and united action toward rapidly deploying such systems across biophysical and socioeconomic settings.

Many people, including policy makers, regard the use of arable land to produce fuels as competing with food production. We believe, however, that "food versus fuel" is a false dichotomy that perpetuates unsustainable systems and misdirects efforts to satisfy pressing human needs for both energy and food.

Here, we call for refocused conversation and united action toward building coupled, regenerative, biodiverse, and climate-resilient food, energy, and wealth production systems. Humankind urgently needs policies that promote ecological intensification, long-term carbon sequestration, markets for ecosystem services, and large-scale, distributed renewable energy production to create wealth, increase equity, and reduce injustice. We provide examples from developed and developing countries that help achieve these aims.

Addressing global challenges at scale

The "food versus fuel" dichotomy is rooted in the idea that food and bioenergy systems always compete for land, labor, infrastructure, and capital [1–3]. Proponents of this idea argue that deploying agriculture for any purpose other than food production results in higher food costs and economic incentives to destroy natural ecosystems. This view remains prevalent in public sentiment and policy despite a decade of advancements demonstrating that ecologically benign and synergistic food and fuel production systems are possible[4–11].

We are presently at an historic moment to change fundamental policies toward promoting coupled, regenerative, biodiverse, and climate-resilient food and energy systems. The sixth report of the Intergovernmental Panel on Climate Change stresses humanity's urgent need to both eliminate dependence on fossil energy and draw carbon dioxide out of the atmosphere[12]. New policies and investments are expected to unfold with the Biden administration's commitment to aggressive actions to curtail the climate crisis (https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-ontackling-the-climate-crisis-at-home-and-abroad) and as a result of the recent United Nations Climate Change Conference (https://unfccc.int/process-and-meetings/conferences/glasgow-climate-change-conference), Food Systems Summit (https://www.un.org/en/food-systems-summit), and Biodiversity Conference (https://www.unep.org/events/conference/un-biodiversity-conference-cop-15). Countries are furthermore uniting to devise policy strategies for the successful expansion of their bioeconomies (http://www.biofutureplatform.org/about).

We urge that the coupled, regenerative food and energy system options discussed in this article play a central role in the conversation at these and other efforts and be incorporated in the resulting policy recommendations. Viable policies and investments are urgently needed to increase ecological intensification and long-term carbon sequestration using approaches such as those detailed in this article. Such policies and investments can enhance food production accompanied by carbon capture and storage through bioenergy coupled with markets for ecosystem services, including reduced greenhouse gas emissions, reduced flooding, and greater nutrient retention, pollination, and biological control of pests.

To move beyond "food versus fuel" as an either/or choice, we focus here on managed farming and grazing operations. We do not advocate for land use dedicated solely to bioenergy production or for large-scale bioenergy monocultures, but rather for integrated, diverse, regenerative food-feed-bioenergy production on lands currently used by humankind. Regenerative systems capture and store large amounts of carbon while also producing food and energy, supporting rural communities, and improving the environment.

Globally, agriculture and grazing take place on nearly five billion hectares (http://www.fao.org/faostat/en/#home). Assuming one percent conversion of solar energy to plant matter, at a global average ground-level solar power of 240 watts per square meter (https://earthobservatory.nasa.gov/features/EnergyBalance), agriculture and grazing lands could potentially capture 106 terawatts of energy in plant matter, or nearly six times total current human power use from all energy carriers (18 terawatts; https://www.theworldcounts.com/stories/current_world_energy_consumption). About four kilowatts of power per capita are required to provide good health, education, and wealth outcomes as measured by the human development index (HDI)[13]. Thus, about one-quarter of the estimated 106 terawatts of potential solar energy capture by plants could help provide decent lives for all eight billion people on the planet.

