

Meeting Global Challenges with Regenerative Agriculture Producing Food and Energy

Lisa A. Schulte^{1,*}, Bruce E. Dale², Stefano Bozzetto³, Matt Liebman⁴, Glaucia M. Souza⁵, Nick Haddad⁶, Tom L. Richard⁷, Bruno Basso⁸, Robert C. Brown⁹, Jorge A. Hilbert¹⁰, J. Gordon Arbuckle¹¹

¹Department of Natural Resource Ecology and Management and Bioeconomy Institute, Iowa State University, Ames, IA, USA (ORCID: 0000-0003-4433-5008).

²Department of Chemical Engineering and Materials Science, Michigan State University, Lansing, MI, USA (ORCID: 0000-0002-6120-7406).

³Biogas Refinery Development srl, Cittadella, Italy.

⁴Department of Agronomy, Iowa State University, Ames, IA, USA (ORCID: 0000-0001-6193-3849).

⁵Instituto de Química, Universidade de São Paulo, Brazil.

⁶Kellogg Biological Station and Department of Integrative Biology, Michigan State University, Hickory Corners, MI, USA (ORCID: 0000-0002-1591-9322).

⁷Department of Agricultural and Biological Engineering and Institutes of Energy and the Environment, Penn State University, State College, PA, USA (ORCID: 0000-0002-0833-4844).

⁸Department of Earth and Environmental Sciences and Kellogg Biological Station, Michigan State University, Lansing, MI, USA (0000-0003-2090-4616).

⁹Department of Mechanical Engineering and Bioeconomy Institute, Iowa State University, Ames, IA, USA.

¹⁰Ingeniería Rural Centro, Investigación Agroindustria, INTA, Argentina (ORCID: 0000-0003-2683-3310).

¹¹Department of Sociology, Iowa State University, Ames, IA, USA (ORCID: 0000-0001-9419-4624).

*Corresponding author email: lschulte@iastate.edu

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

36
37 Many people, including policy makers, regard the use of arable land to produce fuels as
38 competing with food production. We believe, however, that “food versus fuel” is a false
39 dichotomy that perpetuates unsustainable systems and misdirects efforts to satisfy pressing
40 human needs for both energy and food.

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

47 **Addressing global challenges at scale**

48 The “food versus fuel” dichotomy is rooted in the idea that food and bioenergy systems always
49 compete for land, labor, infrastructure, and capital ¹⁻³. Proponents of this idea argue that
50 deploying agriculture for any purpose other than food production results in higher food costs
51 and economic incentives to destroy natural ecosystems. This view remains prevalent in public
52 sentiment and policy despite a decade of advancements demonstrating that ecologically benign
53 and synergistic food and fuel production systems are possible⁴⁻¹¹.

54 We are presently at an historic moment to change fundamental policies toward promoting
55 coupled, regenerative, biodiverse, and climate-resilient food and energy systems. The sixth
56 report of the Intergovernmental Panel on Climate Change stresses humanity’s urgent need to
57 both eliminate dependence on fossil energy and draw carbon dioxide out of the atmosphere¹².
58 New policies and investments are expected to unfold with the Biden administration’s
59 commitment to aggressive actions to curtail the climate crisis

60 (<https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad>) and as a result of the recent United
61 Nations Climate Change Conference (<https://unfccc.int/process-and-meetings/conferences/glasgow-climate-change-conference>), Food Systems Summit
62 (<https://www.un.org/en/food-systems-summit>), and Biodiversity Conference
63 (<https://www.unep.org/events/conference/un-biodiversity-conference-cop-15>). Countries are
64 furthermore uniting to devise policy strategies for the successful expansion of their
65 bioeconomies (<http://www.biofutureplatform.org/about>).