The regenerative practices we describe here will increase soil carbon, the largest potential store of additional carbon in the biosphere. It is estimated that the world's soils, which have been significantly depleted of soil carbon by historical agricultural and grazing practices, could store an additional 114-242 Pg (114-242 billion tonnes) of carbon, sufficient to reduce atmospheric greenhouse gas levels by 156 parts per million[14]. Indeed, it is difficult to envision practical, effective means of reducing atmospheric carbon dioxide levels that do not involve recarbonizing the world's soils, including cropland soils[15].

Why food and fuel

The false dichotomy of "food versus fuel" has three implications. First, "food versus fuel" is contrary to physical and historical reality[16]. All organisms need to assimilate carbon and energy from the environment to survive. Through most of agricultural history, a significant fraction of land and other farm resources was invested to grow fodder[16,17]. Fodder provided energy for working farm animals that supported food production. In the industrial age, tractors replaced working animals and the required energy has largely come from fossil fuels. With the replacement of draft animals by machinery relying on fossil fuels, demand for traditional farm-based energy resources such as winter crops and perennials in crop rotations largely disappeared[17,18]. Soil and habitat degradation, nutrient loss, and water pollution have ensued[17,19].

Current food and energy systems are predominantly linear[20]. That is, these systems take resources and convert them into wastes, not infrequently at levels that damage the environment and threaten human well-being. Linking bioenergy production with food production helps enable the circular flow of carbon, water, and nutrients. Carbon negative bioenergy offers especially compelling advantages[7,10,21,22]. In fully sustainable systems there is no waste: instead there are cycles of carbon, water, and nutrients that must be intelligently managed[10,23,24].

Bioenergy, when generated appropriately, is inherently coupled within agricultural systems to ensure circularity[10,25,26]. *Scientists, farmers, and policy makers can unite around this fact: food and energy production have been synergistic for millennia, and keeping them closely coupled enables circularity.*

Second, "food versus fuel" focuses on products rather than processes. Decades of research have shown that the primary drivers of food insecurity are distribution problems, poverty, corruption, war and conflict, natural disasters and climate change, rather than shortage of global food production capacity[27–30]. Access to energy is critical because energy consumption supplies the work that creates wealth and can alleviate poverty[31]. Using land for crop, livestock, and energy production can provide basic sustenance and also an energy surplus that can help lift billions of people from poverty[1,32].

A fundamental challenge is that the work of people who produce food is chronically undervalued[33]. Farmers have attempted to reduce costs, and to grow and stabilize their income by pursuing economies of scale, often with negative impacts on farm workers and the environment, and also by diversifying markets[1]. In spite of these efforts, farm revenue is volatile and net income continues to decline with the globalization of economic power and markets[34,35]. The cost-price squeeze of input-intensive agriculture places inexorable downward pressure on net farm income[36]. Meanwhile, income inequality worldwide pits farmers in need of prices that sustain their livelihoods against poor consumers dependent on cheap food[35,37]. The necessary investments in people, improved farming, and grazing systems and increased sustainability will not occur under these conditions[38,39].

In contrast, a fully sustainable system emphasizes equitable access to resources and sustainable livelihoods within agroecosystem cycles of carbon, water, and nutrients[40]. *To move toward greater sustainability, scientists, farmers, and policy makers must also unite around a drive for fairness and equity: more of the value generated through agriculture should be returned to the land and to the people who manage and work on farms and pastoral systems based on grazing.*

Third, the "food versus fuel" dichotomy misses opportunities for improvements. Moving forward, carbon and energy could come from a mix of low, zero, and negative carbon sources. Bioenergy—in its solid, gaseous, and liquid forms—provides dispatchable high-density energy, achieves energy storage without resource-intensive batteries, and confers resilience to overall energy systems[1,25].

While renewable electricity from water, wind, and solar sources should certainly be used where appropriate, bioenergy can be a more efficient option in remote and cold areas. Battery capacity and vehicle range decrease substantially in cold climates. Remote areas are more expensive and difficult to service within electric power grids. Dispatchable low-carbon bioenergy could therefore enable more rapid adoption of intermittent wind and solar energy by better matching energy supply with demand, thereby reducing the required massive investments in and emissions from the production of batteries and other electricity storage systems.

A compelling reason to pursue bioenergy in conjunction with food production is its crucial role in enabling large scale, net negative carbon emissions[4,7,26,41,42]. Whereas other energy sources can be zero emissions, bioenergy can provide negative emissions by harnessing green plants that capture and sequester carbon dioxide[43]. Other compelling reasons to pursue bioenergy include the roles that diverse perennial bioenergy crops can play in regenerating soils, increasing soil organic matter levels, retaining water and nutrients, and supporting biodiversity, especially when thoughtfully integrated into low productivity or environmentally sensitive croplands and grazing lands[44–49].

If we think only in terms of “food versus fuel,” we will overlook the role bioenergy can play in building coupled, regenerative, biodiverse, and climate-resilient food, energy, and wealth production systems. *Scientists, farmers, and policy makers can unite around the need to improve food and energy systems to provide multiple benefits: fossil energy (and the extraction and exhaustion of ancient water and nutrient sources) must be replaced with renewable sources of energy and nutrients that can underpin sustainable economies and more widespread prosperity, reduce waste, promote resilience, sequester carbon and regenerate soils, retain water and nutrients, and support biodiversity.*

Pathways forward

Transformative agricultural systems already exist, and they can be adapted to diverse situations and then improved and scaled to large regions (see figure). An inspiring example of how food, energy, and wealth production can be coupled comes from a group of more than 700 Italian farmers organized as the Italian Biogas Consortium. These farmers make more efficient use of sunlight, cropland, nutrients, carbon, water, labor, and equipment[4,9]. Food production continues as before during the regular growing season. However, these farmers now use ecological intensification[50], including growing additional crops during periods when cropland would otherwise be left unplanted. These double crops capture more sunlight, carbon, and rainfall and improve the cycling of carbon, water, and nutrients[4]. On-farm anaerobic digesters convert double crops and what would otherwise be organic wastes into valuable energy carriers, including biogas (a mixture of methane and carbon dioxide), electricity, and/or biomethane.

Farmers in the consortium return digestate, the unconverted residue from the anaerobic digestion process, to their fields as a valuable soil amendment. Digestate contains much of the nitrogen, phosphorus, and potassium required to grow crops and thus displaces most fertilizer inputs[51]. Biologically stable compounds in digestate also sequester and store carbon in soils, thereby improving soil health, including aeration and water and nutrient-holding capacity, thereby enhancing crop productivity, resilience to extreme weather, and farm value. Farm finances are improved through energy sales, using some bioenergy on-farm, and reduced fertilizer costs[9]. Farm labor, land, and equipment are more efficiently utilized by being spread across additional farming activities[4].

Societally, the system helps guarantee food production and improves air and water quality through soil regeneration, year-round vegetative cover, and retention of more nutrients on-farm. These regenerative agricultural practices also help farms reduce and mitigate climate change by reducing greenhouse gas emissions and providing extensive carbon storage in soils[4]. When combined with solids-liquid separation systems, anaerobic digestion can further reduce greenhouse gas and also ammonia emissions[52], which have substantial negative impacts on human health[53]. To further improve the climate benefits of this approach, carbon dioxide generated from on-farm anaerobic digesters could be captured and piped or shipped to locations with viable reservoirs for geologic carbon sequestration[54].

Two catalysts were crucial in building this coupled, regenerative, and climate-resilient food and energy system. First, these Italian farmers faced an existential challenge to find new ways to cut costs and access new markets. Second, a 2012 change in Italian national energy policy used feed-in tariffs to increase the portion of renewable energy in its electricity sector, providing guaranteed markets for farm-generated electricity.

Creativity, collaboration, information, time, and diversification enabled by a stable market for farm-produced energy were essential in developing the current Italian biogas system. Markets for ecosystem services generated on these bioenergy-producing farms—including improved air quality, water quality, and carbon sequestration—could further improve the financial proposition associated with the Italian biogas model and thus speed its adaptation and adoption elsewhere to the benefit of farmers, ranchers, society, and the environment.