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

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

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

93 The regenerative practices we describe here will increase soil carbon, the largest potential store
94 of additional carbon in the biosphere. It is estimated that the world's soils, which have been
95 significantly depleted of soil carbon by historical agricultural and grazing practices, could store
96 an additional 114-242 Pg (114-242 billion tonnes) of carbon, sufficient to reduce atmospheric
97 greenhouse gas levels by 156 parts per million¹⁴. Indeed, it is difficult to envision practical,
98 effective means of reducing atmospheric carbon dioxide levels that do not involve
99 recarbonizing the world's soils, including cropland soils¹⁵.

100 **Why food and fuel**

101 The false dichotomy of "food versus fuel" has three implications. First, "food versus fuel" is
102 contrary to physical and historical reality¹⁶. All organisms need to assimilate carbon and energy
103 from the environment to survive. Through most of agricultural history, a significant fraction of
104 land and other farm resources was invested to grow fodder^{16,17}. Fodder provided energy for
105 working farm animals that supported food production. In the industrial age, tractors replaced
106 working animals and the required energy has largely come from fossil fuels. With the
107 replacement of draft animals by machinery relying on fossil fuels, demand for traditional farm-
108 based energy resources such as winter crops and perennials in crop rotations largely

109 disappeared^{17,18}. Soil and habitat degradation, nutrient loss, and water pollution have
110 ensued^{17,19}.

111 Current food and energy systems are predominantly linear²⁰. That is, these systems take
112 resources and convert them into wastes, not infrequently at levels that damage the
113 environment and threaten human well-being. Linking bioenergy production with food
114 production helps enable the circular flow of carbon, water, and nutrients. Carbon negative
115 bioenergy offers especially compelling advantages^{7,10,21,22}. In fully sustainable systems there is
116 no waste: instead there are cycles of carbon, water, and nutrients that must be intelligently
117 managed^{10,23,24}.

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

122 Second, “food versus fuel” focuses on products rather than processes. Decades of research
123 have shown that the primary drivers of food insecurity are distribution problems, poverty,
124 corruption, war and conflict, natural disasters and climate change, rather than shortage of
125 global food production capacity²⁷⁻³⁰. Access to energy is critical because energy consumption
126 supplies the work that creates wealth and can alleviate poverty³¹. Using land for crop, livestock,
127 and energy production can provide basic sustenance and also an energy surplus that can help
128 lift billions of people from poverty^{1,32}.

129 A fundamental challenge is that the work of people who produce food is chronically
130 undervalued³³. Farmers have attempted to reduce costs, and to grow and stabilize their income
131 by pursuing economies of scale, often with negative impacts on farm workers and the
132 environment, and also by diversifying markets¹. In spite of these efforts, farm revenue is
133 volatile and net income continues to decline with the globalization of economic power and
134 markets^{34,35}. The cost-price squeeze of input-intensive agriculture places inexorable downward
135 pressure on net farm income³⁶. Meanwhile, income inequality worldwide pits farmers in need
136 of prices that sustain their livelihoods against poor consumers dependent on cheap food^{35,37}.
137 The necessary investments in people, improved farming, and grazing systems and increased
138 sustainability will not occur under these conditions^{38,39}.

139 In contrast, a fully sustainable system emphasizes equitable access to resources and sustainable
140 livelihoods within agroecosystem cycles of carbon, water, and nutrients⁴⁰. *To move toward
141 greater sustainability, scientists, farmers, and policy makers must also unite around a drive for
142 fairness and equity: more of the value generated through agriculture should be returned to the
143 land and to the people who manage and work on farms and pastoral systems based on grazing.*

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

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

157 A compelling reason to pursue bioenergy in conjunction with food production is its crucial role
158 in enabling large scale, net negative carbon emissions^{4,7,26,41,42}. Whereas other energy sources
159 can be zero emissions, bioenergy can provide negative emissions by harnessing green plants
160 that capture and sequester carbon dioxide⁴³. Other compelling reasons to pursue bioenergy
161 include the roles that diverse perennial bioenergy crops can play in regenerating soils,
162 increasing soil organic matter levels, retaining water and nutrients, and supporting biodiversity,
163 especially when thoughtfully integrated into low productivity or environmentally sensitive
164 croplands and grazing lands^{44–49}.