The integration of crop, livestock, and biogas production is not limited to agricultural systems in developed countries. Preston[6] described how farmers and private-sector institutions in the Cauca Valley of Colombia established a technology development and transfer program to make better use of residues and byproducts from local crops and trees to feed monogastric and ruminant livestock, poultry, and fish; to generate biogas from animal excreta as an on-farm energy source; and to recycle the digestate materials as productivity-enhancing soil amendments. The diverse, multi-species system developed in this region enhanced solar energy capture, minimized requirements for purchased inputs, increased local protein production, reduced methane emissions per kilogram of carcass meat, and proved technically and economically feasible.

Variations on these systems are employed by farmers all over the world [5,7,8,10,21], and could be adapted, improved, and expanded to provide more value to society. Importantly, through ecological intensification, bioenergy supports food systems in these examples, and competition among food and fuel systems is avoided. Food production continues as previously, but the added bioenergy system improves resource utilization and contributes to farm sustainability. Increasing soil carbon by digestate recycling and cover cropping enhances food production potential by increasing soil quality. These systems also address the globally-urgent need to reduce methane emissions from agriculture[55].

The incorporation of crop diversity within agricultural systems, particularly through inclusion of perennial grasslands and agroforestry systems, enables biodiversity conservation in conjunction with ecological intensification and long-term carbon sequestration on farms[26,47,56]. Expansion of coupled food-bioenergy systems is especially needed to improve the productivity and carbon sequestration of rangelands, the globally dominant form of land use by humankind, covering roughly 4 billion hectares[57]. Soil degradation is commonplace in the world's rangelands[58].

Focused research and development are needed to better understand, then design, build, and test different regenerative food and energy systems suitable for diverse locations, from intensively-managed croplands characteristic of the global North to the less-managed, extensive grazing operations characteristic of the global South. In addition, research is needed to improve crop integration, increase energy conversion efficiency of heterogeneous feedstock mixtures, further reduce greenhouse gas emissions, and more fully quantify changes in ecosystem services and effects on livelihoods. Such work should be complemented with examination of the most effective policy options for implementing diverse food and energy systems.

Policies for regenerative food and energy

Bioenergy systems deployed across the world's 5 billion hectares of farming and grazing operations can potentially supply enough widely-distributed energy to underpin sustainable, more just economies while also providing negative emissions at a scale that meaningfully addresses the climate crisis[26].

Policies that encourage shifts beyond *sustainable* toward *regenerative* food and energy systems are needed to support food production over the long-term while addressing climate change and other forms of environmental degradation. Regenerative systems capture and store carbon while also producing food and energy, supporting rural communities, and improving the environment. Regenerative agriculture is imperative for addressing the persistent challenge of food insecurity, as several of its key drivers—poverty, war and conflict, and natural disasters—are expected to worsen with climate change[27,59].

Unfortunately, effective policies supporting food and pastoral systems that return value to those who farm and/or graze animals are currently in short supply[1]. Farmers worldwide face an existential challenge. Food systems alone often do not return enough value to farmers to enable them to continue farming[33,36], let alone support a good life or invest in transitions toward regenerative farming systems[39].

We cannot expect coupled, regenerative, biodiverse, and climate-resilient food and energy systems to emerge spontaneously if farmers and those who graze animals are capital-starved, at least not without high risk to the environment and the social fabric of rural communities[60]. A key issue for policy development will therefore be to provide the needed capital for farm-level investments in regenerative food and energy production systems suitable for diverse situations and communities.

We offer two general policy suggestions. First, in the developed world, the Italian model might serve as a policy framework in many regions. The Italian model incentivizes farm-level bioenergy production by providing guaranteed markets with stable long-term prices for the energy. Double cropping and digestate recycling drive the recarbonization and regeneration of soils. Additional farm level income might be generated through payment for environmental services. Local capital markets should provide the needed financing using these guaranteed energy and/or environmental service markets as security.

Second, in the less-developed world, the situation is often different. Local capital markets may not be available. Therefore, socially just and effective policies that respect local cultures and environments must be different from those in the global North [1,2]. Policies that undermine indigenous rights or protected areas do not meet the need for fairness and for returning more of the value from agriculture and pastoral activities to people and the land.

Public and private policy approaches for the less-developed world should promote grants, low-interest or forgivable loans, and technical assistance to low-resource communities to enhance their capacity to: 1) institute regenerative food and energy systems, including grazing operations, 2) develop training for broad scale implementation of effective regenerative practices, and 3) ensure proper oversight and accountability. Community control of the land system must be assured, while also recognizing that communities will change over time. Local use of the energy (e.g., fuelwood, biogas, bioethanol, biodiesel) and food produced would be prioritized. Each community would decide how much of its surplus food and bioenergy would be exported.

Many other policies might be developed for both the global North and global South. In all cases, however, the objectives of the policies would be the same: 1) provide the capital necessary to implement bioenergy coupled with regenerative agricultural and pastoral practices suitable for local social and economic conditions and 2) increase the wealth of rural communities and thereby reduce the injustices associated with unequal wealth distribution.

Agriculture's value to society can be much greater by integrating food *and* fuel production. Ongoing scientific investigations and refinements in farming practice demonstrate that better food and bioenergy systems are possible. The relevant discussion is how to intelligently and rapidly expand fully coupled, regenerative, biodiverse, and climate-resilient food, energy, and wealth production systems for the present and the future.

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Author contributions

L.A.S. and B.D. conceptualized and wrote the original draft. All authors contributed to writing and editing subsequent drafts.

Competing interests

The authors declare no competing interests.

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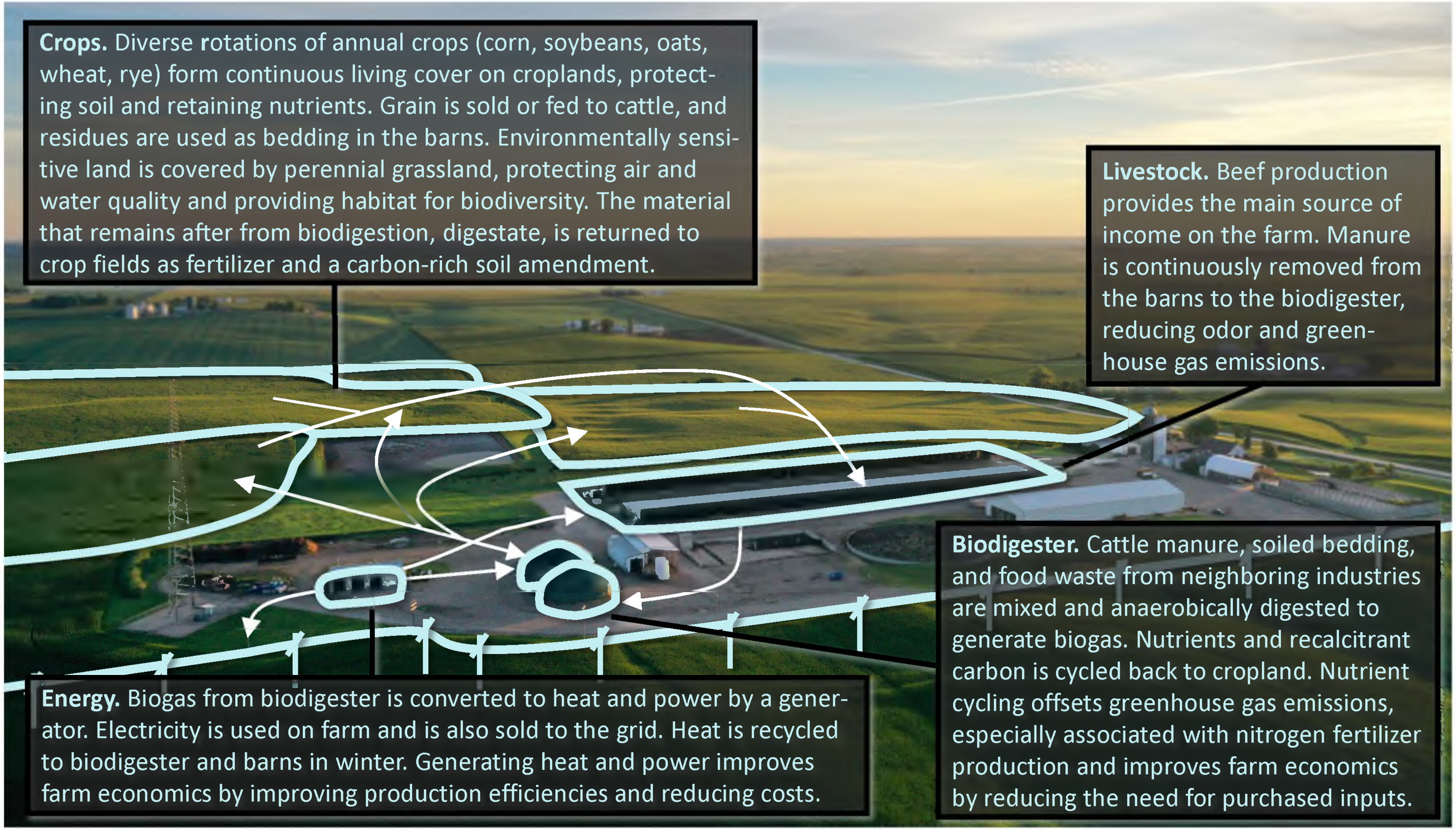
Figure Legend