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

173 **Pathways forward**

174 Transformative agricultural systems already exist, and they can be adapted to diverse situations
175 and then improved and scaled to large regions (see figure). An inspiring example of how food,
176 energy, and wealth production can be coupled comes from a group of more than 700 Italian
177 farmers organized as the Italian Biogas Consortium. These farmers make more efficient use of
178 sunlight, cropland, nutrients, carbon, water, labor, and equipment^{4,9}. Food production
179 continues as before during the regular growing season. However, these farmers now use
180 ecological intensification⁵⁰, including growing additional crops during periods when cropland
181 would otherwise be left unplanted. These double crops capture more sunlight, carbon, and
182 rainfall and improve the cycling of carbon, water, and nutrients⁴. On-farm anaerobic digesters
183 convert double crops and what would otherwise be organic wastes into valuable energy
184 carriers, including biogas (a mixture of methane and carbon dioxide), electricity, and/or
185 biomethane.

186 Farmers in the consortium return digestate, the unconverted residue from the anaerobic
187 digestion process, to their fields as a valuable soil amendment. Digestate contains much of the
188 nitrogen, phosphorus, and potassium required to grow crops and thus displaces most fertilizer
189 inputs⁵¹. Biologically stable compounds in digestate also sequester and store carbon in soils,
190 thereby improving soil health, including aeration and water and nutrient-holding capacity,

191 thereby enhancing crop productivity, resilience to extreme weather, and farm value. Farm
192 finances are improved through energy sales, using some bioenergy on-farm, and reduced
193 fertilizer costs⁹. Farm labor, land, and equipment are more efficiently utilized by being spread
194 across additional farming activities⁴.

195 Societally, the system helps guarantee food production and improves air and water quality
196 through soil regeneration, year-round vegetative cover, and retention of more nutrients on-
197 farm. These regenerative agricultural practices also help farms reduce and mitigate climate
198 change by reducing greenhouse gas emissions and providing extensive carbon storage in soils⁴.
199 When combined with solids-liquid separation systems, anaerobic digestion can further reduce
200 greenhouse gas and also ammonia emissions⁵², which have substantial negative impacts on
201 human health⁵³. To further improve the climate benefits of this approach, carbon dioxide
202 generated from on-farm anaerobic digesters could be captured and piped or shipped to
203 locations with viable reservoirs for geologic carbon sequestration⁵⁴.

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

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

215 The integration of crop, livestock, and biogas production is not limited to agricultural systems in
216 developed countries. Preston⁶ described how farmers and private-sector institutions in the
217 Cauca Valley of Colombia established a technology development and transfer program to make
218 better use of residues and byproducts from local crops and trees to feed monogastric and
219 ruminant livestock, poultry, and fish; to generate biogas from animal excreta as an on-farm
220 energy source; and to recycle the digestate materials as productivity-enhancing soil
221 amendments. The diverse, multi-species system developed in this region enhanced solar energy
222 capture, minimized requirements for purchased inputs, increased local protein production,
223 reduced methane emissions per kilogram of carcass meat, and proved technically and
224 economically feasible.

225 Variations on these systems are employed by farmers all over the world^{5,7,8,10,21}, and could be
226 adapted, improved, and expanded to provide more value to society. Importantly, through
227 ecological intensification, bioenergy supports food systems in these examples, and competition
228 among food and fuel systems is avoided. Food production continues as previously, but the
229 added bioenergy system improves resource utilization and contributes to farm sustainability.
230 Increasing soil carbon by digestate recycling and cover cropping enhances food production
231 potential by increasing soil quality. These systems also address the globally-urgent need to
232 reduce methane emissions from agriculture⁵⁵.

233 The incorporation of crop diversity within agricultural systems, particularly through inclusion of
234 perennial grasslands and agroforestry systems, enables biodiversity conservation in conjunction
235 with ecological intensification and long-term carbon sequestration on farms^{26,47,56}. Expansion of
236 coupled food-bioenergy systems is especially needed to improve the productivity and carbon
237 sequestration of rangelands, the globally dominant form of land use by humankind, covering
238 roughly 4 billion hectares⁵⁷. Soil degradation is commonplace in the world's rangelands⁵⁸.

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

248 **Policies for regenerative food and energy**

249 Bioenergy systems deployed across the world's 5 billion hectares of farming and grazing
250 operations can potentially supply enough widely-distributed energy to underpin sustainable,
251 more just economies while also providing negative emissions at a scale that meaningfully
252 addresses the climate crisis²⁶.

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

260 Unfortunately, effective policies supporting food and pastoral systems that return value to
261 those who farm and/or graze animals are currently in short supply¹. Farmers worldwide face an
262 existential challenge. Food systems alone often do not return enough value to farmers to
263 enable them to continue farming^{33,36}, let alone support a good life or invest in transitions
264 toward regenerative farming systems³⁹.

265 We cannot expect coupled, regenerative, biodiverse, and climate-resilient food and energy
266 systems to emerge spontaneously if farmers and those who graze animals are capital-starved,
267 at least not without high risk to the environment and the social fabric of rural communities⁶⁰. A
268 key issue for policy development will therefore be to provide the needed capital for farm-level
269 investments in regenerative food and energy production systems suitable for diverse situations
270 and communities.

271 We offer two general policy suggestions. First, in the developed world, the Italian model might
272 serve as a policy framework in many regions. The Italian model incentivizes farm-level
273 bioenergy production by providing guaranteed markets with stable long-term prices for the

274 energy. Double cropping and digestate recycling drive the recarbonization and regeneration of
275 soils. Additional farm level income might be generated through payment for environmental
276 services. Local capital markets should provide the needed financing using these guaranteed
277 energy and/or environmental service markets as security.

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

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

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

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

302 **References**

- 303 1. Kline, K. L. *et al.* Reconciling food security and bioenergy: priorities for action. *GCB
304 Bioenergy* **9**, 557–576 (2017).
- 305 2. Rosegrant, M. W. & Msangi, S. Consensus and contention in the food-versus-fuel debate.
306 *Annu. Rev. Environ. Resour.* **39**, (2014).
- 307 3. Tomei, J. & Helliwell, R. Food versus fuel? Going beyond biofuels. *Land use policy* **56**,
308 320–326 (2016).
- 309 4. Valli, L. *et al.* Greenhouse gas emissions of electricity and biomethane produced using
310 the Biogasdoneright™ system: four case studies from Italy. *Biofuels, Bioprod. Biorefining*
311 **11**, 847–860 (2017).
- 312 5. Al Mamun, S., Nasrat, F. & Debi, M. R. Integrated farming system: prospects in

350 21. Zhu, T., Curtis, J. & Clancy, M. Promoting agricultural biogas and biomethane production:
351 Lessons from cross-country studies. *Renew. Sustain. Energy Rev.* **114**, 109332 (2019).

352 22. Basso, B., Jones, J. W., Antle, J., Martinez-Feria, R. A. & Verma, B. Enabling circularity in
353 grain production systems with novel technologies and policy. *Agric. Syst.* **193**, 103244
354 (2021).

355 23. Corona, B., Shen, L., Reike, D., Carreón, J. R. & Worrell, E. Towards sustainable
356 development through the circular economy—A review and critical assessment on current
357 circularity metrics. *Resour. Conserv. Recycl.* **151**, 104498 (2019).

358 24. Jones, J., Verma, B., Basso, B., Mohtar, R. & Matlock, M. Transforming food and
359 agriculture to circular systems: a perspective for 2050. *Resour. Mag.* **28**, 7–9 (2021).

360 25. Souza, G. M. *et al.* The role of bioenergy in a climate-changing world. *Environ. Dev.* **23**,
361 57–64 (2017).

362 26. Gelfand, I. *et al.* Empirical evidence for the potential climate benefits of decarbonizing
363 light vehicle transport in the US with bioenergy from purpose-grown biomass with and
364 without BECCS. *Environ. Sci. Technol.* **54**, 2961–2974 (2020).