Fig. 1 | Diverse, coupled, circular food and energy systems provide more value to society. Fully coupled, circular food and energy systems—such as in the farm shown—offer substantially more benefit to society than decoupled systems, and could enable large scale, net negative carbon emissions if combined with carbon capture and storage. The farm shown produces corn, soybeans, oats, wheat, rye, beef, and electricity with negative carbon emissions[7]. Ecosystem services in terms of lower greenhouse gas emissions, higher soil carbon storage, improved water quality, and habitat for biodiversity are not currently compensated. The carbon balance could be strongly negative if biogas, an intermediate product on this farm, was upgraded to biomethane and the carbon dioxide byproduct was captured and sequestered. Such farms are models that can be refined and expanded through policies designed to promote ecological intensification, long-term carbon sequestration, bioenergy carbon capture and storage, and markets for ecosystem services. Photo by Omar de Kok-Mercado, Iowa State University.


Crops. Diverse rotations of annual crops (corn, soybeans, oats, wheat, rye) form continuous living cover on croplands, protecting soil and retaining nutrients. Grain is sold or fed to cattle, and residues are used as bedding in the barns. Environmentally sensitive land is covered by perennial grassland, protecting air and water quality and providing habitat for biodiversity. The material that remains after from biodigestion, digestate, is returned to crop fields as fertilizer and a carbon-rich soil amendment.
Livestock. Beef production provides the main source of income on the farm. Manure is continuously removed from the barns to the biodigester, reducing odor and greenhouse gas emissions.
Biodigester. Cattle manure, soiled bedding, and food waste from neighboring industries are mixed and anaerobically digested to generate biogas. Nutrients and recalcitrant carbon is cycled back to cropland. Nutrient cycling offsets greenhouse gas emissions, especially associated with nitrogen fertilizer production and improves farm economics by reducing the need for purchased inputs.
Energy. Biogas from biodigester is converted to heat and power by a generator. Electricity is used on farm and is also sold to the grid. Heat is recycled to biodigester and barns in winter. Generating heat and power improves farm economics by improving production efficiencies and reducing costs.