365 27. Pawlak, K. & Kołodziejczak, M. The role of agriculture in ensuring food security in
366 developing countries: Considerations in the context of the problem of sustainable food
367 production. *Sustainability* **12**, 5488 (2020).

368 28. Thurow, R. & Kilman, S. *Enough: why the world's poorest starve in an age of plenty*.
369 (PublicAffairs, 2009).

370 29. Godfray, H., Beddington, J., Crute, I. & Haddad, L. Food security: the challenge of feeding
371 9 billion people. (2010).

372 30. Allee, A., Lynd, L. R. & Vaze, V. Cross-national analysis of food security drivers: comparing
373 results based on the Food Insecurity Experience Scale and Global Food Security Index.
374 *Food Secur.* 1–17 (2021).

375 31. Nordhaus, T., Shaiyra, D. & Trebbath, A. *Energy for human development*. (2016).

376 32. Lee, C.-C. Energy consumption and GDP in developing countries: a cointegrated panel
377 analysis. *Energy Econ.* **27**, 415–427 (2005).

378 33. Aksoy, M. A. & Beghin, J. C. *Global agricultural trade and developing countries*. (World
379 Bank Publications, 2004).

380 34. Howard, P. H. *Concentration and power in the food system: who controls what we eat?*
381 vol. 3 (Bloomsbury Publishing, 2016).

382 35. Naylor, R. & Falcon, W. Food security in an era of economic volatility. *Popul. Dev. Rev.* **36**,
383 693–723 (2010).

384 36. der Ploeg, J. D. *et al.* The economic potential of agroecology: Empirical evidence from
385 Europe. *J. Rural Stud.* **71**, 46–61 (2019).

386 37. Shattuck, A., Schiavoni, C. M. & VanGelder, Z. Translating the politics of food sovereignty:

387 Digging into contradictions, uncovering new dimensions. *Globalizations* **12**, 421–433
388 (2015).

389 38. FAO [Food and Agriculture Organization of the United Nations]. *The state of food and*
390 *agriculture: social protection and agriculture – breaking the cycle of rural poverty.*
391 <http://www.fao.org/documents/card/en/c/ab825d80-c277-4f12-be11-fb4b384cee35/>
392 (2015).

393 39. Fairbairn, M. *et al.* Introduction: new directions in agrarian political economy. *J. Peasant*
394 *Stud.* **41**, 653–666 (2014).

395 40. Gliessman, S. Transforming food systems with agroecology. *Agroecol. Sustain. Food Syst.*
396 **40**, 187–189 (2016).

397 41. Yang, Y. & Tilman, D. Soil and root carbon storage is key to climate benefits of bioenergy
398 crops. *Biofuel Res. J.* **7**, 1143–1148 (2020).

399 42. Northrup, D.L., Basso, B., Wang, M.Q., Morgan, C.L.S., Benfey, P. N. Novel technologies
400 for emission reduction complement conservation agriculture to achieve negative
401 emissions rrom row crop production. *Proc. Natl. Acad. Sci.* **118**, e2022666118 (2021).

402 43. Terrer, C. *et al.* A trade-off between plant and soil carbon storage under elevated CO₂.
403 *Nature* **591**, 599–603 (2021).

404 44. Brandes, E. *et al.* Targeted subfield switchgrass integration could improve the farm
405 economy, water quality, and bioenergy feedstock production. *GCB Bioenergy* **10**, 199–
406 212 (2018).

407 45. Basso, B., Shuai, G., Zhang, J. & Robertson, G. P. Yield stability analysis reveals sources of
408 large-scale nitrogen loss from the US Midwest. *Sci. Rep.* **9**, 5774 (2019).

409 46. Schulte, L. *et al.* Prairie strips improve biodiversity and the delivery of multiple ecosystem
410 services from corn-soybean croplands. *Proc. Natl. Acad. Sci.* **114**, 11247–11252 (2017).

411 47. Tamburini, G. *et al.* Agricultural diversification promotes multiple ecosystem services
412 without compromising yield. *Sci. Adv.* **6**, eaba1715 (2020).

413 48. Horton, P., Long, S. P., Smith, P., Banwart, S. A. & Beerling, D. J. Technologies to deliver
414 food and climate security through agriculture. *Nat. plants* **7**, 250–255 (2021).

415 49. Martinez-Feria, R. & Basso, B. Predicting soil carbon changes in switchgrass grown on
416 marginal lands under climate change and adaptation strategies. *GCB Bioenergy* **12**, 742–
417 755 (2020).

418 50. Pretty, J. Intensification for redesigned and sustainable agricultural systems. *Science (80-.*
419 *J.* **362**, (2018).

420 51. Möller, K. & Müller, T. Effects of anaerobic digestion on digestate nutrient availability
421 and crop growth: A review. *Eng. Life Sci.* **12**, 242–257 (2012).

422 52. Holly, M. A., Larson, R. A., Powell, J. M., Ruark, M. D. & Aguirre-Villegas, H. Greenhouse
423 gas and ammonia emissions from digested and separated dairy manure during storage
424 and after land application. *Agric. Ecosyst. Environ.* **239**, 410–419 (2017).

425 53. Domingo, N. G. G. *et al.* Air quality--related health damages of food. *Proc. Natl. Acad. Sci.*
426 **118**, (2021).

427 54. NASEM [National Academies of Science, Engineering, and Medicine]. Negative emissions
428 technologies and reliable sequestration: a research agenda. (2019) doi:10.17226/25259.

429 55. United Nations Environment and Climate and Clean Air Programme. *Global methane*
430 *assessment: benefits and costs of mitigating methane emissions.* (2021).

431 56. Liebman, M. & Schulte, L. A. Enhancing agroecosystem performance and resilience
432 through increased diversification of landscapes and cropping systems. *Elementa* **3**, 41
433 (2015).

434 57. Ellis, E. C., Beusen, A. H. W. & Goldewijk, K. K. Anthropogenic biomes: 10,000 BCE to 2015
435 CE. *Land* **9**, 129 (2020).

436 58. Sanderman, J., Hengl, T. & Fiske, G. J. Soil carbon debt of 12,000 years of human land
437 use. *Proc. Natl. Acad. Sci.* **114**, 9575–9580 (2017).

438 59. Intergovernmental Panel on Climate Change. *Climate Change 2014 Impacts, Adaptation,*
439 *and Vulnerability Part A: Global and Sectoral Aspects.* (Cambridge University Press, 2014).

440 60. De Schutter, O., Mattei, U., Vivero-Pol, J. L. & Ferrando, T. Food as commons: Towards a
441 new relationship between the public, the civic and the private. in *Routledge Handbook of*
442 *Food as a Commons* (Taylor & Francis, 2018).

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451 **Author contributions**

452 L.A.S. and B.D. conceptualized and wrote the original draft. All authors contributed to writing
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455 **Competing interests**

456 The authors declare no competing interests.

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458 **Additional information**

459 **Correspondence** should be addressed to L.A.S.

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462

463 **Figure Legend**

464 **Fig. 1 | Diverse, coupled, circular food and energy systems provide more value to society.**
465 Fully coupled, circular food and energy systems—such as in the farm shown—offer substantially
466 more benefit to society than decoupled systems, and could enable large scale, net negative
467 carbon emissions if combined with carbon capture and storage. The farm shown produces corn,
468 soybeans, oats, wheat, rye, beef, and electricity with negative carbon emissions⁷. Ecosystem
469 services in terms of lower greenhouse gas emissions, higher soil carbon storage, improved
470 water quality, and habitat for biodiversity are not currently compensated. The carbon balance
471 could be strongly negative if biogas, an intermediate product on this farm, was upgraded to
472 biomethane and the carbon dioxide byproduct was captured and sequestered. Such farms are
473 models that can be refined and expanded through policies designed to promote ecological
474 intensification, long-term carbon sequestration, bioenergy carbon capture and storage, and
475 markets for ecosystem services. Photo by Omar de Kok-Mercado, Iowa State University.

